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# SOLAR RADIATION FOR SEA-WATER DESALINATION AND ELECTRIC POWER GENERATION VIA VACUUM SOLAR COLLECTORS

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**Abstract**

The present report concerns the energetic potential of vacuum solar collectors which are rather versatile and efficient devices for converting solar energy into thermal energy. Two main energetic applications have been analysed : the first one for a solar sea water desalination plant which has been operated in Abu Dhabi for the past ten years, the other for a conceptual solar thermo-electric-power plant having a fair thermodynamic efficiency ( ~ 15-20 % ).

A simple technology for the manufacture of vacuum solar collectors in a standard mechanical shop is being developed in collaboration between ENEL SpA (DSR-CRIS, Milano) and WED (Abu Dhabi). Such technology should have an important economy-saving potential per se and would also make repair and substitution operations simple enough for the actual operators of the vacuum solar collector system without any need of external assistance.

The technico-operative-economical features of the Abu Dhabi solar desalination plant suggest that the use of novel simplified vacuum solar collectors could have a considerable technico-economical potential.

The analysis of the conceptual solar thermo-electric-power plant focuses on its general layout and singles out key technological issues which ought to be addressed in an overall feasibility study.

## 1. INTRODUCTION

Solar radiation, emitted roughly as the electromagnetic radiation of a black body at a temperature of ~ 5762 K, is essential for the sustainance of all forms of life on earth and is also a most versatile renewable energy source with applications ranging from the simple crop drying of early human civilizations to the complex operation of present-day electro-mechanical systems incorporating centuries of technological and scientific advances. Solar radiation is generally understood as an environment-friendly renewable energy source; however, its conversion into thermal or electric energy must be proven viable both from the technical and the economical viewpoints.

The present report concerns the energetic potential of vacuum solar collectors which are rather versatile and efficient devices for converting solar energy into thermal energy [1]. In the following section, a general description of the technological features of these collectors points out the considerable potential of a new design under development at ENEL SpA (DSR-CRIS, Milano) in collaboration with WED (Abu Dhabi) for achieving a simple and economic manufacturing technology with acceptable maintenance requirements.

The third section concerns a solar sea-water desalination plant, utilizing vacuum solar collectors of advanced design (Sanyo), which has been operated by WED (Abu Dhabi) for the past ten years. The analysis of the main technico-operational-economic features of this plant suggests sizable economic improvements through the use of the new types of simplified vacuum solar collectors now under development.

The fourth section concerns solar thermo-electric-power generation via vacuum solar collectors. The discussion takes into account a general layout and singles out key technological issues which ought to be addressed in an overall feasibility study. The last section summarizes some conclusive comments and ideas for future work.

## 2. VACUUM SOLAR COLLECTORS

Several types of vacuum solar collectors have been developed for heating water (or other suitable fluid) to temperatures up to around 200 °C [1]. An efficient absorption of solar radiation can be achieved with the help of vacuum technology since removing the air between the absorber section and the glazing of a solar collector eliminates loss of heat from the absorber itself by conduction and convection.

The technological problems involved in the manufacture of vacuum solar collectors can be gathered from the illustrative sketch of Fig.1. In a basic design, a single tube made of transparent glass contains a selectively coated absorber plate which is placed axially and is attached to a central copper tube through which flows the heat collecting fluid (generally water plus a suitable antifreeze agent). Since a high vacuum must exist inside the glass tube, adequate manufacturing and vacuum technologies must be applied. Different technological solutions have been devised [1,2]. The one adopted for the Sanyo vacuum solar collectors utilized in the Abu Dhabi solar sea water desalination plant described in section 3 is rather successful as confirmed by field tests made during more than ten years.

The Sanyo key vacuum technological solutions consist in utilizing end caps made in a special metal alloy having the same thermal expansion coefficient as glass, in sealing these caps to the glass tube through a ceramic glass sealant, and in connecting one end of the central copper collector tube to its relative end cap through expansion bellows so as to take care of the different thermal expansions of glass and copper.

The various known designs of vacuum solar collectors encompass rather complex and expensive technologies which tend to limit any large scale application of these devices despite the fact that solar radiation would be, per se, a free source.

A collaboration between ENEL SpA (DSR-CRIS, Milano) and WED (Abu Dhabi) is under way for developing a simple manufacturing technology for vacuum solar collectors. In a novel design under investigation, the basic tools for obtaining both mechanical simplicity and a good vacuum are represented by elastomer-based o-ring seals applied in specially designed caps at the ends of the solar collector glass tube.

