
If you can make steam, you can make electricity.

MAKING STEAM FROM

SOLAR ENERGY

for

Small Steam Turbines and Engines

Part 4

The Parabolic Trough

Solar Collector/Concentrator

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By

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Soon shall thy arm, unconquered steam! afar
Drag the slow barge, or drive the rapid car;
Or on wide-waving wings expanded bear
The flying-chariot through the field of air.

— Erasmus Darwin. The Botanic Garden. 1792

From 'Botanic Garden' (1781), part 1, canto 1, lines 289-92. The Botanic

www.todayinsci.com/QuotationsCategories/S_Cat/SteamEngine-Quotations.htm

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Preface

The use of the term *Junkyard Mechanics* has been criticized, as in some sense being degrading. That is not the intent of the author. The term was adopted from a popular television show from the 1980s called Junkyard Wars, which, in some cases, pitted teams of students from different colleges and universities against each other in a competition to see which team was more innovative in solving technical problems using only a pile of junk parts. The show originated in the UK under the name *Scrapheap Challenge*:

http://en.wikipedia.org/wiki/Scrapheap_Challenge

> “This engineering challenge started off some years ago in the UK and has now made it over to TLC. In 2001 they filmed two seasons' worth of programs with a whole series of extreme Junkyard machines being built by teams of bikers, high-tech engineers, school teachers, and even hillbillies!”:

http://tv.blinkx.com/show/junkyard-wars/jo9FyhRptgeLuVDq

It is the intent of the author to encourage DIYers, inventors and tinkerers to innovate, and to know the standards and codes that need to be adhered to in building any steam based equipment. This is essential to avoid dangerous situations and to prevent injury.

Corrections and Addendum to Part 3

1. In section 3.1.11 entitled The Alternator and Generator Head the following sentence should read “for a 1 kW system” instead of “for a 10kW system”.
It is recommended that the minimum size alternator needed for a 1kW system should be rated at 100 amps continuous and should have a built-in regulator.

2. In section 4, Steam Consumption, Specific should have read:

Specific: 29.36 lb/kWh

Table of Contents

1 Solar Power

1.1 A Short History of Solar Power from the 7th Century BC

The following website traces in outline form the history of solar use from the 7th century BC until recent times.

http://www1.eere.energy.gov/solar/pdfs/solar_timeline.pdf

1.2 A Steam Renaissance?

There is a lost art related to steam that needs to be revived and brought up-to-date. It should first be mentioned that nearly everything we understand about steam today was first learned in the early 1900's and even earlier. Consider the following statement from the *Smithsonian Report*, 1913, regarding what we today refer to as a satellite dish.

> **….** Pifres sun-power plant. (from *Smithsonian Report*, 1913) The mirrors are held in a reflector-shaped-frame unit which can be faced toward the sun. A hand wheel is used to rotate the unit to such a position that the sun's rays will fall directly on the mirrors. The rays from the sun then strike the mirrors and are reflected onto the boiler which is located in the center or "focus". The water in the boiler absorbs heat from the sun's rays and is thereby transformed into steam. The steam, thus formed, is used to drive the engine. The exhaust heat from the engine is used in a feedwater heater to heat the previously cold water which is pumped into the boiler.

From: *Practical Heat, Part 1, Power Plant Series, pg. 61, edited by Terrell Croft, 1923*.

> Note. It is suggested that small-scale solar steam systems have not been more popular because there were few if any small-scale steam engines or turbines available at reasonable costs, and with sufficient power to satisfy the needs of a household. Considering today's fuel and energy costs, such systems can be expected to become much more popular in the near future. Environmental concerns and widespread goals of energy independence are accelerating this process.

1.3 Learning More About Steam

It has been the objective of this series of articles to learn at least enough to make steam from solar energy and to convert that energy into electricity. An attempt has been made to convey to the reader information needed to understand the subject, with only a minimum reliance on arithmetic or higher mathematics. The following website is rich in information about steam, steam systems, and steam products. Click on *Resources* and then click on *Steam Engineering Tutorials*.

http://www.spiraxsarco.com/resources/steam-engineering-tutorials.asp

Solar Collectors and Concentrators.

The solar concentrator used in previous examples was the familiar 3-meter satellite dish. Many configurations and sizes of solar concentrators are in existence today. The common objective among all solar collectors is that the apparatus face directly toward the sun as long as the sun is visible. A heliostat is a device that tracks the sun as it crosses the sky. An attached drive mechanism causes the collector to adjust azimuth and elevation to continuously point toward the sun. The efficiency of the entire system partially depends upon the accuracy of the heliostat tracking mechanism. There are two basic approaches to performing the function of the heliostat.

Digital. One approach can be considered digital where a computer either uses a look-up table to determine the exact position of the sun at any time during daylight hours, or a computer is used to calculate the position of the sun at any time using rather complicated algorithms. A source for this data is the Solar Ephemeris. For those readers interested in learning more about the relevant mechanics of the solar system, the following website might be a convenient place to begin.

www.ephemeris.com/space-time.html

Analog. Another less complicated and less expensive method uses sensors that track the sun by *looking* directly at it. Such analog sensors can detect direction and sometimes speed of the movement of the sun. A slight drawback these sensors have is the need to hunt for the exact location of the sun, especially when the sun is obscured by the clouds.

> Note. A quick search of the internet for useful information for the DIYer interested in building an inexpensive heliostat proved disappointing. See George's Workshop below for more information.

1.4 Some Other Concentrator Types

The following website has compiled a number of references and an array of diverse concentrator types. However, most of them are designed only to heat water.

www.builditsolar.com/Projects/Concentrating/concentrating.htm

2 What is a Parabolic Trough?

2.1 Basic Description of a Parabola

Whether the reader intends to build or buy a parabolic trough solar collector, it is important to understand some of the physical and performance specifications of the unit to be evaluated.

> Note. A detailed discussion of the mathematics needed to precisely describe parabolic shapes is beyond the scope of this paper. Fortunately, there is much more information available on the Internet for the reader with a deeper mathematical curiosity.

