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SOLAR THERMAL CONVERSION TECHNOLOGIES, TRENDS IN RESEARCH, DEVELOPMENT AND COMMERCIALIZATION*

prepared by

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INTRODUCTION

In some countries notably Australia, Israel, and the USA there has been a sustained programme of solar energy R & D since the middle of this century. This programme was accelerated in the mid - seventies when there was an increasing awareness of the finite nature of conventional fossil fuel reserves and of the fragility of a world energy economy based heavily on petroleum products.

Over the last thirty years therefore there has been a continual development of products designed to harness the incoming stream of solar electromagnetic radiation by converting the energy flux to useful heat. Products are now, in some cases, commercially available to provide a thermal output at various temperature levels which can be matched to the load requirement.

Acceptance and use by the public in many countries has often been dictated by the local energy cost factors and by the political decision making process rather than by the technological feasibility of the solar product under consideration. There are many papers and books written which deal with the institutional constraints militating against the introduction of new solar technologies into an existing energy infrastructure, e.g. HEEDE et.al. [1].

In recent times with the apparent 'oil-glut' on the international market there has been an increasing tendency to decry the usefulness of solar energy in providing a substitution for conventional fuels purely based on short term economics even though the stability of the international oil delivery system has not been improved in the intervening post OPEC formation period.

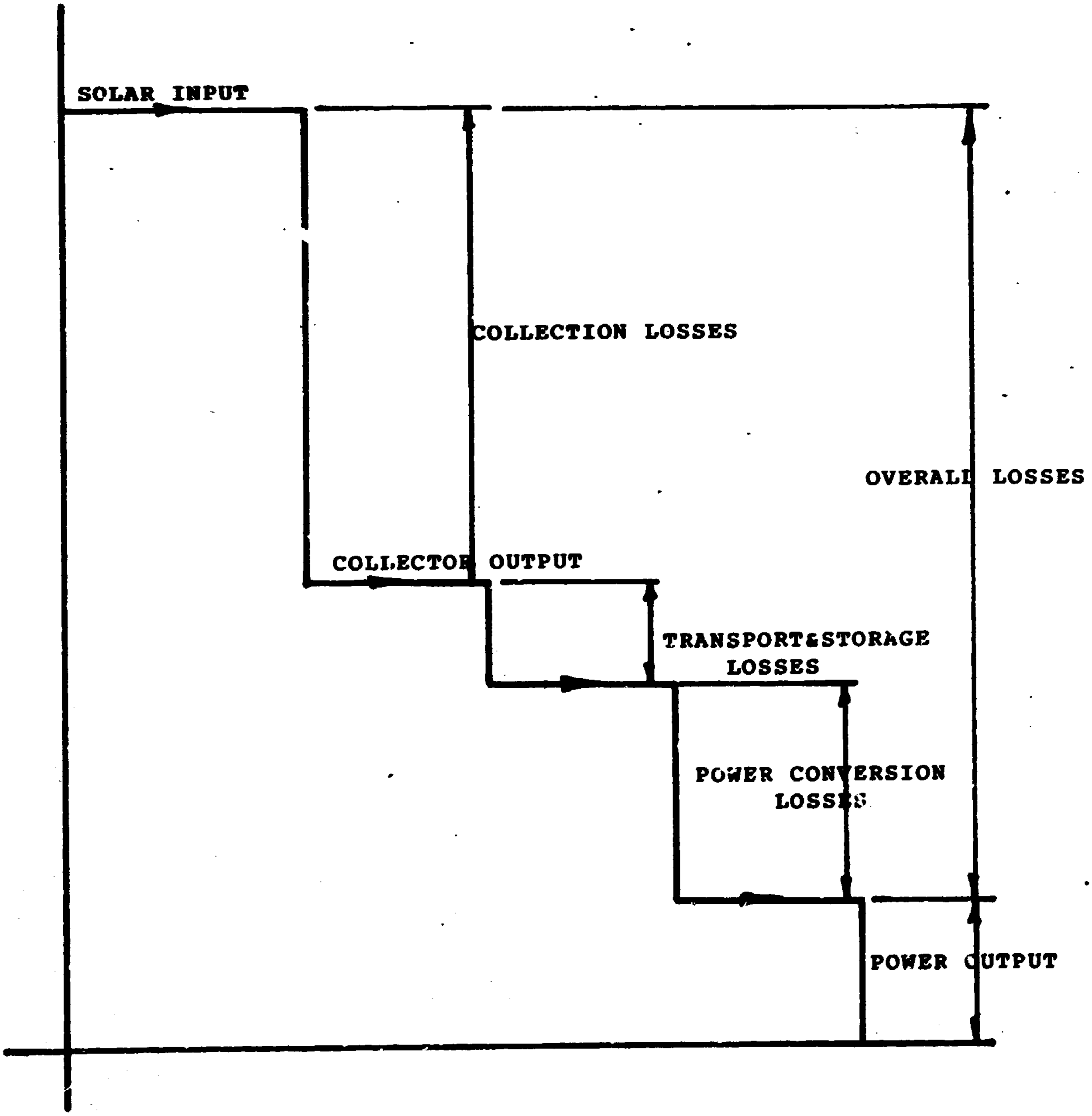
SOLAR THERMAL SYSTEMS

Any overall solar thermal system is made up of individual components, and sub-systems designed to cope with the tasks of solar radiation collection, conversion, thermal transport, and storage and delivery to the load either
(i) in the form of heat as in a solar industrial process heat system or
(ii) in the forms of mechanical or electrical power as in a solar thermal power system., see Fig. [1].

Solar collectors.

The working heart of any solar thermal system is the solar energy collection device which is designed to capture the incoming solar radiation and convert this to output heat. Any such collector must have an absorbing surface of high solar absorbtance and preferably of low infra-red emittance to optimise the collection process by minimising the infra-red thermal losses. In practice such surfaces are known as selective surfaces. The second essential feature of such a device lies in the provision of fluid flow passages to allow extraction from the absorber of the thermal energy collected.

To increase the useful operational temperature of a collector it becomes necessary to
(i) provide better thermal insulation of the absorbing element,
(ii) to provide a collector cover transparent to the incoming solar radiation and opaque to re-emitted radiation (usually formed from glass) and
(iii) to minimise or eliminate the internal heat transfer effects of free or natural convection.