## 3. THE ABU DHABI SOLAR SEA WATER DESALINATION PLANT

### Description of Plant

The large solar radiation flux available in the Arab Gulf Region suggests that solar energy may be usefully utilized as a renewable energy source for the desalination of sea water. For testing the technical and economical feasibility of this idea, a demonstration plant was built at Umm Al Nar, about 20 km from Abu Dhabi, within a joint research project between WED (Abu Dhabi) and NEDO (Japan). A picture of this solar desalination plant is shown in Fig.2. The Abu Dhabi desalination plant was designed for an expected yearly average fresh water production of 80 $m^3$/day; it was commissioned in September 1984 and has been in operation since then.

A bank of evacuated tube collectors [2], whose orientation with respect to the sun has been optimised to collect the maximum amount of solar energy, is used to heat the collector fluid (water) to a maximum temperature of about 99 °C. The effective collector area of the bank is 1862 $m^2$.

The heat collecting water leaving the collector bank flows onto the top of a heat accumulator which is of the stratified liquid type and has a total capacity of 300 $m^3$ . The heat collecting water is drawn from the top of the accumulator tank by the heating water circulating pump and is forced to flow into the tube bundle of the first evaporator effect.

The evaporator is of the horizontal tube, falling film, multiple-effect stack type (MES) and consists of 18 effects stacked vertically into two tiers (double stack). This double stack arrangement is incorporated into one evaporator vessel. The evaporator also has 17 preheaters to heat up the feedwater before entering into the first effect, and a final condenser designed to condense the vapor generated in the last (18th) effect. The evaporator has a rated capacity of 120 $m^3$/day. A water seal vacuum pump is used to create the vacuum inside the evaporator shell which is necessary for operation. Electrical power required by this vacuum pump, the feedwater pump, the brine blowdown pump, the product water pump, and the chemical dosing pumps is provided by the main electrical grid.

### Performance of the Collectors

The solar collector field consists of 1064 panels of Sanyo (model STC-BH250 R/L B) evacuated tube collectors. The specifications of a single panel are given in Table 1 [2]. The efficiency $\eta_p$ of a typical panel (measured under ideal conditions in the manufacturer's laboratory) is given by the following equation :

$$\eta_p = 0.913 - 2.46\,x - 1.92\,x^2 \quad \text{with} \quad x = \frac{\frac{T_{in} + T_{out}}{2} - T_{amb}}{I_t} \quad [°\mathrm{C\ m^2\ hr/kcal}]$$

$T_{in}$ , $T_{out}$ , $T_{amb}$ , and $I_t$ being, respectively, the panel inlet and outlet water temperatures, the ambient temperature (all measured in °C), and the solar radiation flux on the absorber plate measured in kcal/hr $m^2$.

Fourteen different collector panels are connected in series by coupling the different header tubes to form one collector array. Each array is provided by an inlet, outlet, and drain valves as well as an air vent. Two such panels are grouped together to form a single array pair with its own support structure as shown in Fig. 3. Thirty eight array pairs are arranged together in a U-shape to form the whole collector field. All the array pairs are connected in parallel.

The whole collector field is divided into six blocks connected in parallel and designated by the letters A,B,C,D,E, and F. Each block has either 12 or 13 arrays. All the blocks are connected together with a piping system which is well insulated with polyurethane foam in order to reduce heat loss from the exterior surface of the pipes.

The daily heat collection efficiency fluctuates due to variations in climatic conditions, heat collecting water temperature, and the frequency of cleaning of the collectors [3]. Figure 4 shows the daily heat collection efficiencies of Block F and for all blocks (the whole field) for the month of September 1985. Around the sixth of this month, all the blocks were cleaned with a jet of water and the result was an appreciable increase in the daily efficiency. The larger daily efficiency of Block F can be attributed to the higher frequency of cleaning of this block (once or twice per week) as compared with the other blocks which were cleaned only once per month. The aim was to keep Block F always clean as a standard reference for all the other blocks. Recent experimental data (taken in 1995) show that a drop in efficiency around 15% has taken place during the 10 years of operation of Block F. Similar results obtain for the other blocks.

The vacuum inside the glass tubes is expected to worsen as years go by due to two effects.

i) leakage at brazed sections where the glass tube and end caps are sealed with ceramic glass,

ii) outgas generation by the absorber plate when its temperature becomes rather high as during a sunny day when the collectors are drained and there is no water flowing through the copper tube.