A parabola is a conical curve, the points of which fall on a series of locations defined in one case by the following equation where p is the distance from the focus of the parabola to the vertex, or intersection of the centerline and the curve.

y= x^2 / 4p

A science project on the following website offers a very understandable explanation of both how a parabola works and how to build a parabolic trough.

www.jc-solarhomes.com/fair/parabola20.htm

2.2 Mathematics of Parabolas

For a rather extensive mathematical description of a parabola, the reader can refer to the following website:
http://en.wikipedia.org/wiki/Parabola

Parabolic information in the following website is more application oriented.

http://mysite.du.edu/~jcalvert/math/parabola.htm

2.3 Parabolic Trough Collectors

Much of the relevant material found in the literature and on the web is concerned with large mega-dollar and mega-power industrial and commercial solar power generating systems. Fortunately, many of the same principles can be applied to small systems that are the subject of this paper.

http://en.wikipedia.org/wiki/Parabolic_trough

From: *Solar Energy Generating Systems* (SEGS)

http://en.wikipedia.org/wiki/Solar_Energy_Generating_Systems

> "Heat transfer …
>
> The sunlight bounces off the mirrors and is directed to a central tube filled with synthetic oil, which heats to over 400 °C (750 °F). The reflected light focused at the central tube is 71 to 80 times more intense than the ordinary sunlight. The synthetic oil transfers its heat to water, which boils and drives the Rankine cycle steam turbine,[3] thereby generating electricity. Synthetic oil is used to carry the heat (instead of water) to keep the pressure within manageable parameters."

www.nrel.gov/csp/troughnet/faqs.html

2.4 George's Workshop.

The reader is encouraged to especially note the website for *George's Workshop* for what appears to be an inexpensive DIY buildable trough-type tracking solar concentrator.

www.ffwdm.com/solar/solar-index.htm

This concentrator, as described, is specifically designed to generate hot water. However, it appears reasonable that it can be modified in such a way that it can be made to work with steam. In that case, all the pipes and joints must be made to withstand pressure and temperature by using flair fittings or brazed and welded joints and connections. George has given us more technical information in the following websites:

http://georgesworkshop.blogspot.com/2009/07/performance-of-tracking-solar-parabola.html

> Author's note: It appears that George has done a lot of work. He has by trial and error accomplished a huge task in solving problems and in collecting information needed to design and build a successful solar tracking trough collector. The information offered on this website is sure to save the reader considerable time and effort toward building a similar system to generate steam.

www.ffwdm.com/solar/solar-index.htm

2.5 Single Section Trough Concentrator.

The following figure shows the receiver pipe in a single section of a trough concentrator. In this configuration water flowing through the receiver pipe follows a straight path as it collects heat, through the walls of the pipe, from the reflected solar energy. Water enters one end of the pipe and exits the other end at a higher temperature. The temperature of the water, steam or other fluid in the pipe at any point depends on several factors:

- Solar intensity
- Accuracy of the trough azimuth, elevation, etc.
- How long the fluid remains in the pipe
- Fluid flow through the pipe
- Pipe diameter
- Length of the pipe
- Thermal characteristics and insulation of the pipe
- Heat lost from the pipe
- Optical properties of the pipe
- Ambient temperature and wind conditions

Note. Use is made of the word *receiver* in this paper. The receiver is also referred to as an a*bsorber* in other contexts. Unless otherwise noted, the reader can assume the meanings of both words are identical, and the words are interchangeable.

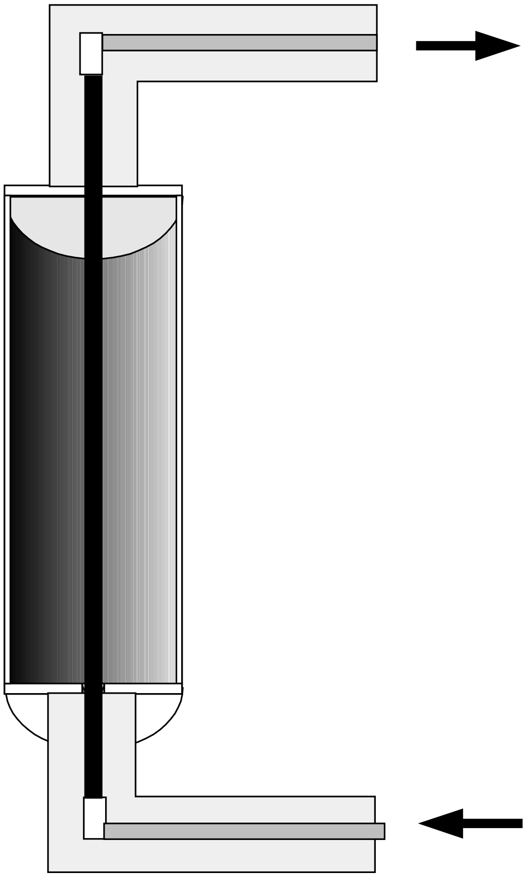

Figure 2-1 Single Trough Collector

2.6 Single Trough Calculations.

The size of the parabolic trough determines the amount of energy that can be collected from the sun.

A = Area exposed to the sun when trough is *accurately pointed* toward the sun.
L = Length of a section.
W = Width of a section.
A = L * W

The area of a single section as shown in the figure is:

L = 3 meters
W = 1 meter
A = 3 sq m

If the intensity of the sun is 1 kilowatt per square meter, then a single section has 3 kW available from the sun. How much water:

- can be heated on a sunny day
- to what temperature
- how long will it take

2.7 Volume of Water in the Receiver Pipe

If the pipe is filled with hot water, near the boiling point, i.e., from the condenser, and the internal diameter and the length of the pipe are known, then an estimate can be made of how long it will take to begin generating steam. Only the length of pipe directly within and at the focus of the parabolic reflector is included in the calculation. For this estimate efficiency can be assumed to be 100%, and adjustments can be made later.

Assume the following pipe dimensions:

D = Diameter (inside) = 2 in.
L = Length = 3m = 118.1 in.
A = pi * D^2 / 4
V = Volume = A * L
Q = Qty (gals)
Q’= Qty (lbs)

The volume of a 2” x 3m pipe is:

V = (pi x 4 / 4) x 118.1in. = 371 cu. in.

Since 1.0 U.S. gal. liq. = 231.0 cu. in.

Q = 371 (cu in) / 231 (cu in/ gal) = 1.606 gallons

Since: 1.0 gal. water = 8.3 lbs

Q' = 1.606 gal. x 8.3 lb/gal = 13.33 lb

2.8 Time Required to Heat to the Boiling point

If the intensity of the sun is 1 kilowatt per square meter, how long does it take to heat 13.33 lbs of cold water in the pipe from 40 deg F to 212 deg F, at atmospheric pressure?

T = T2 – T1 = 212 deg – 40 deg = 172 deg

Therefore Total heat required, Qt, is:

Qt = 1.0 Btu / lb-deg * 172 deg * 13.33 lb = 2293 Btu.

If the total area of the collector exposed directly toward the sun, i.e. the aperture, is:

A = 1.0 m x 3.0 m = 3 sq m

The total heat supplied by the sun, Qs, is:

Qs = 3412 Btu / hr / sq m * 3.0 sq m = 10,236 Btu / hr.

