# Vacuum Tube Liquid-Vapor (Heat-Pipe) Collectors

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**ABSTRACT**

The high temperature operation of Evacuated Heat Pipe Tubes (EHPT) and their very low radiant heat losses make them ideal for solar water heating, solar space heating, desiccant air conditioning, thermal driven cooling and industrial process heating applications. The tubular, iron-free cover glass tube and vacuum within protect the absorber coating and all structure materials from corrosion and adverse weather conditions. The vacuum tube envelope minimizes heat loss and ensures high collector durability and steady performance.

The heart of the EHPT is a heat pipe. The heat pipe is an evaporating-condensing device for rapid heat transfer. The latent heat of vaporization is transferred by means of evaporating a water-based liquid in the solar heat inlet region, and condensing its vapor in the discharge region. The heat source is the absorber plate that is continuously bonded to the heat pipe. The condenser (heat discharge region of the heat pipe) is in direct contact with a manifold, which serves as a heat exchange/sink. In addition, the heat pipe has a diode function; i. e. heat transfer is always in one direction - from absorber to the manifold (thus collector to storage tank) and never the reverse.

A thermodynamic valve adjusts the heat flux of the heat pipe to a minimum level, when the collector operation temperature approaches a preset maximum point. The adjustment of the valve is achieved by utilizing a memory metal. The metal changes its elasticity module at the programmed temperature and pushes the plug closing the heat pipe passage at the condenser. Consequently, a twofold effect occurs. Firstly, the hot vapor stream from the evaporating region to the condenser is constrained. Secondly, the condensed heat transfer fluid is partially captured in the condenser. As a result, the amount of effective heat transfer fluid inside the heat pipe is proportionally reduced. Thus this thermodynamic valve controls the operating temperature at the collector level.

## 1. HEAT PIPE TECHNOLOGY

The basic heat pipe is a closed container consisting of a capillary wick structure and a small amount of vaporizable fluid.

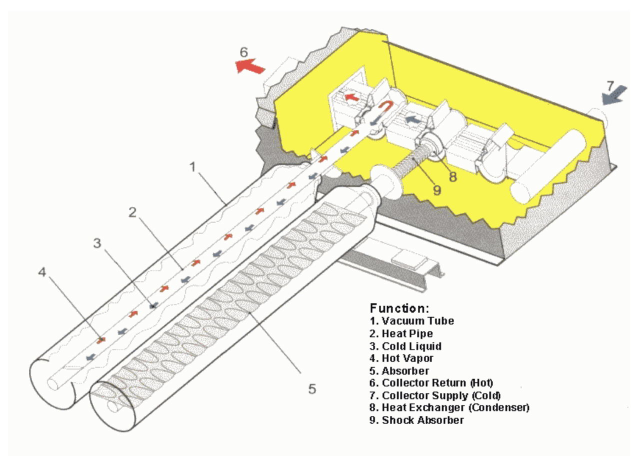


**Figure 1**: *The Titanium Nitride Oxide coated absorber fin transfers heat to the condenser via a heat pipe. The heat pipe is bonded continuously to an absorber fin inside a vacuum-sealed tube, as shown. Condensers are inserted into a chamber in the manifold header where a heat transfer liquid circulates.*

The heat pipe employs an evaporating-condensing cycle, which accepts heat from an external source. This external heat source elevates the heat pipe's liquid to its boiling region. The heat pipe liquid evaporates (latent heat) and then it releases latent heat by reverse transformation (condensation) at the heat sink section. This process is repeated continuously by a gravity return feed mechanism of the condensed fluid back to the heat zone.

A heat pipe acts as a high conductance thermal conductor. Due to its thermal-physical properties, its heat transfer rate is thousands of times greater than that of the best solid heat conductor of the same dimensions.

In an EHPT a sealed cooper pipe (heat pipe) is bonded to a copper fin (absorber plate) that fills the evacuated glass tube. A small copper condenser is attached to the top of each heat pipe. These condensers are inserted into a super insulated heat exchanger chamber in the manifold at the top of the solar collector system.

As the sun shines on the absorber, the heat pipe liquid boils and hot vapor rises towards the condenser on the top of the heat pipe. Water, or glycol, flows through the manifold and cools the condensers. This heat transfer fluid circulates through another heat exchanger and gives off its heat to a media (typically potable water) that is stored in a solar storage tank.

The maximum operating temperature of a heat pipe is the critical temperature of the used heat transfer medium. Since no evaporation/condensation above the critical temperature is possible, the thermodynamic cycle interrupts when the temperature of the evaporator exceeds its critical temperature.