ENERGY FLOW DIAGRAM

Figure 1

Low Temperature Collectors.

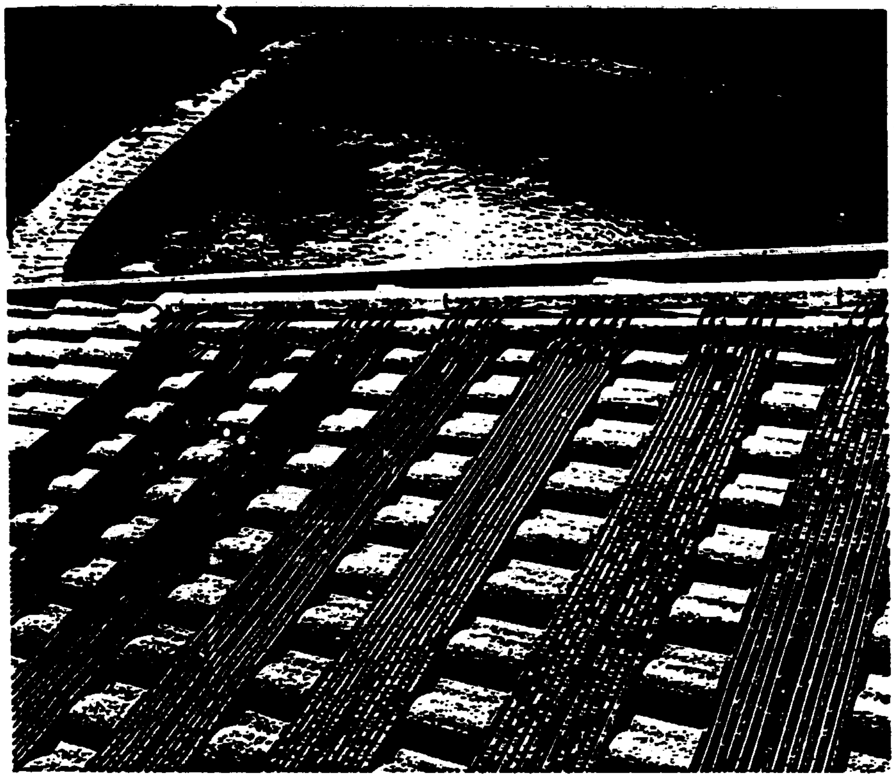
This design process leads one through the unglazed flat plate collector conventionally used for swimming pool heating and for low temperature heat supply to heat pumps, through the glazed flat plate collector in domestic and industrial hot water systems to the advanced flat plate collectors such as honeycomb collectors and non-concentrating vacuum tubes., Charters [2], see Figures 2 & 3. Each of these collector types has been extensively developed over the last 20 years and a summary of some data relevant to their use is given in Table 1.

Typical low temperature collectors for thermal applications at temperatures < 120°C.

Collector Type.	Materials	Max Operational Temperature	Approx. cost US$/$m^2$
Unglazed collector (Fig. 2 (a))	Synthetic Rubber (EPDM)	40°C	60
Glazed Collector (Fig. 2 (b))	Cu or Al plate Glass, acrylic, or polycarbonate cover	80°C	120
Honeycomb collector (Fig. 3 (a))	As above plus glass or Teflon honeycomb	100°C	150
Vacuum tube collector (Fig. 3 (b))	Glass tubes or Glass tube plus Cu or Al plate	120°C	150

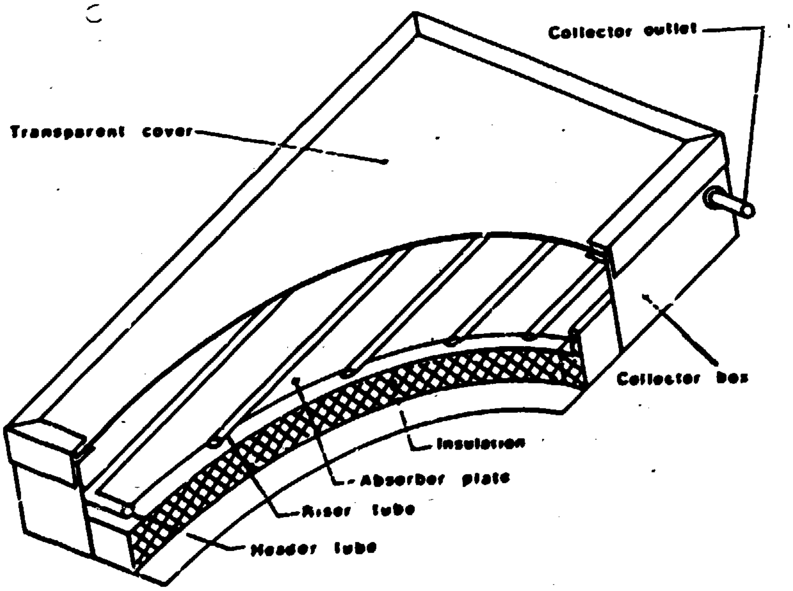
* Conventionally working fluid is water or air but other options such as heat transfer oils and refrigerant fluids have been used.
* Costs are based on selling price of collector modules, and do not include installation costs. Typical installed costs may be as high as US$350/$m^2$.

Table I



UNGLAZED STRIP COLLECTOR

Figure 2(a)