Therefore the time needed to raise the temperature of the water to 212 deg F is:

T ' = Qt / Qs = 2293 Btu / 10236 Btu / hr = 0.224 hours (13.4 minutes)

If it takes approximately 13 minutes to heat 1.6 gallons of cold water, then in one hour approximately 8.8 gallons of cold water can be heated to near boiling, at atmospheric (ATM) pressure. That suggests a flow rate of 7.4 gal/hr (0.12 gal/min) could thus be heated using a single section trough concentrator.

> **Question.** From the above calculations, if ten sections can produce ten times as much hot water as a single section, what is the difference if the ten sections are connected in series, in parallel or in a combination of both?

2.9 Time and Energy Required to Make Steam

The time required to make steam from water at the boiling point was discussed in Part 1. It was learned that it takes an additional 970 Btu at atmospheric pressure to convert one pound of water at the boiling point to steam. This additional heat is identified as the *Latent Heat of Vaporization.* It is assumed that pressure is at atmospheric pressure unless otherwise stated.

In this section it will be learned that pressure affects both the temperature of the boiling point of water as well as the Latent Heat and the Sensible Heat content of the steam. It will be shown that the ratio of latent heat to sensible heat in saturated steam is inversely proportional to pressure.

2.10 Difference Between Gauge Pressure and Absolute Pressure

The difference between Gauge Pressure (psig) and Absolute Pressure (psia) is determined by the instrument used to measure the pressure. The basic difference is that the device used to measure absolute pressure (psia) is referenced to a pressure of zero pounds per square inch (psi), or some other units of measure, and the device that measures gauge pressure measures a differential pressure and is referenced to some known level of pressure, such as sea level pressure of 14.7 psia.

In a previous example using the Katmar Calculator, 165 psia was entered for the *Inlet Steam Pressure* and 15 psia was entered for the *Exhaust Pressure*, which equals a differential pressure, or gauge pressure, within the turbine of 150 psig.

Readers interested in learning much more about pressure measurements and measuring pressures are referred to the following website:

http://en.wikipedia.org/wiki/Pressure

2.11 Effects of Pressure and Temperature on Latent Heat

There are some things to review here from previous discussions. Specifically, the boiling point of water increases as the pressure increases. The boiling point of water is 212 deg F at atmospheric pressure of 15 psig, but under pressure of 100 psig it is approximately 338 deg F. It is also true that while the latent heat of steam is 970 Btu per lb at atmospheric pressure of 15 psia, it is only 882 Btu/lb at 100 psia. The latent heat decreases and the sensible heat increases as the pressure increases.

Sensible heat. When water is heated to create steam it is *sensible heat* that is measured using a thermometer. It was termed *sensible* because the thermometer can be used to *sense* temperatures as heat is added or removed.

Latent heat. Latent heat cannot be sensed or measured directly by any device, but it can be calculated by knowing other properties of the steam, specifically temperature and pressure. Latent heat added to steam does not result in an increase in temperature.

Super heat. Heat added to dry steam causes the temperature to increase and is considered super heat, and the steam is said to be superheated.

Enthalpy. Total energy contained in steam, termed *enthalpy*, is referenced to 32 deg F. No physical device exists that can measure Enthalpy but it can be determined from the Steam Tables or a Mollier Diagram or estimated from equations.

When steam is raised to a superheated level and is applied in a process, such as driving a turbine, steam engine or other device, it is the super heat that is converted to work in the form of mechanical energy. Latent heat is not converted to work and is either lost in the condenser or used in another non-condensing process. That process could be as simple as heating domestic hot water, preheating make-up water or heating a living space..

This notion is very important because it is absolutely necessary to prevent wet steam from existing in the turbine. The exhaust steam must therefore remain superheated while the turbine is in operation.

3 Introduction to the Steam Tables

Anything more than a cursory introduction of the Steam Tables is beyond the scope of this paper. The *Steam Tables and Mollier Diagram,* by J. H. Keenan, first appeared in 1930, Am. Soc.Mech. Eng.. and were published in a book: *Thermodynamic Properties of Steam*, Keenan and Keyes, 1936, Wiley (thirty-fifth printing, January, 1963)

The Katmar *Software Steam Consumption Calculator* does the necessary calculations that saves the time needed to reference the Steam Tables.

While it is not necessary to become an expert in the use of Steam Tables, the reader can consider it an accomplishment to understand the origin of some of the numbers quoted by manufacturers and service providers of heating and air conditioning equipment.

Fortunately, the reader has a choice of referring to printed Tables or to use one of several Steam Table Calculators, one of which, along with understandable explanations, can be found on the following website:

www.spiraxsarco.com/resources/steam-tables/superheated-steam.asp

For the reader planning to build, buy or operate a domestic steam power plant, it is very important that the relationship between temperature and pressure and the concepts and details of saturated steam and superheated steam be well understood. To accomplish this, the reader needs to be able to refer to the Steam Tables. Readers who are familiar with the Katmar Steam Consumption Calculator have already learned some of the steam condition terms and variables found in the steam tables. For readers who need to refresh, update or expand their understanding of steam, it is suggested that the following website offers an understandable and thorough explanation of steam conditions:

www.spiraxsarco.com/resources/steam-engineering-tutorials/steam-engineering-principles-and-heat-transfer/what-is-steam.asp

Much literature relating to steam has been published over the years. One such book is entitled *STEAM, Its Generation and Use, by The Babcock & Wilcox Company*. The book contains the Steam Tables and explanations thereof and has been through many editions. It can usually be found in the libraries of most engineers, at least those who were exposed to Thermodynamics. Although it concentrates mostly on the generation of steam using their boilers, the book focuses on the properties of steam and its applications throughout its pages. The following website offers a history of this very old company.

http://en.wikipedia.org/wiki/Babcock_and_Wilcox

3.1 Condition of Steam at Saturation

It is commonly accepted that at sea level, and according to Steam Table 2 (Saturation Pressures), at a pressure of 14.696 psia, water boils at 212 deg F. Also from Table 2, at a pressure of 165 psia, water boils at a temperature of 365.995 deg F (extrapolate between 164 and 166 psia). The same results are found in Steam Table 1 (Saturation: Temperatures) where the table is organized *by Temp. Fahr.* Table 2 is organized by *Abs. Press., Lb/Sq. In.* Other column headings in both tables include: *Specific Volume*, *Enthalpy* and *Entropy*. Table 2 also includes a column heading *Internal Energy*.