In the solar collector, the condensation zone is located at a higher elevation than the evaporation zone. Gravity returns the condensed fluid back to the evaporating region. Therefore, there is no need of capillary wick structure.

## 2. PHOTO THERMAL CONVERSION

A solar collector absorbs solar radiation and converts it into heat (photo thermal conversion). The EHPT absorbs the maximum incident solar radiation with a minimum of thermal and optical loss. The absorber coating characteristics, glass seals, mechanical shock absorber, and the vacuum insulation are the most important parts of an EHPT solar collector.

Titanium – Nitride – Oxide (TINOX) absorber coating is a highly selective absorber. It has high absorption (low reflection) for the solar spectrum and low emissivity for the infrared heat radiation.

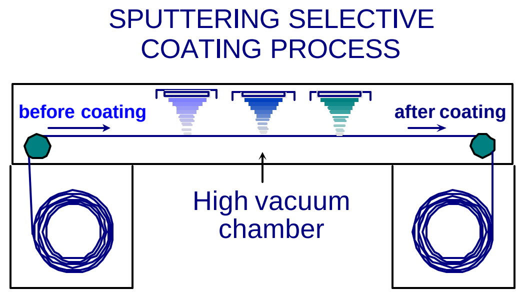


**Figure 2a:** *The sputtering is a physical manufacturing process that involves coating a substratum with metal particles. The manufacturing process takes place in a high vacuum chamber and the coating process involves three stages, stabilizing layer coating, semi-conductor layer coating (radiation absorbent layer) and anti-refection layer coating.*

The coating used in the EHPT is composed of a very thin TINOX coating (thickness about 60 nm). It is deposited by using a patented evaporation process on a copper substrate. This technology makes an additional important step towards ecology. The TINOX manufacturing process is non-toxic and emission free.

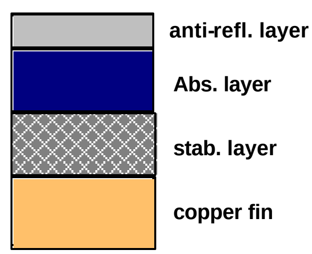


**Figure 2b:** *The sputtering selective-coating absorber is high resistance to long-term vapor condensation, high corrosive sulfur dioxide and high operating temperature. The effective resistance measured in the test is equivalent to a product life span exceeding 30 years.*

In the vacuum chamber three target plates are installed above the copper fin. By creating a high-tension field between the targets and the copper fin and a magnetic field parallel to the target plates, positive helium ion release titanium atoms from the target plate. The atoms strike the copper fin and because of high kinetic energy of the atoms they attach themselves to the top of the copper fin. During the process this copper fin passes three targets plates. First, a stabilizing layer of pure titanium is laid on the copper fin. This layer gives the surface of the copper fin long-term stability. Secondly, the titanium atoms react with oxygen to form an absorbent layer of titanium oxide (TINOX) on the first layer. In this semi-conductor layer titanium atoms are orientated in such a way that 98% of incoming solar radiation can be absorbed. Finally, an anti-reflection layer is added on the absorbent layer. The anti-reflection layer has a very low reflection index and can let 98 to 99 % of incident solar radiation pass through the layer to be absorbed by the semi-conductor layer.