GLAZED FLAT PLATE COLLECTOR

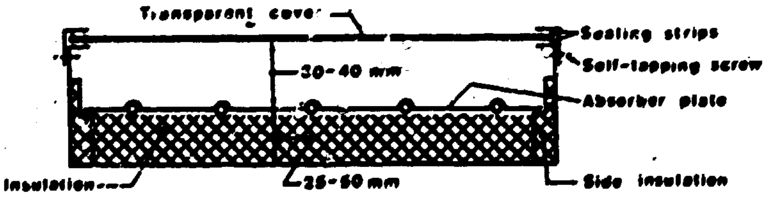
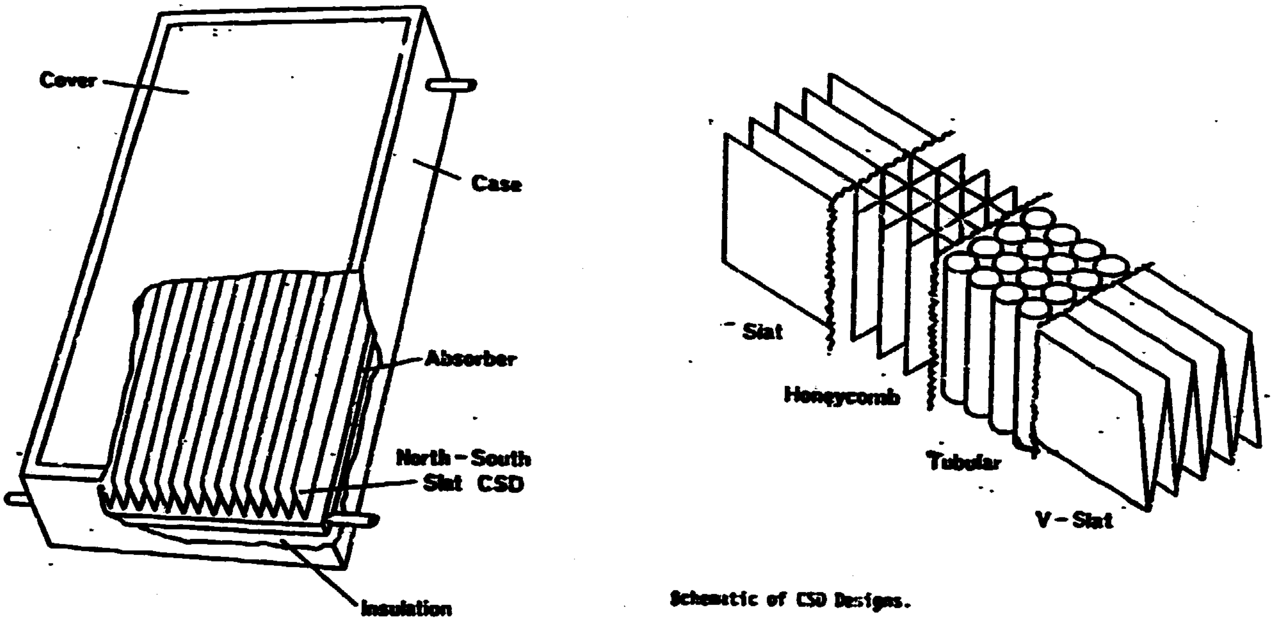


Figure 2(b)

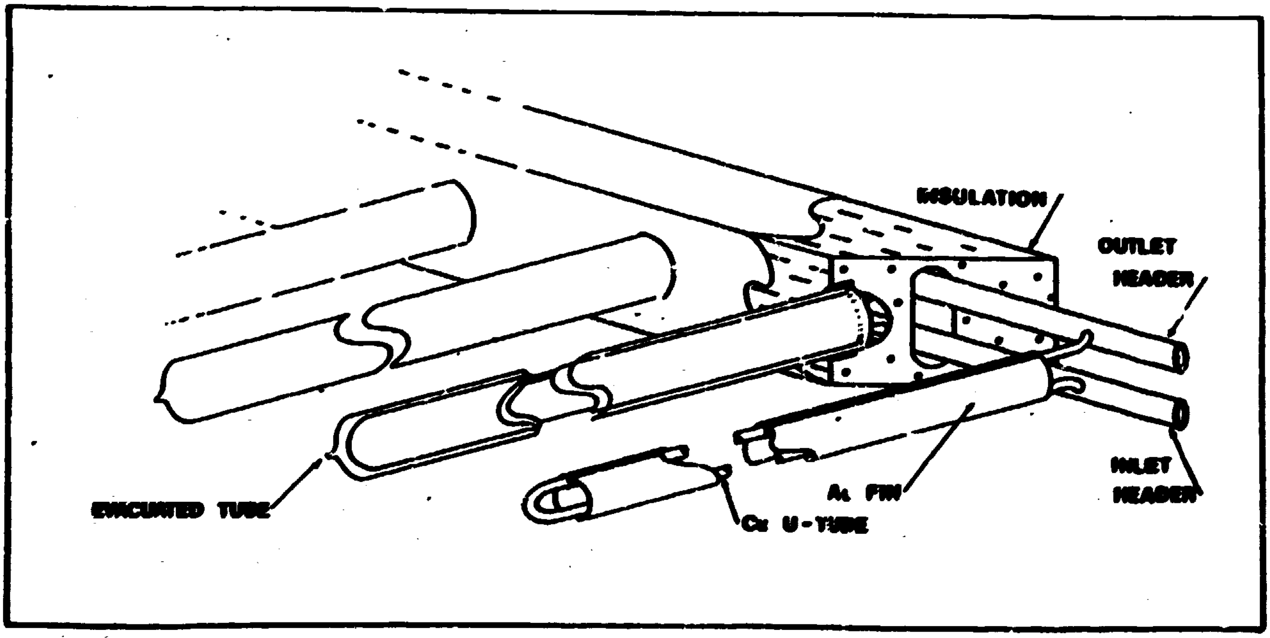


Schematic of Flat-Plate Collector with Slat CSD.

Schematic of CSD Designs.

HONEYCOMB COLLECTOR

Figure 3(a)



VACUUM TUBE COLLECTOR

Figure 3(b)

Solar Ponds.

Another variant of low temperature collector which has been developed and partially commercialized over the last five years is the stratified water body known as a solar pond (Fig. 4). This solar energy collector lends itself to large scale use in practice provided there is availability of land, water and salt at reasonable costs. The operation and cost economics of such ponds are highly site specific because of the wide variation in geophysical soil properties and the large variations in material costs at the sites chosen. Typically solar ponds constructed in the USA and in Australia have cost between US\$40-00/m^2 to US\$90/m^2 and have been able to deliver thermal energy at about US\$5/GJ to US\$10/GJ. Lower cost figures reported from Israel should be treated with some caution as their site conditions and brine availability, close to the Dead Sea, provide specific advantages to such collection systems. The largest pond built to date covers 250,000m^2 (62 acres) at Beith Ha-Arava - TABOR & DORON [4].