- The *saturation point* of steam is reached when water and steam are in equilibrium or when water begins to boil.
- The term *saturation* refers to the condition where heat added to the liquid will not increase the temperature of the boiling point, but will cause more liquid to turn to steam.
- The term *steam* refers only to the vapor created when water boils, and does not refer to the boiling of any other liquid.
- From Keenan and Keyes, pg. 16: "It is customary to make the enthalpy zero for the saturated liquid state at 32 deg F…"
- To be consistent absolute pressure, psia, is used throughout this discussion, unless otherwise noted
- The reader should recognize that 165 psia is about the same pressure as 150 psig at sea level.
- Unless otherwise noted atmospheric pressure of 14.696 psia is rounded off to 15 psia

Consider the following example using Tables 1 and 2 of the Steam Tables:

1. In Table 1, find 212 deg. F in column labeled *Temp. Fahr.*
2. In the column labeled *Abs. Pressure, Lb/Sq.In.*, sea level pressure is 14.696 psia
3. In the column labeled *Enthalpy*, note the three subheadings, hf, hfg and hg
    - hf is the sensible heat of water at the boiling point
    - hfg is the latent heat of vaporization added to make steam
    - hg is the enthalpy or total heat of saturated steam

Case 1: The purpose of this calculation is to determine the total heat (Enthalpy) contained in one lb. of saturated steam at atmospheric pressure, consisting of sensible heat, hf, plus latent heat, hfg,.

- In Table 1, the Saturation *Pressure* of water at the saturation temperature, t = 212 deg. F is p = 14.696 psia
- In Table 2, the Saturation *Temperature* of water at the saturation pressure of p =14.696 psia is t = 212 deg. F
- hg = hf + hfg

Given **p = 14.696 psia** and **t = 212 deg. F**

hf = 180.07 Btu/lb
hfg = 970.3 Btu/lb
hg = 180.07 Btu/lb + 970.3 Btu/lb = 1150.4 Btu/lb

Case 2:

The purpose of this calculation is to determine the total heat, hg, contained in one lb. of saturated steam at a pressure of 150 psia, consisting of sensible heat, hf, plus latent heat, hfg.

- In Table 2. find 150 psia in column labeled *Abs. Press., Lb./Sq. In.*
- In the column labeled *Temp. Fahr.* the saturation temperature, t = 358.42 deg. F

Given **P = 150 psia** and **t = 358.42 deg. F**
hg = hf + hfg
From Table 2:
hf = 330.51 Btu/lb
hfg = 863.6 Btu/lb
hg = 1194.1 Btu/lb

In this discussion *saturated temperature* and the *boiling point* are the same. However, it should be noted that the contents of the vessel at the saturation temperature might be entirely liquid, a mix of liquid and vapor, or entirely vapor.

This shows that for saturated steam:

- the sensible heat, hf, in one lb. of water at the boiling point increases from 180 Btu/lb at 14.7 psia to 330.51 Btu/lb at a pressure of 150 psia.
- the latent heat, hfg, in one lb. of water at the boiling point decreases from 970 Btu/lb at 14.7 psia to 864 Btu/lb at a pressure of 150 psia

- the total heat, hg, in one lb. of water at the boiling point increases from 1150 Btu/lb to 1194 Btu/lb, an increase in Enthalpy of 44 Btu/lb.

At this point in the discussion it is sufficient to understand that whenever water and steam exist together in a pipe or vessel, the steam is considered to be saturated and the combination of temperature and pressure are always at their *saturation values* as found in the Steam Tables. It is also noted that saturated steam is always to be avoided in the operation of steam turbines and steam engines. Such inlet steam must be superheated and must remain superheated throughout the cycle of the steam machine.

3.2 Conditions of 600 Degree F Superheated Steam at 150 psig Pressure.

Case 3: The purpose of this calculation is to determine additional heat, hx, required to create superheated steam at 600 deg F from saturated steam at 150 psia. Find from Table 3 the total heat, or Enthalpy, hg, contained in one lb. of steam superheated to a temperature of 600 deg F at 150 psia. Enthalpy, hg, or total heat, includes sensible heat, hf, plus latent heat, hfg, plus the additional heat, hx, needed to superheat it, where:

hg = total heat
hf = sensible heat
hfg = latent heat
hx = superheat
hx = hg – (hf + hfg)

From Table 3, *Superheated Vapor*, of the Steam Tables, the additional heat required to raise the saturated steam temperature to superheated steam at 600 degree F and 150 psia can be determined. In the previous section, from Table 2, the total heat or Enthalpy of saturated steam was determined to be:

hg = 1194 Btu/lb

In Table 3, *Superheated Vapor*, the intersection of 150 psia in the horizontal row and 600 deg. F in the vertical column indicates an Enthalpy:

h = 1325.7 Btu/lb

Heat needed to raise one lb. of saturated steam to 600 deg. F superheated steam is:

hx = h – hg = 1326 – 1194 = 132 Btu/lb

If water is available at the boiling point from the condenser at atmospheric pressure, the additional heat needed to make 600 deg F superheated steam at a pressure of 150 psia is as follows where:

hfg = 970 Btu/lb
hg = 1194 Btu/lb

hx = 132 Btu/lb
htot = hfg + hg + hx
htot = 970 + 1194 +132 = 2296 Btu/lb

3.3 Graphical Analysis

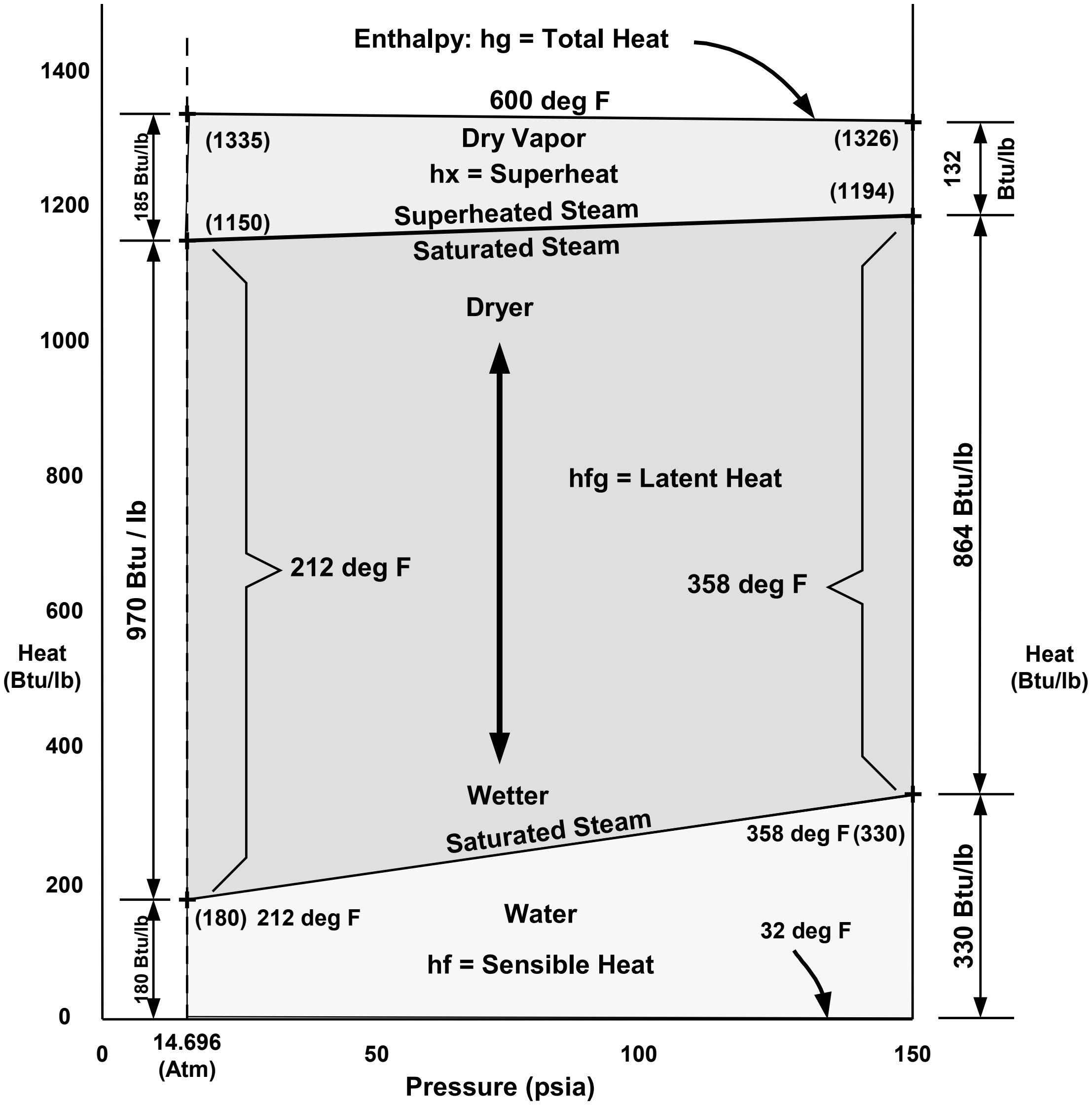

Figure 2 Effects of Heat and Pressure

The graph illustrated above is intended to give the reader a visual sense of the relationship between the relative steam conditions existing within the scope of this paper.

In the horizontal direction:

- Curvilinear boundaries between sections are drawn as straight lines

- Horizontal dimension denotes pressure only
- The upper pressure boundary, 150 psia, was selected from previous discussions

In the verticle direction:

- Sensible heat increases as pressure increases
- Latent heat decreases as pressure increases
- Superheat decreases with increasing pressure
- The upper temperature boundary, 600 deg F, was selected from previous discussions

In general:

- Steam conditions shown are independent of the turbine
- Most of the energy in the saturated steam is latent heat and is not available for work in the turbine, but is available for other downstream processes, e.g., for heating domestic hot water or living spaces, etc.
- All of the heat in the superheated area is available for work in the turbine
- Exhaust in the form of saturated steam consists mostly of latent heat
- All of the heat below the saturation region is sensible heat
- Enthalpy from Steam Tables: hg = 1325.7 Btu/lb

Question: Show Enthalpy from the Calculator: hg = 1,325.6 Btu/lb

3.4 The Backpressure Turbine (BPT)

In certain industrial environments, small turbines are generally considered *backpressure turbines.* Such applications refer to turbines that are inserted in a *process steam* main line. Because the turbine exhaust is returned to the process steam line, it is not returned to a condenser and is therefore considered a non-condensing turbine. One concept is to add some additional heat to the existing flow of saturated steam to create superheated steam, which can be used to generate power by running a steam turbine or steam engine, and then returning the exhaust steam back to the main steam line. While a steam turbine needs superheated steam, most industrial processes use only saturated steam.

Another concept is to consider the backpressure turbine as taking the place of a Pressure Reducing Valve (PRV). In this case steam is not consumed, but a pressure drop occurs as steam passes through the turbine, thus providing the energy required to operate the turbine. This explanation, offered on the following website, appears to be somewhat oversimplified.

http://www1.eere.energy.gov/industry/bestpractices/pdfs/steam22_backpressure.pdf

The concept of replacing a PRV with a BPT is expanded upon in the following website. Note: The reader should view the cost savings estimates with a bit of skepticism.

www.nrel.gov/docs/fy02osti/31155.pdf

The objective in this paper is to further develop the concept of using solar energy to run a small turbine as a prime mover. In that light, consider the need to generate enough power to satisfy the minimal or emergency needs of an average household.

Case 4. Assume a solar DSG system is running a 1 kW turbine and is continuously producing superheated steam at a temperature of 600 deg F and at a pressure of 150 psia.

1. From the graph, without looking at the Steam Consumption Calculator, find the approximate amount of superheated steam, w'x, in lbs/min/m^2, the system needs to produce, given the following:

hs = available solar heat = 3412 Btu/hr/m^2

hx = superheated steam = 132 Btu/lb

ht = 1 kW turbine output is 3412 Btu/hr

wx = turbine steam consumed in lb/hr

w'x = turbine steam consumed in lb/min/m^2

t = 600 deg F
p = 150 psia

wx = hs / hx = (3412 Btu/hr-m^2) / 132 Btu/lb = 26 lb/hr-m^2

w'x = (26 lb/hr-m^2) / 60 min/hr = 0.43 lb/min-m^2

2. Using the Calculator, find the approximate efficiency of the turbine. Hint: find by trial and error.

3.5 An Example: Making Steam for 10 kW (From Part 3 – Section 4)

Author's note: The following is repeated from Section 3: "As previously stated, the subject of steam properties is complicated, confusing and tedious, especially if it is necessary to use published steam tables." In this Part, it was learned that using the Steam Tables is easy if the procedure followed is taken one step at a time. It is shown below that using the steam tables should yield the same results as using the Katmar Calculator.

Using the *Turbine Steam Consumption Calculator, Version 2.1* from Part 2, enter the following:

Input data:

Inlet Steam Press (abs):	**165**	**psia**
Inlet Steam Temperature:	**600**	**Fahrenheit**
Exhaust Pressure (abs):	**15**	**psia**
Turbine Efficiency:	**25**	**Percent**
Turbine Power:	**10**	**kW**

Inlet steam properties:

Saturation Temperature:	**365.9**	**Fahrenheit**
Enthalpy:	**1324.6**	**Btu/lb**
Entropy:	**1.7**	**Btu/lb-deg F**

Exhaust steam properties:

Enthalpy:	**1271.9**	**Btu/lb**
Entropy:	**1.908**	**Btu/lb-deg F**
Temperature:	**467.9**	**Fahrenheit**
Degree superheated	**254.7**	**Fahrenheit**

Steam consumption:

Specific:	**29.36**	**lb/kWh**
Actual:	**10.79**	**lb/min**

3.6 Analysis of Steam Consumption

A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
CASE		**#1**	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**
Input Data								
Inlet Steam Pressure	**psia**	**165**	**165**	**165**	**150**	**180**	**165**	**165**
Inlet Steam Temperature	**Deg F**	**600**	**600**	**600**	**600**	**600**	**550**	**600**
Exhaust Pressure	**psia**	**15**	**15**	**15**	**15**	**15**	**15**	**1**
Turbine Efficiency	**Percent**	**25**	**25**	**25**	**25**	**25**	**25**	**25**
Turbine Power	**kW**	**10**	**5**	**1**	**10**	**10**	**10**	**10**
Inlet Steam Properties								
Saturation Temperature	**Deg F**	**365.9**	**365.9**	**365.9**	**358.4**	**373.0**	**365.9**	**365.9**
Enthalpy	**Btu/lb**	**1324.6**	**1324.6**	**1324.6**	**1325.6**	**1323.5**	**1,298.8**	**1,324.6**
Entropy	**Btu/lb-deg F**	**1.7**	**1.7**	**1.7**	**1.711**	**1.689**	**1.675**	**1.7**
Exhaust Steam Properties								
Enthalpy	**Btu/lb**	**1271.9**	**1271.9**	**1271.9**	**1274.6**	**1269.3**	**1,248.4**	**1,230.8**
Entropy	**Btu/lb-deg F**	**1.908**	**1.908**	**1.908**	**1.911**	**1.905**	**1.882**	**2.159**
Temperature	**Deg F**	**467.9**	**467.9**	**467.9**	**473.6**	**462.5**	**418.0**	**376.5**
Degree Superheated	**Deg F**	**254.7**	**254.7**	**254.7**	**260.4**	**249.3**	**204.8**	**274.9**
Steam Consumption								
Specific	**lb/kWh**	**29.36**	**29.36**	**29.36**	**30.2**	**28.56**	**30.67**	**16.51**
Actual	**lb/min**	**10.79**	**5.393**	**1.079**	**11.13**	**10.49**	**11.27**	**6.067**

Many of the differences noted in the above table can be explained by what has already been learned from the Steam Tables. For example: Notice the changes in

- Columns #1, #2 and #3, a change was made to the size of the turbine and in each case the only change was in the Steam Consumption.
- Column #4, the Inlet Steam Pressure was dropped from 165 psia to 150 psia

Notice the single change that has been made in each column, Case #2 thru Case #7, compared to Case #1.

4 Solar Energy and the Trough Collector

The area of the trough collector facing the sun and the intensity of the sun's rays determine the amount of solar energy concentrated on the surface of the receiver pipe (also called absorber tube). For purposes of this example, assume the available solar power density is 1.0 kW/m^2 or 3412 Btu/m^2/hr.

If the length of the parabolic reflector is 3.05 meters (10 ft) and the width of the trough facing the sun is 1.0 meter, then the total collector area is 3.05 square meters and the total available solar energy is 3.05 kWh/h.

From Part 1 of this paper, it is known that 3412 x 3.05 or 10,407 Btu's per hour are available from the sun. It is also known that the latent heat of vaporization of 970 Btu's per lb of water at atmospheric pressure is needed to turn water at the boiling point to steam. Assume water entering the receiver is at the boiling point.

$$H_{tot} = 970 \text{ Btu/lb} \times 13.5 \text{ lb} = 13{,}095 \text{ Btu}$$

Therefore, it requires 13,095 Btu's to convert the 13.5 lbs of water in the pipe to steam. The time required to convert the volume of water in the tube to steam is equal to the total heat required divided by the amount of heat available per hour.

$$t = 13{,}095 \text{ Btu} / 10{,}407 \text{ Btu/hr} = 1.26 \text{ hrs}$$

4.1 Effect of Receiver Pipe Diameter on DSG Process

Two terms the reader may encounter frequently are Hot Transfer Fluid (HTF) and Direct Steam Generation (DSG). Generally, they relate to the method used to transfer heat from a heat source, such as the solar collector receiver tube, to another destination.

It is left for the reader to show that if the receiver pipe diameter is reduced by one half, the time required to boil the water is only 18.9 minutes.

$$t' = 18.9 \text{ min}$$

The reader should also be able to show that while the time required to make the steam is reduced by a factor of four, the amount of steam produced is also reduced by a factor of four. While this is a tradeoff, there is no difference in the amount of solar energy collected in the process.

4.2 Heat Transfer Fluid (HTF)

In the HTF case, a fluid other than water, such as a special high temperature synthetic oil, can be used to fill the receiver pipe and the associated plumbing that carries the fluid and its heat to another unit, called a Heat Exchanger (HE). The advantage of this method is

that the temperature of the transfer fluid can be raised to a much higher temperature than that at which water will boil, and raise the pressure accordingly. The disadvantage is the cost of the HTF and the addition of another HE unit.

Using a heat transfer fluid that has a very high temperature property, without boiling or a phase change, eliminates the need for high pressure steam within the trough collector plumbing.

www.paratherm.com/heat_transfer_fluids.asp

Where the fluid is specified at 343 deg C (649.4 deg F) without a phase change high pressure does not exist in the collector system. The HTF transfers heat energy in a heat exchanger where circulating water is converted to steam.

4.3 Heat Exchangers

There are important concepts that at present are beyond the scope of this discussion regarding heat transfer that can drastically alter heat transfer rates and the ability of the receiver, heat exchangers and other plumbing to absorb, remove or transfer heat.

www.multitherm.com/multitherm-ig-4.html

www.radcoind.com/TechTips2.html

4.4 Direct Steam Generation (DSG)

While the DSG method might be less complicated and less expensive, it does involve a phase change of the fluid within the receiver tube and the complication of dealing with the resulting high temperature and pressure. In this case all the plumbing connections, valves, joints and other devices must be designed to handle the associated temperatures and pressures in the system. The tradeoff to using HTFs is the simplicity of the overall concept for a small solar system.