In order to limit the rate of vacuum drop, a device, called "getter", is used to absorb any outgas liberated by conversion into a white powdery oxide. The getter used by Sanyo consists of an alloy of barium and aluminum which was heated to about 1,000 ~ 1,200 °C using a high frequency source which causes part of the metal to flash into vapor and subsequently deposit onto the inside of the glass tube forming a black or silvery patch or flash mark. The getter remains effective as long as the color of the flash mark has not changed from black or silver into white. In the course of time, the original flash mark is replaced by a smaller black or silver mark in the center surrounded by a white cloudy patch. The vacuum starts to drop as soon as the original patch is completely oxidized. The condition of the getter is therefore indicative of the state of the vacuum inside the glass tube.

Table 2 gives the results of observations made on the getters of Block F during 1984, 1986, and 1995. The symbol "Δ" indicates that the flash mark is starting to decrease while the symbol "▲" indicates that the getter area has mostly diminished. In these vacuum tubes, the fact that the getter is still there indicates that the initial degree of vacuum has been maintained. The symbol "X" indicates that the flash mark has turned completely white suggesting that the degree of vacuum has deteriorated.

The experimental observations suggest that slow leakage at brazed sections is mostly to blame for the deterioration in the getter. The process of slow leakage is such that once it has started, it will not stop. As a consequence, in all vacuum tubes in which the getter area has begun to diminish through slow leakage, the getter will eventually turn white, diminishing the degree of vacuum.

## Economic Aspects of a 1,200 $m^3$/day Solar Sea Water Desalination Plant

On the basis of the operative experience of the Abu Dhabi plant, it is possible to make cost projections for a plant ten times larger, i.e. having a rated capacity of 1,200 $m^3$/day. The specifications for this plant are given in Table 3 [4].

The plant construction cost (based on the 1985 capital costs figures escalated at the rate of 4% per year) is detailed in Table 4 [5]. The cost of a single collector panel was estimated at 512 $/ m$^2$ and the cost of the structural support, piping, etc. was taken as 279 $/m$^2$. As can be seen from this table, the cost of the collector field (collectors,support, piping, etc.) represents about 75% of the total manufacturirg cost of the plant. Therefore, a substantial saving in fabrication cost of the plant if the vacuum solar collectors could be produced at a lower cost by changing or modifying their design and manufacturing procedure.

## 4. SOLAR THERMO-ELECTRIC- POWER PLANTS

Various types of solar thermo-electric-power plants have been designed in view of achieving a large-scale tapping of solar radiation . We mention in particular those based on the *nonconvecting salt gradient solar pond* [6,7], the *centralized mirror field* [8], the *ocean thermal energy converter* [9,10], and the *Luz parabolic trough collector field* [8]. We note that all these solar power systems have proven technological feasibility and that even relatively small working temperature differences have been exploited (e.g. ~ 25 °C in an ocean thermal energy converter and ~ 55 °C in a solar pond system).

In a most simplified description, we may assume that in a thermo-electric-power plant, electric power is generated by converting the mechanical power produced by a suitable working fluid which is made to flow in a closed cycle absorbing heat (vaporization stage) from a heat source at a high temperature $T_h$ and releasing heat (condensation stage) to a heat sink at a low temperature $T_l$.

The ideal (Carnot) efficiency for thermal to mechanical energy conversion, $\eta_c = (T_h - T_l) / T_h$, with temperatures measured in degrees Kelvin, may be utilized in a preliminary technical evaluation of any novel conceptual thermo-electric-power scheme.

Clearly, the temperature difference $\Delta T = T_h - T_l$, between heat source and heat sink, can only be as large as the structural integrity and operability of all plant components make possible.

Since vacuum solar collectors can be designed for reaching temperatures over 150 °C in their heat collecting fluid, they might be utilized in a solar-thermo-electric-power plant for the generation of electric power with a fair thermodynamic efficiency (~15-20 %).

A general simplified layout of a solar thermo-electric-power plant utilizing vacuum solar collectors is presented in Fig. 5. The operation of this solar power plant is immediately apparent.The energy input required for driving a conventional vapor power cycle is furnished by solar radiation which heats a body of water circulating in a closed pressurized loop (p ~ 5 bar) consisting of three main components connected through thermally insulated conduits :

i) the solar collector units where the flowing water absorbs solar radiation and is heated to a temperature $T_h$ ~ 150 °C,

ii) the pressurized vessels, with thermally insulated walls, for the storage of hot pressurized water,

iii) the heat exchanger section for heating and vaporizing the working fluid of the vapor power cycle.