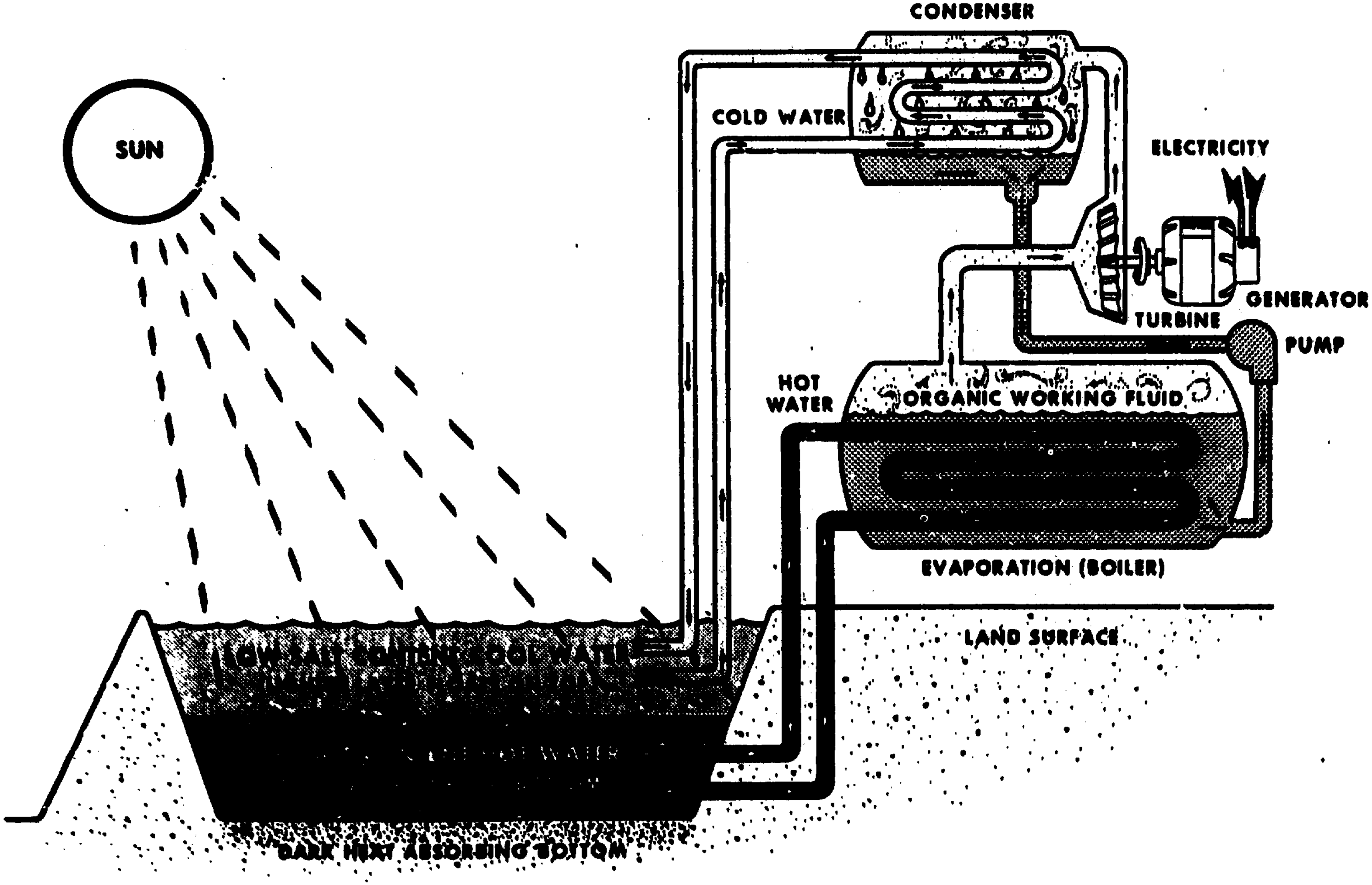
Medium to High Temperature Collectors.

For purposes requiring heat supply at temperatures in excess of 120°C it is necessary to provide some method of concentrating the incoming solar flux using lens or mirror systems - Fig. 5, 6. Currently all commercially available concentrating systems are based on mirror reflectors and the concentration ratios (based on area of aperture to receiver) may range from 10/1 for low concentration line focus parabolic troughs up to 300/1 for a solar thermal heliostat power tower system such as in Solar One, Barstowe, California or for a point focus paraboloidal dish system, STINE & HARRIGAN - [5].

It should be noted that as the concentration ratio increases, in an attempt to achieve higher operational temperatures, the cost of the collection process will increase substantially due to the increasing accuracy required for sun tracking.

Because of this increased complexity and cost several proposals have been considered for fixed mirror assemblies in which the absorber element is constrained to track the sun. Such collectors based on hemispherical dishes can be operated under higher wind speed conditions than the power tower or dish plant, see Figure 7.

Some typical data for concentrating collectors is presented in Table II.



SOLAR POND POWER SYSTEM

Solar pond generating concept

Figure 4

Typical Concentrating collectors for use at medium to high temperatures: 150°C-550°C

Collector type	Materials	Max. Operational Temperature	Approx. Cost US$/m²
Vacuum Tube (Fig. 5 (a))	Glass tubes or Glass tubes plus Cu or Al plate	200°C	250
Parabolic Trough (Fig. 5 (b))	Rear silvered glass mirrors plus vacuum tube	350°C	250
Paraboloidal dish (Fig. 6 (a))	Rear silvered glass mirrors plus metal absorber	650°C	300
Heliostat field (Fig. 6 (b))	Rear silvered glass mirrors plus metal boiler	520°C	200

* Costs are based on selling price of collector modules and do not include installation.

Typical installed system costs may be as high as US\$750/m².