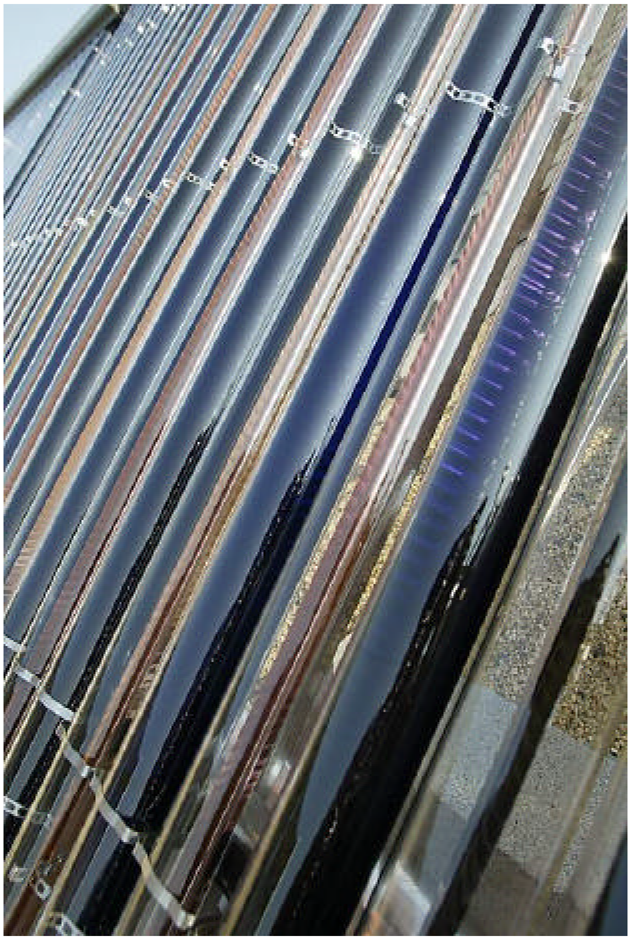

**Figure 2c**: *Due to the high quality of materials and automated manufacturing process, the evacuated heat pipe collectors are durable and reliable.*

TINOX coatings reach their high temperatures by selective absorbing behavior. They suppress radiation losses in the infrared wavelengths region by a very low emission coefficient. At short wavelengths a high absorption coefficient is responsible for excellent radiation absorption:

| | |
|---|---|
| Emission | $\varepsilon_{\mu}$ (212 $^{o}$F) = 0.05 |
| Absorption | $\alpha_{sol} > 0.94$ |
| Maximum temperature in vacuum | $T_{Max}$ = 707 $^{o}$F |
| Temperature at 50 % efficiency | $T_{50\%}$ = 536 $^{o}$F |

## 3. TECHNIQUES TO RESTRICT THE OPERATING TEMPERATURE OF HEAT PIPE

Solar radiation is intermittent and varies stochastically. The load of thermal energy also varies with time. Therefore, the solar collector system faces potential overheating whenever the solar gain and the load are significantly mismatched.

### 3.1 Heat pipe critical temperature

One technique to limit the maximum operating temperature of the Tube is to select a heat pipe fluid with suitable physical properties and correct quantity. This causes the heat pipe to contain only vapor (no fluid) at the critical point, causing the heat transfers mechanism to stop. Another limiting strategy is a thermo-dynamic valve.

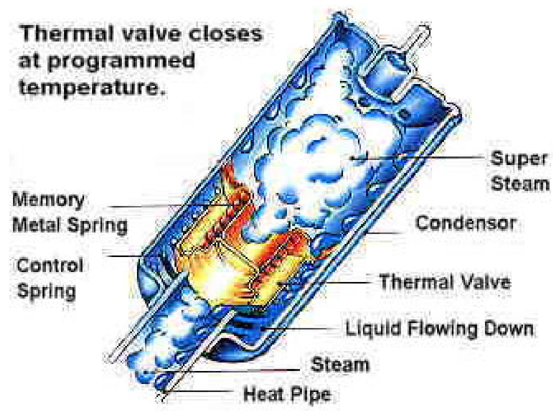


**Figure 3a**: *The Memory Metal Spring is compressed by another spring. The neck of Heat Pipe is open, allowing super steam flow into the condenser. The Heat Pipe is transferring heat to the condenser.*

### 3.2 Thermo-dynamic valve

In the newly developed Memotron tube the maximum working temperature is controlled by means of a memory metal spring (thermo-dynamic valve) that is positioned inside the heat-pipe's condenser. The valve adjusts the heat flux of the heat pipe to a minimum level when the operation temperature approaches its limit.

The memory metal is programmed to change its shape at a pre-set temperature. This allows for the condenser fluid to be retained inside the condenser. When the programmed temperature has been achieved, the memory metal spring expands and pushes a plug against the neck of the heat pipe blocking the return of the condensed fluid and stopping heat transfer.

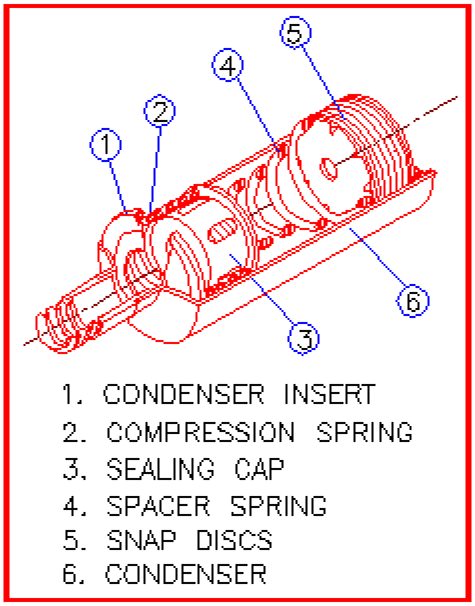


**Figure 3b**: *The Memory Metal Spring has expanded and pushed the plug closing the Heat Pipe neck. The condensed liquid is captured in the condenser. The vapor flow and the heat transfer process of the Heat Pipe are suppressed.*