The following article discusses recent developments in large-scale solar projects. While the subject is confined to very large projects, some concepts and principles discussed are also relevant to the small solar systems that are the subject of this paper.

http://social.csptoday.com/industry-insight/direct-steam-generation-streamlining-parabolic-trough-plants

4.5 Serial Trough Configuration.

The following figure shows a serial arrangement of piping in a trough concentrator. In the serial configuration of the trough, water flowing through the pipes follows a single continuous path as it collects heat from the reflected solar energy. Water enters one end of the pipe and exits the other end at a higher temperature. The temperature of the water and steam in the pipes at any point depends on several factors:

- Size, shape and reflectivity of the reflector
- Trough position relative to the sun
- Diameter, length and volume of the receiver
- Thickness and color of the receiver tube
- Flow rate through the receiver
- Hot water must be supplied to the receiver under pressure
- Purity of the water
- Insulation design and wind protection
- Latitude, availability and intensity of the sun

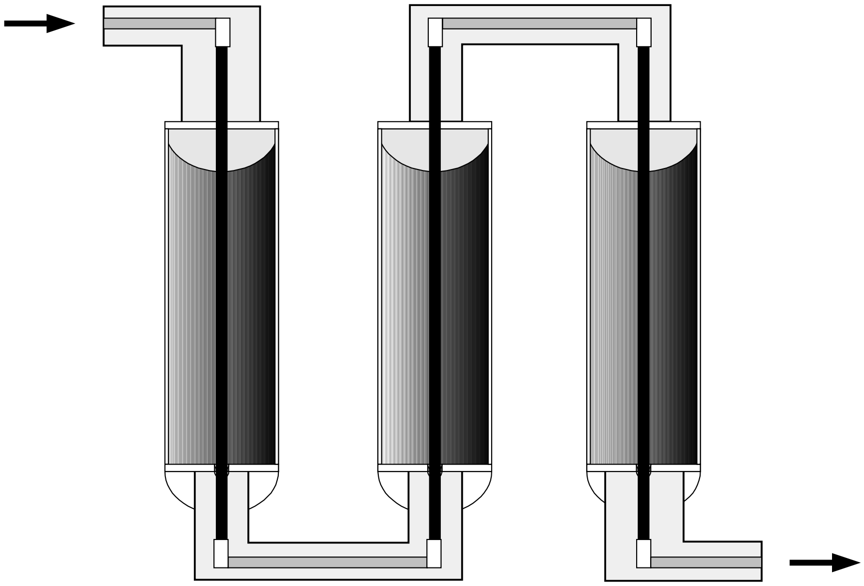

Figure 3 Serial Trough Configuration

4.6 Parallel Trough Configuration.

The following figure shows a parallel arrangement of piping in a trough concentrator. In the parallel configuration, water flowing through the pipes split and follow a multiple paths as it collects heat from the reflected solar energy. Water enters one end of the pipe and exits the other end at a higher temperature. The temperature of the water and steam in the pipes at any point depends on some additional factors different from the serial configuration:

- The top common input pipe, call it the *supply header*, needs to be able to provide all the sections of the collector with equal pressure and equal flow
- The bottom common output pipe, call it the *output header*, needs to be able to collect all the steam from the multiple sections of the collector without becoming a bottleneck to any section
- Both the input and output headers must have a cross section area at least equal to the sum of the cross section areas of all the pipes in the collectors
- Hot water must be supplied to the input header under pressure

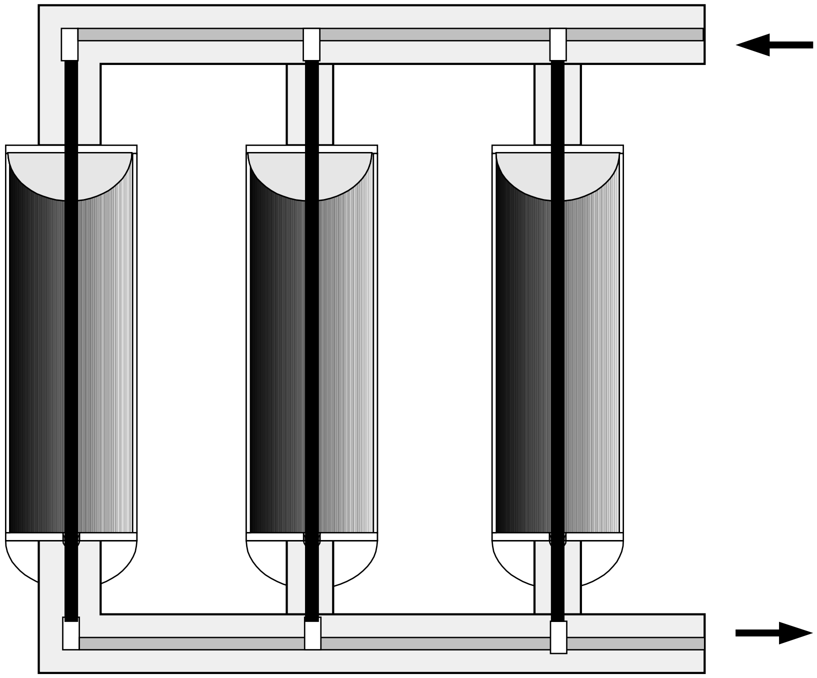

Figure 4 Parallel Trough Configuration

4.7 Insulating the Connecting Pipes

The purpose of this exercise is to acquire a respect for heat losses that will occur when steam pipes are not insulated. It can also be expected that when temperatures and pressures increase, heat losses increase accordingly. In the above figures, insulation is shown for the connecting pipes, other than the receiver pipe.

Heat loss and thermal conductivity are subjects beyond the scope of this discussion. However, the following should give the reader a respect for the need to minimize such losses. The following very interesting and informative paragraph is copied from a 1994 booklet, prepared by the Energy Efficiency Office of the Department of the Environment in London, entitled: *Steam Fuel Efficiency Booklet 2*.

> **"3.2 (pg. 8) Uninsulated surfaces**
>
> Heat can be lost due to radiation from steam pipes. Every square metre of uninsulated steam heated surface (both steam pipes and steam-heated equipment) means that at a pressure of 7 bar (100 psi), 9300 kj (8,850Btu) of heat energy will be lost on an hourly basis, representing 5 kg of steam per hour, or 1 lb of steam from every square foot of uninsulated surface."

It should be recognized that 8,850 Btu/hr is equal to 2.6 kWhr/hr or 2.6 kW. Losing that much power would be unacceptable in a system designed to produce only 5 kW.

> Note. Although the temperature is not specifically stated above, the fact that steam is present implies the temperature is at least high enough to sustain the steam condition in spite of the losses. The higher the temperature, the greater the losses are where insulation is inadequate. Where a turbine is involved, it can be assumed that steam must remain superheated.

From previous calculations, the reader can calculate the volume of a straight pipe using the following relationship:

V = volume
d = internal diameter of pipe
l = length of pipe

$$V = [(\pi \times d^2) / 4] \times l$$

The external area of the pipe can be calculated as follows:

A' = area
d' = external diameter of pipe
l = length of pipe

A’ = pi x d’ x l

Therefore, a 10’ pipe with a 3” outside diameter has an external surface area:

A’ = pi x 3 x 120 = 1131 sq in
A’ = 7.8 sq ft
A’ = 0.73 sq mtr

The heat loss from an uninsulated 3” x 10’ pipe with the above temperature and pressure therefore is approximately:

Q’loss = 0.73 m^2 x 8,850Btu/m-hr = 6461 Btu/hr

Q’loss = 6461 Btu/h / 3412 Btu/kW-hr = 1.89 kWhr/hr = 1.89 kW

4.8 Insulating the Receiver Pipe

The idea of insulating the receiver pipe might seem somewhat counterintuitive until one realizes that only one side of the pipe is receiving radiated energy from the sun. Nearly all the energy reflected by the parabolic reflector remains as radiated energy until it hits the surface of the pipe. There has not been any conduction or convection of energy involved in the collection process. However, the surface temperature of the receiver pipe remains increased as long as more radiated energy arrives from the sun. This increased surface temperature causes heat to be *conducted* through the wall of the receiver pipe to the fluid occupying its internal volume. If thermosiphoning is involved in the process, *convection* occurs as the warmer lighter fluid moves to the top of the supply or storage tank.