Table II

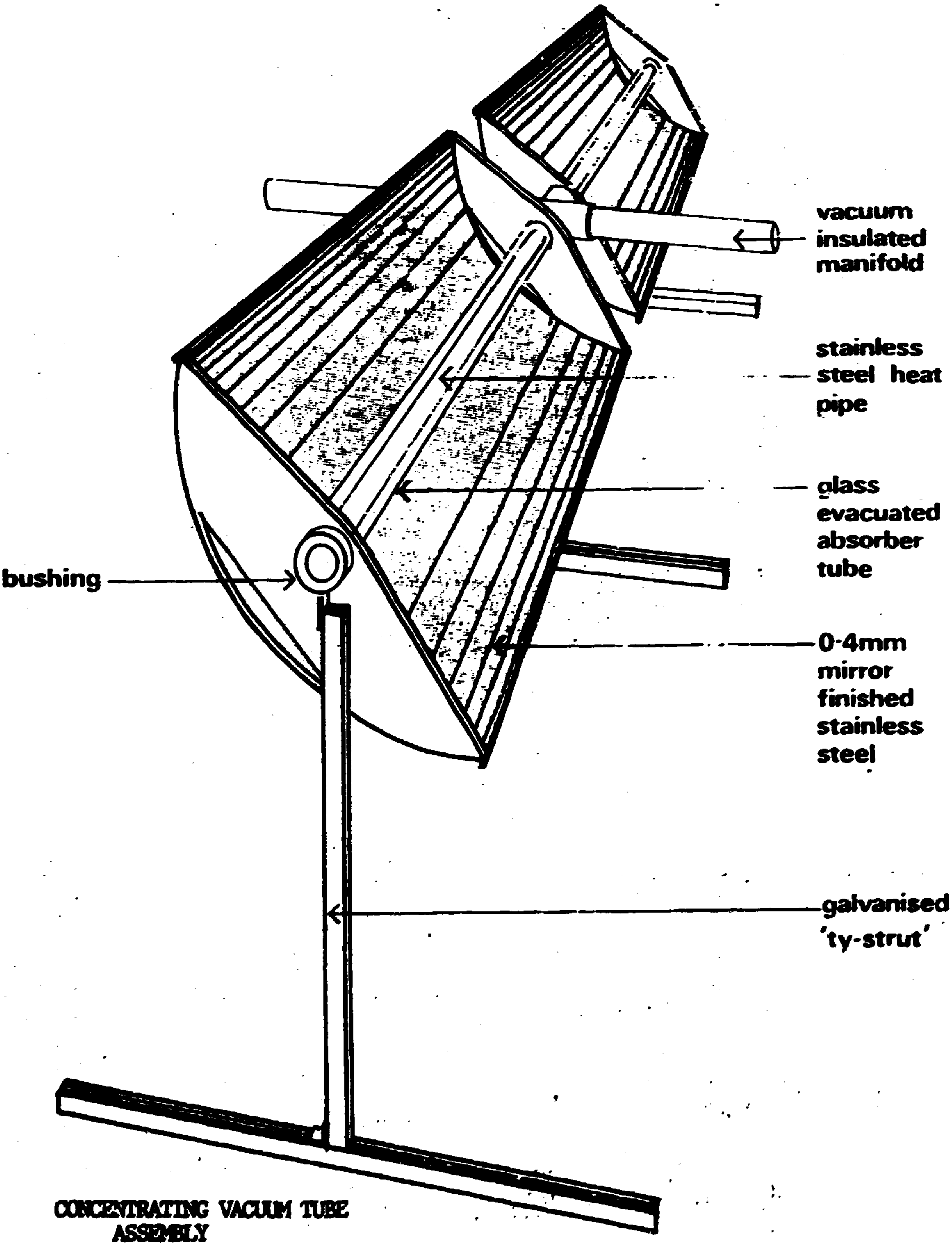
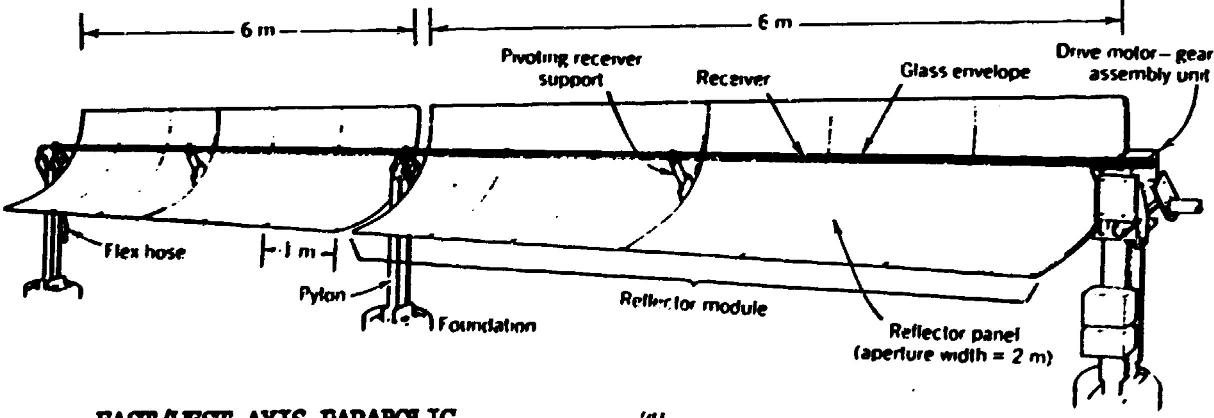

vacuum insulated manifold
stainless steel heat pipe
glass evacuated absorber tube
0·4mm mirror finished stainless steel
bushing
galvanised 'ty-strut'
CONCENTRATING VACUUM TUBE ASSEMBLY

Figure 5(a)

The high efficiency parabolic tracking solar reflector is capable of producing water temperatures up to 300°C.