At temperatures below the maximum programmed limit, the spring contracts allowing the condensed fluid to return to the lower section of the heat pipe. It is then evaporated due to the heat from the absorber plate, transferring thermal energy to the condenser. The patented Memotron tube utilizes state of the art technology and provides complete safety through effective temperature control.

## 4. HIGH VACUUM SEALING TECHNIQUES

The major interest in evacuated solar collectors is that the vacuum ($10^{-5}$ Torr) essentially eliminates conduction and convection losses. The vacuum chamber, being the best possible insulation for a solar collector, suppresses heat losses and also protects the absorber plate from external adverse conditions. This results in exceptional performance, far superior to any other type of solar collector.

Due to the atmospheric pressure and technical problems related to the sealing of the collector casing, the construction of an evacuated flat-plate collector is extremely difficult. To overcome the enormous atmospheric pressure, many internal supports for the transparent cover pane must be introduced.

### 4.1 Mechanical evacuation process

The mass production of fluorescence light bulbs set a precedent for the tubular solar collector design. Building a tubular evacuated solar collector and maintaining of its high vacuum, similar to light bulbs and TV tubes, is a well-established production process. The ideal vacuum insulation of the tubular evacuated solar collector, obtained by means of a suitable evacuating process, has to be maintained during the 25+ years life of the device to reduce the thermal losses through the internal gaseous atmosphere (convection losses).

### 4.2 Chemical evacuation process

The high vacuum of $10^{-5}$ Torr is achieved by carefully preventing all the possible gas efflux from internal solid materials to the vacuum chamber. However, practical experience shows that maintaining the high vacuum level of the tube over a long time period is challenging. It has been found that numbers of evacuated solar collectors face the problem of vacuum degradation due to poor sealing techniques. Therefore, highly reliable vacuum seals for the EHTP are key quality criteria as the seals withstand the thermal stress and temperature shocks.

To absorb material out-gassing due to the high operational temperature, the vacuum is maintained through a Barium getter inserted in the collector tube. The dose of Barium must be calculated for the targeted life cycle of the system. Thermomax tubes are designed to maintain their high vacuum for a period of 25-30 years under normal operation conditions. System stagnation reduces the life expectancy of tubes.

## 5. THERMAL AND MECHANICAL SHOCK ABSORBER

EHTP utilizes the matched glass-to-metal sealing technique to achieve hermetic high vacuum seals. The glass and alloys are carefully selected based on coefficients of thermal expansion. This thermal expansion match avoids stresses in the seal and maintains the integrity of the seal. In practice over the past 23 years of production, it has been shown that the patented glass-to-metal seals are strong and durable. These seals form a bond layer, which is elastic and tolerant to glass displacements during extreme temperature cycling.

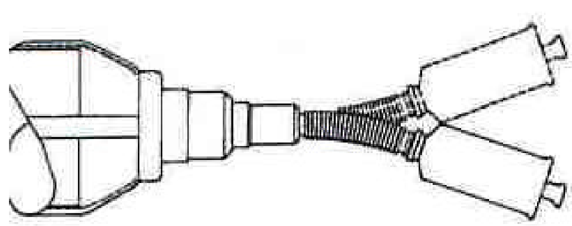

**Figure 4**: *A patented flexible neck system absorbs both thermal*

*and mechanical shocks.*

A flexible stainless steel connection system absorbs mechanical forces caused by mounting structures due to temperature differences.

## 6. EVACUATED HEAT PIPE PERFORMANCE

European and North American independent testing authorities confirm the superior performance of EHTP collectors. The Teknikum Rapperswill of Switzerland tests yield to the following thermal performance equations (Test Report No. 264, August 1997):

$$\eta = 0.84 - 2.02\ (Tm - Ta)/G - 0.0046\ [(Tm - Ta)/G]^2$$

Tests conducted by Florida Solar Energy Center of USA (FSEC Solar Collector Test Report No. 97005, May 1998) are consistent with the performance test reports by Technikum Rapperswill:

Linear fit:

$$\eta = 0.82 - 2.19\ (Tm - Ta)/G$$

Second order fit:

$$\eta = 0.81 - 1.23\ (Tm - Ta)/G - 0.0122\ G\ [(Tm - Ta)/G]^2$$

where:

Tm = mean collector temperature, (Toutlet+Tinlet)/2 [$^o$C]
Ta = ambient air temperature [$^o$C]
G = Solar irradiance [W/sq m]

These test results are shown in the following graph:
(G= 800 W/sq m)

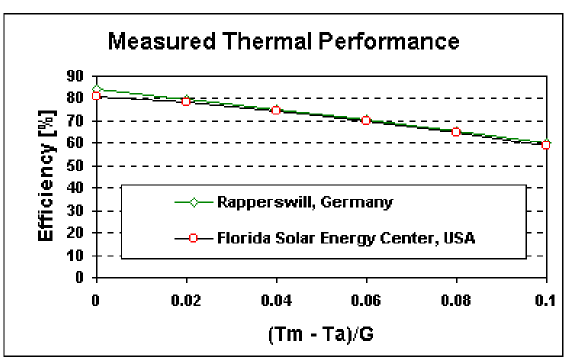


**Figure 5**: *Test results of National and International authorities.*

## 7. APPLICATION OF EVACUATED HEAT PIPE TUBES

Evacuated solar collectors are specifically designed for year-round operation in regions with high humidity and regions with cold winters. They are lightweight and modular; allowing the tubes to be integrated into nearly all-architectural designs.

The high efficiency of EHPT reduces the surface area of collectors relative to conventional flat-plate panels. These collectors are designed to allow flexibility of tube orientation and are relatively insensitive to placement angle (between 25 – 65 degrees).

**Figure 6:** *The flexibility and low wind resistance of Thermomax tubes offer unique designs. They are used as awing in the above installation.*

EHPT collectors transfer the heat to a copper pipe in the manifold via heat exchanger. This eliminates collector contact with the heat-transfer fluid (water, antifreeze), provides a true double-walled telltale heat exchanger, and allows the manifold to accept city water pressures. Therefore, the collector system is suitable for open loop, closed loop, drain down, and drain back or recirculation systems as well as steam generation

**Figure 7**: *The Pentagon evacuated heat pipe solar system is the largest solar thermal system of its type in North America with a rated peak thermal output of 75.6 kW.*

Evacuated solar collectors are unique in that they work effectively at high temperatures, even in adverse weather conditions. This means that regardless of the collector temperature, the same amount of thermal energy will be added to the heat reserve (storage tank) on any given day. Therefore, a smaller storage tank, designed for high temperatures, can be used instead of the traditional large solar hot water tanks.

**Figure 8**: *The Thermomax tubes at the Kennedy Space Station in Florida supplies 53,000 BTUH (200 + $^{o}$F) to drive desiccant cooling units.*

Since there is a high correlation between solar gain and cooling load, solar assisted cooling systems are very attractive. Absorption chillers and desiccant air-conditioning systems are fired directly by EHPT collectors. During winter seasons a solar air-conditioning system provides hot water and space heating.

**Figure 9**: *The 6.3 kW solar thermal energy (system shown above) in Sedona, Arizona, is the space heating primer source.*

## 8. <u>SUMMARY</u>

Thermomax's advanced solar thermal systems are a breakthrough in solar thermal technology. They continue a tradition of innovation begun over five decades ago when NASA invented the heat-pipe technology. Thermomax brings this superb technology to the market place as an economically competitive option for Solar Energy.

Twenty-three successful years of solar water heating have resulted in the integration of Evacuated Heat Pipe Solar Collectors (EHPT) into high temperature industrial process heating, advanced thermal driven cooling systems, residential space heating, and domestic hot water systems. Robotic productions of Evacuated Heat Pipe Tubes are similar to the light bulb industry and are meeting Quality Systems ISO 9001 and ISO 9002. The manufacturing operations of evacuated heat pipe solar collectors are fully automated and geared for volume production.

The working temperature of an EHPT is controlled by the physical properties of the heat pipe fluid and a thermo-dynamic valve. A high vacuum ($10^{-5}$ Torr) envelope eliminates conduction and convection losses while protecting the absorber coating. With the latest developed Titanium – Nitride – Oxide (TINOX) absorber coating temperatures above 450 $^{o}$F are achievable. The TINOX coating gives higher absorption and lower emission, thus resulting in improved collector performance and durability.

Furthermore, because of the vacuum envelope, weathering influences such as condensation and moisture will not cause early deterioration of its interior materials and performance.