> Caution. It is noted that if the process fails or stops for some reason, the receiver pipe will continue to receive radiated energy and the surface of the pipe will continue to get hotter. Eventually the internal fluid can become hot enough to boil and possibly build up a high enough pressure to cause an unsafe condition that might result in serious damage and injury. This condition can be avoided by including a safety valve (SV) or a pressure-relief-valve (PRV) in a strategic location, close to or attached to the receiver pipe.

There is a conundrum with the receiver pipe. While the hot side is receiving radiated heat from the sun, the opposite side, the cool side of the pipe, may be radiating heat into the air. The hot side, receiving the concentrated sunlight, is the side facing the back of the parabolic reflector and the cool side is the side facing the sun. Without insulation on the cool side, the heat from the internal fluid passes through the wall of the pipe by conduction and leaves the surface of the pipe by radiation, conduction and convection. Conduction might not be significant because dry air is not a good conductor of heat. However, convection increases in the presence of wind.

> For a detailed, yet understandable, discussion of heat transfer beyond the scope of this article, the reader is encouraged to review the material from the following website:
>
> http://en.wikipedia.org/wiki/Heat_transfer

A partial but necessary solution to this conundrum is to insulate or encase the cool side of the receiver pipe to prevent heat losses described above.

For an efficient and innovative, but unconventional approach to designing an insulated receiver for a trough reflector, see the following website:

www.ecplaza.net/tradeleads/seller/4473696/evacuated_glass_vacuum.html

The use of evacuated tubes is not new and has been used in thermos bottles for years, if not generations. While this approach may solve a number of trough related problems, the cost benefit might be marginal. However, comparing the overall cost of the trough collector system with a similar solar panel system, the unit cost of the evacuated tube might still be attractive. The temperature specification of 380 deg C (716 deg F) is very workable for an HTF system application, while it probably would not work with a DSG system due to its high-pressure requirements.

4.9 Insulation Designed for Steam Pipes

The following website contains useful information and links to specific commercial products designed to insulate steam heating pipes. The temperature specifications may not be clearly stated for each item.

www.statesupply.com/displayCategory.do?Id=2061

The following website shows several illustrations and descriptions of insulating products with temperature specifications as high as 1000 deg F.

www.industrialinsulation.com/blanket_roll_insulation.htm

For a solar system designed to operate at no higher temperature than 600 deg F, there may be no advantage to selecting insulation with the highest temperature specifications.

4.10 The Reflective Surface

The parabolic trough collector inner surface must be highly reflective. The highest reflectivity possible of 100% could only be obtained from a perfect mirror, and anything less than that reduces the overall potential system efficiency. However, perfect mirrors do not exist. The following manufacturer claims to offer a material with a 99% reflectivity and that is well suited for the application under discussion.

www.mirrorsheeting.com/

Regardless of the supplier, the preferred backing is Mylar, a polymer-based film, because it is recognized as a stable base material. That means it does not tend to stretch or shrink with changes in temperature and humidity. While the thickness of the material is important, the reflectivity remains the most important specification of the material. It is assumed that the mirrored Mylar is to be secured against a smooth rigid backing that forms the parabolic shape of the trough.

> Note. Always be skeptical of a supplier's technical specifications. However, it is generally a good practice to rely on the supplier for instructions and methods of applying their materials. Most suppliers offer samples of their wares, either free or for a modest price. It is suggested that the minimum workable thickness for Mylar is 2 mil (0.002") and preferably 4 mil (0.004") or more. When working with Mylar it is very important not to crease it, because the creases will not come out. Mylar should always be stored in a roll or lying flat, and never folded.
>
> The following supplier of mirrored film has given us another term, CSP, to add to our growing list of acronyms:
>
> *"Mirror Film is used primarily to reflect sunlight onto the receivers of Concentrating Solar Power (CSP) collector systems such as parabolic troughs."*

www.reflectechsolar.com/home.html

www.reflectechsolar.com/pricing.html

www.reflectechsolar.com/technical.html

4.11 Overall Efficiency of the Trough Collector

Things that affect the efficiency of the trough are:

- Size, color, texture and heat absorption of the pipe
- Fluid characteristics
- Reflectivity of the reflector
- Temperature difference between the exposed pipe and the ambient air
- Wind conditions
- Orientation of the trough collector relative to the path of the sun
- Tracking accuracy of the heliostat

If the dimensions of the trough and the steady state power output are known, the efficiency can be calculated as suggested in this example.

> Hint. If the input and output temperatures are known, then the total Btu's added to the contents of the receiver can be calculated. It is also necessary to estimate the intensity of the sun.

length of a section: **l = 8 ft**
Width of a section: **w = 2 ft**
Area of a section: **a = l x w = 16 sq ft**

That gives 16 sq. ft. or approximately 1.5 sq meters per section (1.0 m^2 = 10.76 ft^2).

Therefore: **a = 1.5 sq meters / section**

If the solar power density is 1 kW / m^2, and power out is 800 Watts, the efficiency is:

n = Qout / Qin = 0.8 kW / 1.5 kW = 0.53 or 53%.

Question: What difference does the orientation of the trough collector make if it is oriented in an East-West direction or in a North-South direction?

4.12 Another Solar Trough-Turbine Project

The story in the following website is about what appears to be an MIT project in Lesotho in southern Africa.

www.technologyreview.com/read_article.aspx?id=17169&a=f

The following is a very nice continuation of the above story about Lesotho. It does explain that further efforts were planned for 2008 to produce electricity.

http://peacecorpsconnect.org/lesotho-tech

> **Author's note.** Notice there was never a claim that they actually succeeded in making steam or in generating electricity, but only that the system was *designed* to do it. That was true despite having been funded by the government for $130,000. One lesson to be learned here is that stories about energy should be viewed with some skepticism, regardless of the source.

4.13 The SEGS Project, Kramer Junction, California

It is suggested, as an academic exercise, that the reader scan the following website to compare the concept of a very large system with the concept of a very small system that is the subject of this series of papers. What are the similarities in the two concepts?

http://en.wikipedia.org/wiki/Solar_Energy_Generating_Systems