Leaving aside the well established technology of vapor power cycles, it is clear that the potential for development of the present solar-thermo-electric-power plant depends, essentially, on two key components : the *vacuum solar collector units* for efficient absorption of solar radiation, and the *pressurized vessels* containing hot pressurized water for efficient heat storage.

## Vacuum Solar Collector Units

The technology for manufacturing efficient vacuum solar collectors is available; however, it appears necessary to reduce manufacturing and maintenance costs hence the collaborative research project, mentioned in section 2, for the development of simplified vacuum solar collectors. Apart from the technological problems inherent in the manufacturing of single collectors, quite important is also the general assemblage , with proper thermal insulation, of the various connecting manifolds of the many vacuum solar collector units for an adequate fluid flow distribution in the required series or parallel patterns.

## Pressurized Vessels for the Storage of Hot Pressurized Water

Since the solar radiation reaching a given site does not have a constant and continuous flux, any solar thermo-electric-power plant must have a sizable thermal storage for an adequate and continuous operation.

In the present solar power scheme, heat storage is provided by thermally-insulated pressurized vessels filled with hot pressurized water (temperature $T_h \sim 150$ °C, pressure $p_h \sim 5$ atm) . A very efficient thermal insulation from the environment is required so that a rather thick lining of insulating material is to be applied on the outer wall-surface. In view of reaching an efficient thermal insulation, also double-walled pressurized storage vessels, incorporating a good vacuum in the space between inner and outer wall after the Dewar bottle principle, may be analysed.

While the technological feasibility for constructing pressurized vessels is granted, economical feasibility for large-scale heat-storage must be proven. Since the pressure and temperature ranges are not prohibitive, a specific goal-oriented research will certainly clarify this important point.

We assume steel as basic construction material in view of its outstanding performance records and use versatility. Preliminary evaluations for large spherical and cylindrical pressurized steel vessels for the storage of hot pressurized water (temperature $T_h \sim 150$ °C, pressure $p_h \sim 5$ atm) provide acceptable values for critical physical parameters.

## Preliminary Evaluations for a 100 kw Solar Thermo-Electric-Power Generating Plant

*Assumptions :*

- continuous (24 hr/day) generation of electric power : $W \sim 100$ kw
- power cycle operating temperatures : $T_h \sim 150$ °C, $T_l \sim 40$ °C
- power cycle efficiency : $\eta \sim 0.15$ ( ideal efficiency $\eta_c \sim 0.26$ )
- power cycle heat source thermal power : $W_{th} \sim W/0.15 \sim 666$ kw
- solar radiation power flux : $I_s \sim 0.8$ kw/m$^2$
- 6 hour daily collection of solar radiation with efficiency $f \sim 0.3$
- temperature drop of sun-heated water (temperature $T_h \sim 150$ °C, pressure $p_h \sim 5$ atm) through the boiler heat exchanger : $\Delta T \sim 10$°C.

The required hot water flow rate $Q$ [m$^3$/s] is found from the thermal balance equation :

$$W_{th} \sim Q \rho c_p \Delta T$$

where $c_p \sim 4.18$ kj/kg is the specific heat of water and $\rho \sim 0.92.10^3$ kg/m$^3$ its density. With the assumed values of $W_{th}$ and $\Delta T$, we find $Q \sim 0.0173$ m$^3$/s .

The volume of hot pressurized water required daily is

$$V \sim Q \cdot 8.64\ 10^4\ s \sim 1500\ m^3 .$$

The required overall surface $S_c$ of the solar collector units is found from the energy balance :

$$f\ I_s\ \Delta t\ S_c \sim W_{th}\ 8.64\ 10^4\ s$$

With the assumed values : $f \sim 0.3$, $I_s \sim 0.8$ kw/m$^2$, $\Delta t \sim 2.16\ 10^4$ s, and $W_{th} \sim 6.66\ 10^2$ kw, we find $S_c \sim 1.11\ 10^4$ m$^2$ .

We notice that under the present assumptions the electric power generated per unit collection surface is $W/S_c \sim (10^2 / 1.11\ 10^4)$ kw/m$^2$ $\sim 10$ w/m$^2$.

## 5. CONCLUSIONS

Vacuum solar collectors are versatile and efficient devices which may find useful applications in various solar energy systems, for providing domestic heat, for sea water desalination, and for electric power generation.