TRACKING PARABOLIC TROUGH



EAST/WEST AXIS PARABOLIC TROUGH ASSEMBLY

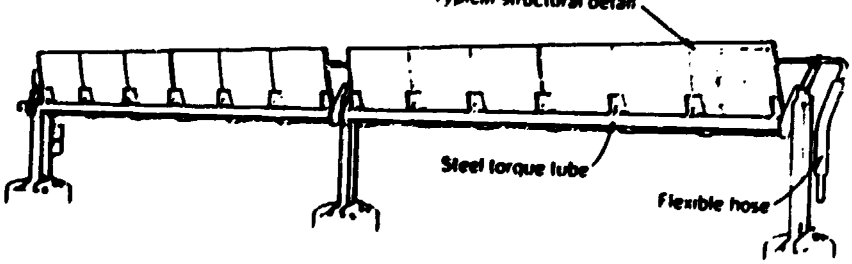
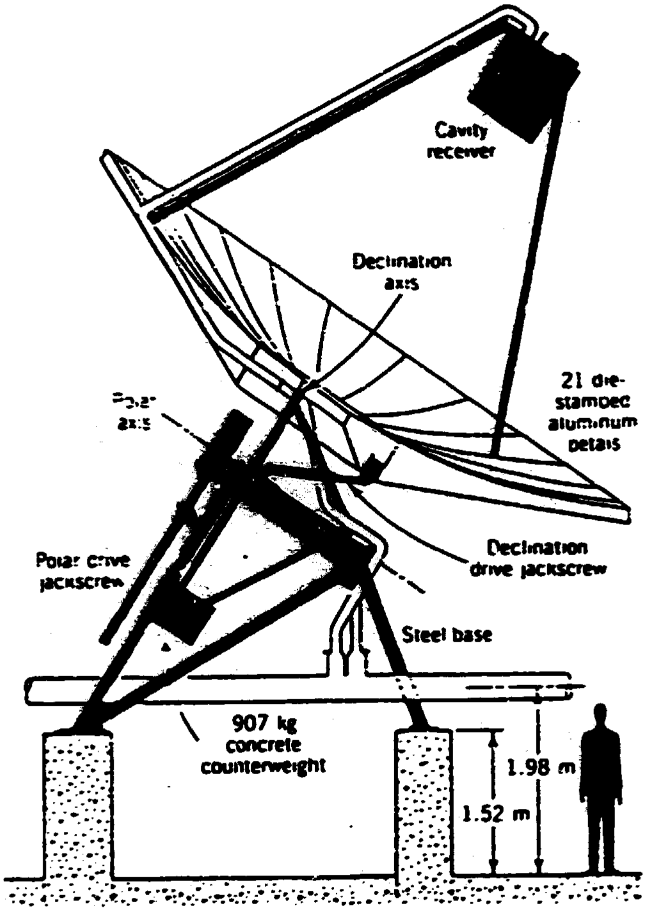
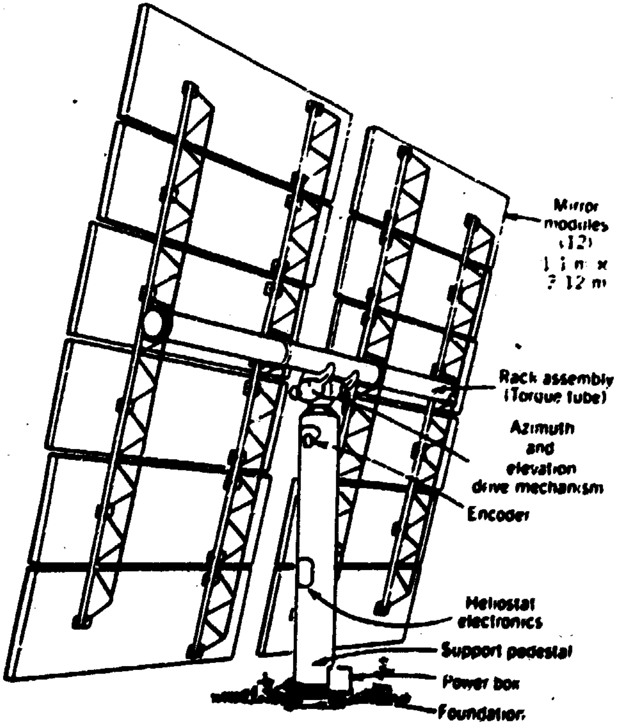


Figure 5(b)

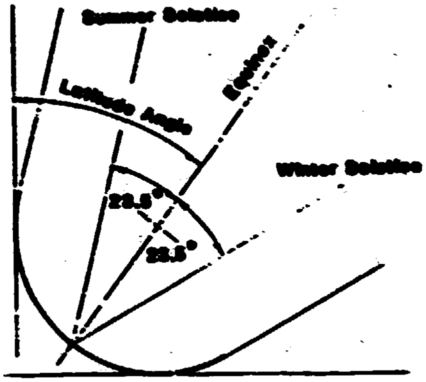


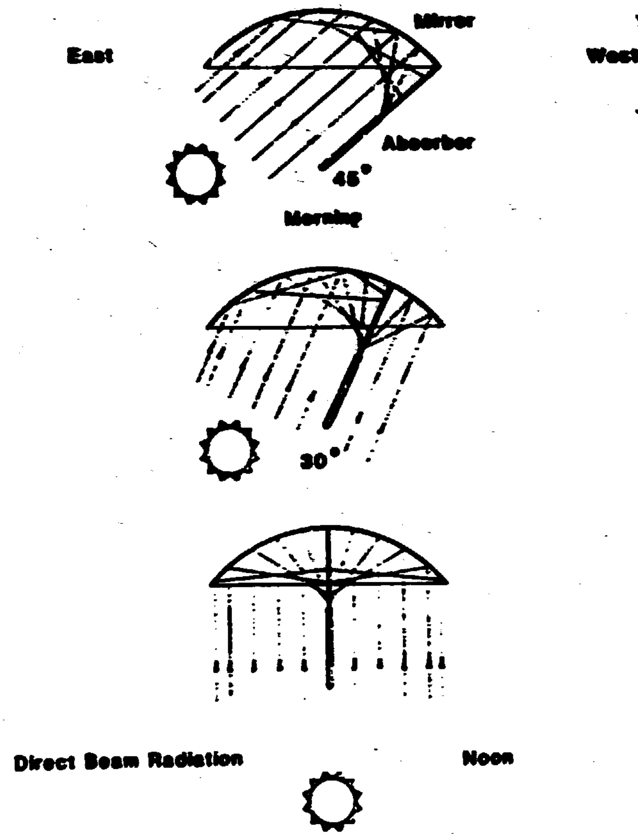
PARABOLOIDAL DISH MODULE
Figure 6(a)