A research collaboration between ENEL Spa (DSR-CRIS, Milano) and WED (Abu Dhabi) is under way for the development of mechanically simple vacuum solar collectors since present manufacturing technologies are rather complex and costly and also generally exclude substitution and repair of defective components. The proposed manufacturing technology, based on the use of elastomer o-ring vacuum seals, is expected to have an important economy-saving potential per se in all basic manufacture, repair, and substitution operations all of which could be made by the actual operators without any need of external assistance. The novel simplified vacuum solar collectors would be expected to significantly improve the performance of the solar sea water desalination plant in Abu Dhabi.

As for the envisaged solar thermo-electric-power plant utilizing vacuum solar collectors, fairly promising preliminary technical evaluations suggest the usefulness of a full range feasibility study.

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## TABLES

TABLE 1 SPECIFICATIONS OF SANYO MODEL STC-BH250 R/L B COLLECTOR PANEL.

| | |
|---|---|
| Absorber plate | selectively coated stainless steel<br>absorptivity $\alpha \geq 0.91$<br>emissivity $\varepsilon \leq 0.12$ |
| Absorber plate area per panel | 1.75 $m^2$ |
| Absorber plate | stainless steel, selective coating |
| Absorber tube | copper, 12.7 mm O.D. |
| Glazing | glass tube, 80 mm O.D. |
| Number of glass tubes per panel | 10 |
| Insulation | glass wool, 20 mm thick. |
| Circulation flow rate | 700-1,800 l/hr |
| Maximum operating pressure | 6 bar |

TABLE 2 GETTER CHECK RECORD FOR BLOCK F SHOWING NUMBER OF GLASS TUBES AFFECTED.

| Getter condition ⇨ | Flash mark started to decrease "Δ" | Flash mark mostly disappeared "▲" | Deterioration in vacuum "X" |
|---|---|---|---|
| Sept. 1984 | 0 | 0 | 0 |
| Feb. 1986 | 6 | 0 | 3 |
| Feb. 1996 | 10 | 1 | 3 |

TABLE 3 SPECIFICATIONS FOR A 1,200 $m^3$/day SOLAR SEAWATER DESALINATION PLANT.

| Plant component | Item | Specifications |
|---|---|---|
| Collector | Type<br>Number of panels<br>Total absorber area | Evacuated glass tube, type STC-BH2<br>10,640<br>18,620 $m^2$ |
| Heat accumulator | Type | Thermally stratified |

| | | |
|---|---|---|
| | Capacity | 3,000 $m^3$ |
| Seawater evaporator | Type | MES |
| | Capacity | 1,200 $m^3$/day |
| | Heat consumption | 29.2 kcal/kg dist. |
| | No. of effects | 30 |
| Power consumption | Collector pump | 54 kW |
| | Evaporator pumps | 155 kW |
| | Total | 209 kW |

TABLE 4 ESTIMATED FABRICATION COST FOR A 1,200 $m^3$/day SOLAR SEAWATER DESALINATION PLANT.

| Plant component | Fabrication cost (1,000 US$) | Percent of total % |
|---|---|---|
| Collector panels | 9,541.3 | 48.46 |
| Collector supports, piping, etc. | 5,204.3 | 26.43 |
| Heat accumulator | 543.17 | 2.76 |
| Evaporator | 4,130 | 20.97 |
| Diesel generators (300 kVA) | | |
| For normal service | 171.20 | 0.87 |
| For emergency | 97.83 | 0.50 |
| Total fabrication cost | 19,687.85 | 100 |

FIGURES

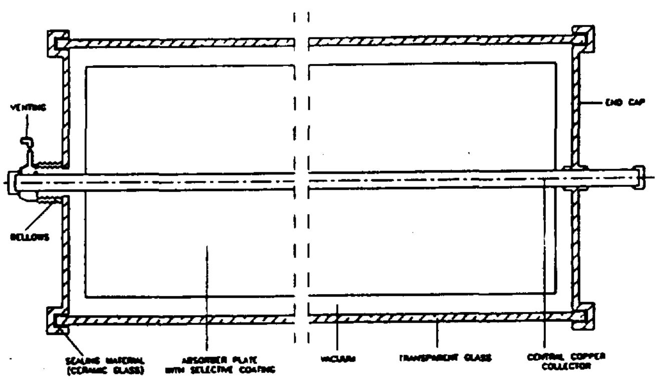


**Fig. 1. Illustrative sketch pointing out technological manufacturing problems of vacuum solar collectors.**

Fig. 2. Picture of the solar sea water desalination plant in Abu Dhabi.