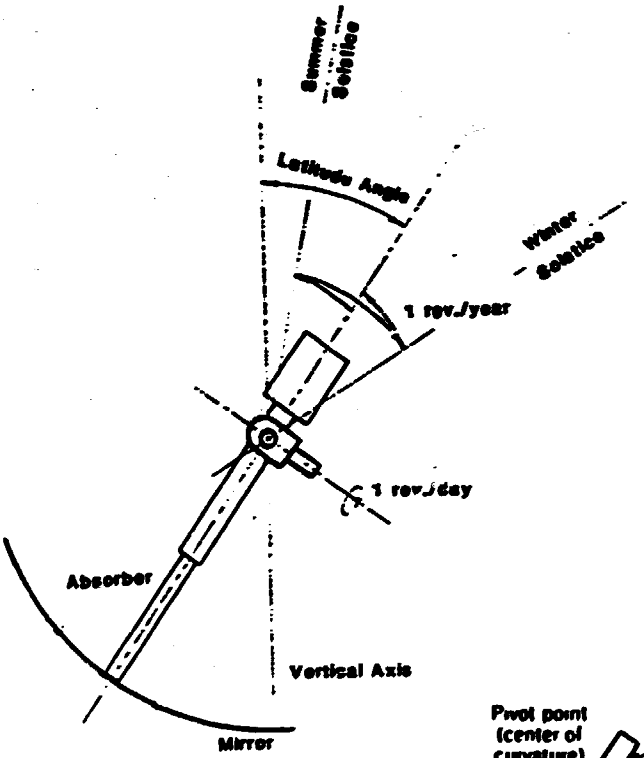


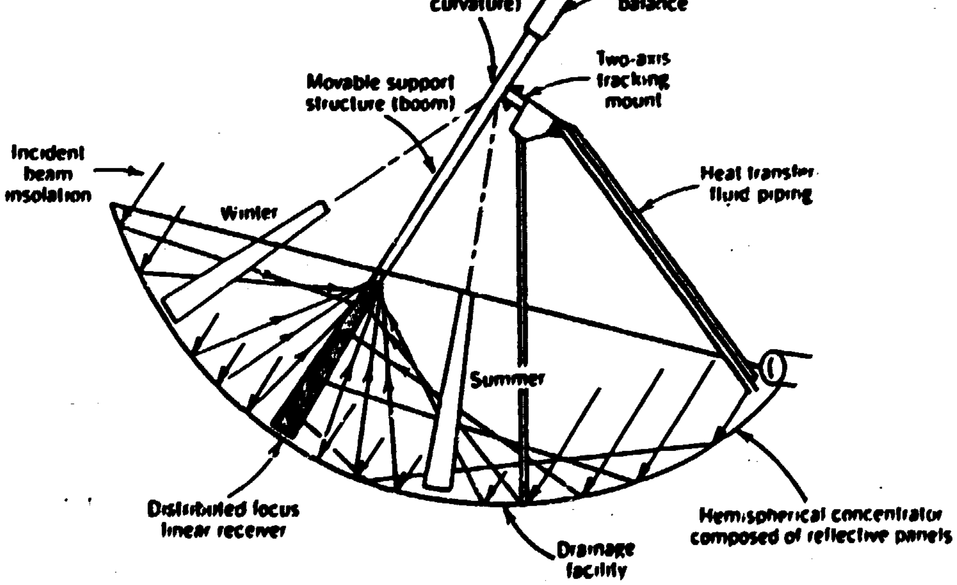
HELIOSTAT MODULE

Figure 6(b)









STATIONARY REFLECTOR/TRACKING ABSORBER UNIT
Figure 7

THERMAL STORAGE SUB - SYSTEMS

Pressurised and unpressurised fluid thermal storage tanks.

Because of the high cost of organic heat transfer fluids considerable effort has been devoted to the use of water or steam as a storage medium in pressurised vessels. However, these evident cost savings are somewhat balanced by the costs associated with high pressure storage tanks eg water at 300°C requires a pressure vessel to withstand about 9 MPa(or 90 atmospheres). High temperature systems tend to use inert solid materials of high thermal capacity, such as rock, to store energy. Such a system using refractory blocks made from MgO bricks has been suggested for use with a high temperature closed loop helium system TURNER [6].

Phase change thermal storage systems.

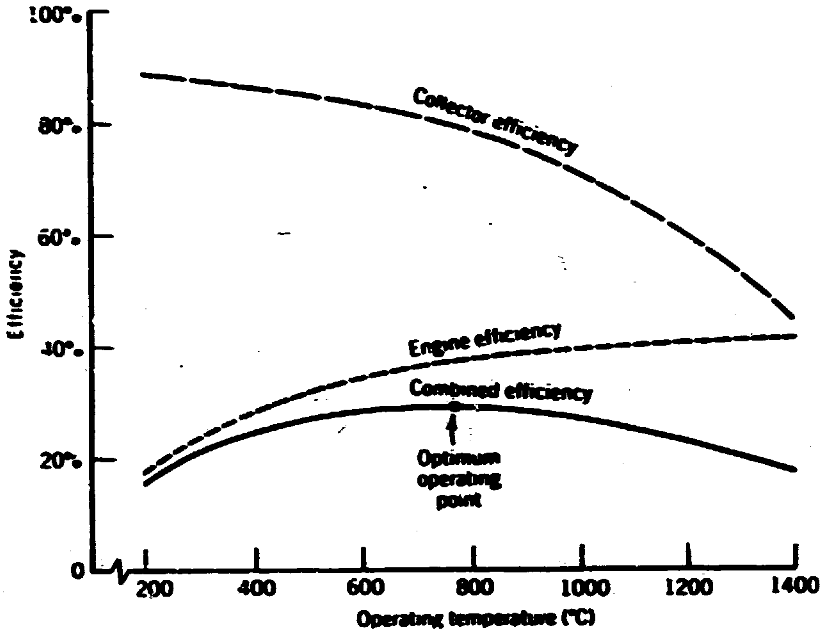
The use of phase change materials has been widely canvassed for thermal storage elements because of the potential to increase the energy density of the storage thus reducing the overall storage tank size and cost. This brings into play, however, the need for an in-tank heat exchange element carefully designed, to take into account the low thermal diffusivities commonly eccountered with solid phase change materials.

POWER CONVERSION SUB - SYSTEMS.