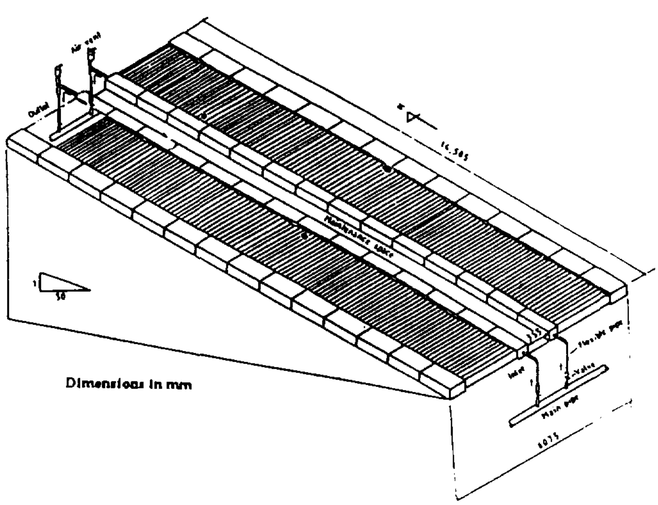


Fig 3. Isometric view of a collector array pair.

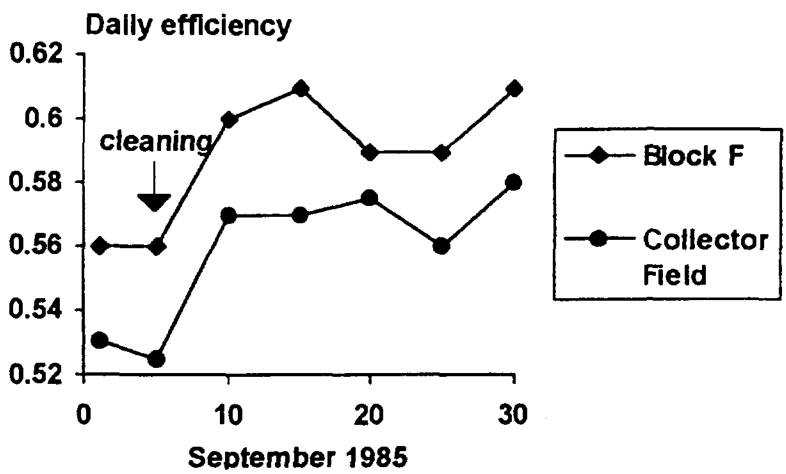


Fig. 4. Daily efficiencies of Block F and of whole collector field in September 1985.

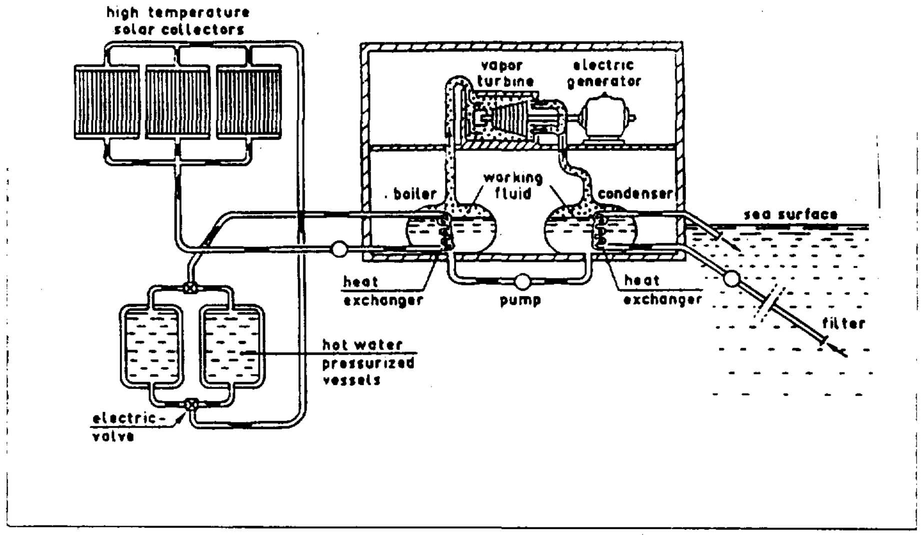


Fig.5. Simplified diagrammatic representation of a solar thermo-electric-power plant exploiting vacuum solar collector units. The high temperature heat source is provided by sun-heated water (temperature ~150 °C, pressure ~5 atm) stored in pressurized vessels with thermally insulated walls. The heat sink is provided by deep sea water (or by any suitably available fluid body in the environment).