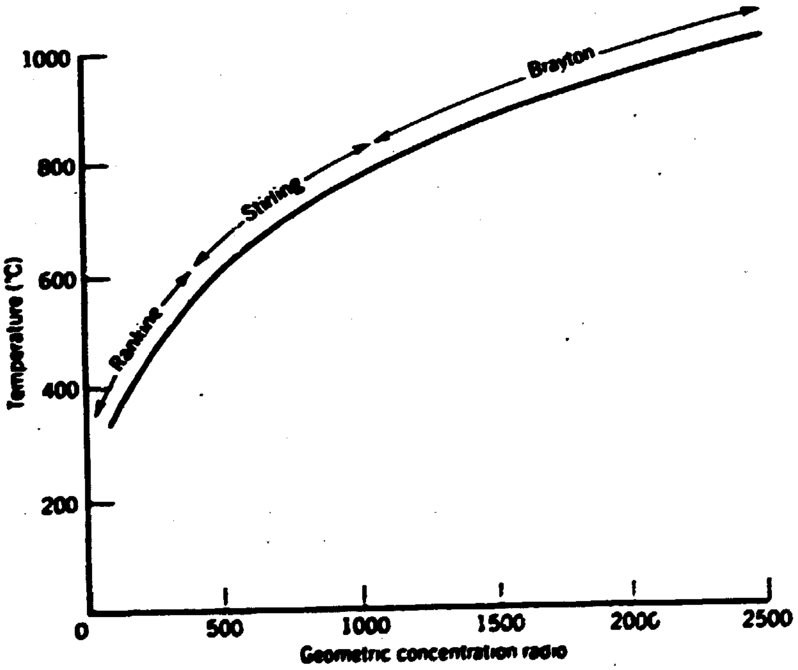
If the ultimate aim is to achieve mechanical or electrical work output from the solar input then it is essential to consider the range of power conversion devices available to perform such a task.

At the lower temperatures available from non-concentrating collectors it is common to use Rankine cycle plant. The prime mover in this case may be a reciprocating engine, a screw expander, or a turbine unit. Fluids commonly used include steam, toluene, or one of a large range of refrigerant fluids such as Freon R-11 or Freon R-113. The final selection of fluid will depend on the comparative cycle thermal efficiency and overall cost effectiveness of the plant. Typical cycle thermal efficiencies range from 5% to 8% depending on the maximum cycle temperature available for the solar collectors, MACDONALD [7].

At the high temperatures potentially available from concentrating collector systems the choice of thermodynamic cycle is widened to include Stirling cycle engines (often associated with point focus paraboloidal dish systems) and Joule (or Brayton) cycle plant using gas turbines (often associated with heliostat power tower systems). Once again typical cycle thermal efficiencies of the prime movers range from 17% to 35% depending on the maximum cycle temperature available from the solar collectors, see Figure 8.



TYPICAL COLLECTOR & ENGINE EFFICIENCY CURVES C=1000/1



OPERATIONAL TEMPERATURE V GEOMETRIC CONCENTRATION RATIO FOR A TYPICAL COLLECTOR

Figure 8

SOLAR THERMAL APPLICATIONS.

The usefulness of solar thermal collection devices has been amply demonstrated on a range of agro-industrial food and chemical processing plant as well as in power production and total energy facilities.

Typical applications could include;
Fish farming
Greenhouse and space heating
Air conditioning and refrigeration
Food and beverage processing
Dairy pasteurisation and sterilization
Desalination and crop drying
Remote area power supply

Each of these applications has been demonstrated using one or other of the solar thermal collector systems described in preceding sections of this paper.

COLLECTOR TESTING, CERTIFICATION AND STANDARDS.

Because of the need to rank the relative advantages and disadvantages of solar collectors and solar thermal systems considerable work has been carried out to develop national and international (ISO) standards for collectors. These include materials standards and minimum thermal performance standards to ensure that the equipment will satisfy the requirements of the task in hand.

Most of the industrial units now produced commercially are made to high standards of workmanship and backed by standard commercial warranties on materials and equipment, GOSWAMI [8]. This is an essential pre-requisite for any major move to widespread use of solar thermal conversion technology and should be carefully considered by Governments and Industries early on in the research, development and commercialisation programme.

COST EVALUATION OF SOLAR THERMAL PLANT.

As all solar equipment in highly capital intensive it is essential to carry out full cost analyses to evaluate the benefits in the long term of installing such equipment, Charters [9]. Some of the relevant factors to be considered in such an evaluation using life cycle costing and discounted cash flow analyses include,

* The life expectancy of the plant and system components.
* The rate of inflation in the economy.
* The prevailing discount rate.
* The prevailing capital costs of the plant.
* The maintenance and operational costs of the plant.
* The estimated rate of inflation on conventional energy prices.

With the inclusion of such factors a realistic appraisal can be given of the cost effectiveness of the solar thermal system as compared with its conventionally fuelled counterpart.

ECONOMIC CRITERIA FOR THE SELECTION OF SOLAR THERMAL PLANT.

For solar thermal process heat plant the important parameters will be the total installed cost ($) and the value of the thermal energy generated in $/GJ as compared with the costs of providing this energy burning conventional fuels.

For solar thermal power plant, on the other hand, the economic indicators will be capital cost/unit power of generating capacity ($/kW) and the annualised cost of the electricity generated in c/kWh. In most off-grid applications the competing system will be a relatively small scale diesel generator set, often badly matched to the load and poorly maintained so that the generating costs using distillate will range from US40c/kWh to US$2.50/kWh under typical Australian 'outback' conditions.

TYPICAL SOLAR THERMAL PLANT FOR INDUSTRIAL PROCESS HEAT & POWER GENERATION.

Application (IPH)	Collector Type	Working Fluid	Max 'T'	Process 'T'
Textile drying	Flat plate collector	Water/ethylene glycol	132°C	88°C
Bleaching Process	Parabolic trough	Pressurised Water	216°C	175°C/0.86MPa
Concrete Curing	Point Focus	Pressurised Water	149°C	158°C/0.52MPa

Application (Mechanical or Electrical Power).

Irrigation Scheme	150kWe	Parabolic trough	Caloria HT-43	288°C	Toluene 268°C/1.31MPa
Total Energy	400kWe 626kg/h steam 468kW cooling	Parabolic Dish	Syltherm 800	399°C Steam	382°C/4.83MPa
Electricity	225kWe	Spherical Bowl	Water/Steam	649°C	Steam 538°C/6.2Mpa
Electricity	5 MWe	Solar Pond	Brine	90°C	Organic fluid 75-80°C
Electricity	10MWe	Power Tower	Water/Steam	516°C/10.4Mpa	

Table III

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