AN ABSTRACT OF THE THESIS OF

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The design of a point focus, distributed receiver solar power system is presented. It is shown that a two axis concentrator, with a two axis solar tracker and drive, has significant advantages over other possible optical systems. It is further shown that each concentrator should have its own optical receiver attached. A new dish and mount design is presented. This design provides a much stronger, lower cost dish. It further provides an easy way to attach a cheap drive system. The new mount is a gimbal, or cradle, in which the dish is mounted. The cradle provides a polar axis mount for the dish. The dish and cradle are very strong and will survive high winds in any orientation.

Several other significant improvements to other parts of the solar energy collection system are presented. These include an improvement to the receiver cavity design, a thermal shield and secondary reflector to be added to the receiver, an improved steam output system for the receiver, a plumbing system that eliminates the need for flexible couplings in the water lines, and a water distribution system that eliminates nearly half of the thermal insulation needed on the pipes going through the collector array.

Two economic optimizations are presented. The first analyses the return on investment for various dish spacings. The second analyses the cost per unit area of the concentrator dish and mount. It is found that the optimum dish diameter is ten meters and the optimum packing density in a conventional array is about 13%.

Design of a Solar Powered High-Pressure Steam Generator

by

Clifford B. Cordy Jr.

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Clifford B. Cordy Jr., Author

PATENT NOTICE

The author is holder of United States patent number 5,347,986 which covers many of the innovations presented in this thesis. Other patents are pending. No commercial application of these designs should be made prior to contacting the author concerning the patents and possible infringements.

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A = Area of mirror aperture, m^2
A_{eff} = Effective aperture = cos (angle between mirror axis and direction to sun)
Ave A_{eff} = Average effective aperture
C_{fix} = The cost of the part of the installation not related to dish packing density - \$/m^2 of dish
C_r = The cost of lengthening the cradle by one meter - \$/m of cradle
D = Dish diameter - meters
E = Young's modulus - Pa
EW = East-west distance between dishes - dish diameters
EW_o = Optimum east-west distance between dishes - dish diameters
E-W = East-west axis of rotation for a trough concentrator
Exp = Exponential scaling factor relating costs of dishes of various sizes
FMTR = fixed mirror tracking receiver
Guy = The cost to the cradle mount of increasing EW by one meter - \$/m
H = Height of a rectangular beam, specifically thedish rib - m
H_{cr} = Minimum height of a rib of thickness T_{cr} which will not overstress the material - m
H_d = Depth of dish below the plane of the edge of the dish - m
H_{min} = Minimum height of rib that will support the whole radius of the dish - m
H_{so} = Height of the effective steam outlet above the receiver axis at sunrise or sunset - m
H_s = Distance from aperture plane to outside edge of secondary reflector - m
I = Moment of inertia - m^4
ID = Inside diameter of structural tube - m
J = Ratio of solar intensity at a given time to the intensity with the sun vertical
K = A constant dependent on geometry in the rib buckling equation
L = Actual column length - m
L_{min} = minimum length over which a tube can be elastically deformed by an angle ω - m
L_r = Length of receiver from aperture plane to the steam outlet - m
L_{so} = Length from the aperture plane to the union of the two steam outlets - m
L_t = Length over which a tube is being elastically deformed - m
Land = Cost of land - \$/m^2 of land
Lat = Latitude of the installation - radians
M = Number of dishes in a N-S row of dishes
N = Number of quarter waves of bending in a column
N_{ns} = Number of dishes in a north - south row
NS = North-south distance between dishes - dish diameters
NS_o = Optimum north-south distance between dishes - dish diameters
N-S = North-south axis of rotation for a trough concentrator
OD = Outside diameter of structural tube - m
P_{cr} = Maximum axial force a column will sustain
P_{ew} = Cost of pipe and insulation going in the east-west direction - \$/m
P_{ns} = Cost of pipe and insulation going in the north-south direction - \$/m

R_a = Radius of receiver aperture - m
R_c = Radius of internal receiver cavity at the aperture - m
R_{cyl} = Minimum allowable radius of a cylindrical receiver cavity - m
R_i = Radius of the housing over the receiver insulation - m
R_{sphere} = Minimum allowable radius of a spherical receiver cavity - m
R_{so} = Radius from the receiver axis to the effective steam outlet - m
R_t = Radius of a tube or rod being stressed, specifically the steam tube - m
S = Ratio of solar intensity at sunrise to intensity with the sun vertical
Sp Gr = Specific gravity
T = Thickness of a rectangular beam, specifically the dish rib - m
T_{cr} = Critical thickness at which a rectangular beam will buckle - m
V_{max} = Maximum wind velocity in m/s
W_t = Watts thermal
W_e = Watts electric
X = Effective column length - m
a_0, a_1 = Constants used by Hottel in calculating atmospheric transmission
$cost_D$ = cost of dish of diameter D - \$
$cost_{10}$ = cost of dish of 10 m diameter - \$
elev = Minimum angle of elevation of dish axis at which the receiver axis can operate - radians
f = Focal length of concentrator - m
f/ = Focal ratio, or optical speed, of concentrator
h = Height of receiver cavity at which radius is computed - m
k = Constant used by Hottel in calculating atmospheric transmission
m = Moment in a structural member - Nm
mr = milliradians
r = Radius of receiver cavity at height h - m
t = time - hours after noon
x = distance from edge of aperture to ray from outside edge of secondary reflector - mm
$\alpha,\beta,\gamma,\delta,\varepsilon$ = angles used in calculation of secondary reflector - radians
Δf = Distance from focal point of dish to aperture plane - mm
Θ = Angle between wind source and dish axis = radians
ν = Poisson ratio
σ = stress in a structural member - Pa
σ_{cr} = Critical stress to cause buckling in a column or rib - Pa
σ_{max} = Yield stress of the material - Pa
τ = Atmospheric transmission - per unit
Φ = Angle between direction of wind induced lift and the vertical - radians
ϕ = Angle between the vertical and the direction to the sun - radians
ø = acceptance angle of aperture as seen from the edge of the dish - mr
Ψ = Minimum angle of elevation of dish axis at which the receiver axis can operate - radians
ω = angle through which a tube is elastically deformed

PREFACE

I became seriously interested in solar power at the start of 1985, ten years ago. It started as an interest in heating my house in Medford, Oregon, to cut the power bill in the winter. The rooftop collectors used for water heating are economic nonsense. Without an optical concentrator the heat loss is so great that they are practically useless. Even if the price dropped an order of magnitude, they would still be economic nonsense. I began by designing a trough concentrator, which is the right approach for moderate temperature differences. When summer came and I had to pay the bill for running the irrigation pumps, I began to think about making steam to drive an engine hooked to the pumps. This soon expanded to the general problem of making high pressure steam for whatever purpose.

I immediately recognized that the heat loss from a 1-axis concentrator would be prohibitive with the higher temperatures needed to generate high pressure steam. I started with a power tower concept. Since I had never read anything about solar concentrators, I thought this was a new invention. After a few weeks, I convinced myself that the mutual shading of the mirrors was an insurmountable problem and switched to the distributed receiver with paraboloidal dishes. The only optical system that I did not figure out independently was the fixed mirror tracking receiver.

For two or three years this was strictly a mental exercise. I think that was good. It has prevented me from being led astray by following the bad ideas of other people. Eventually I started reading about things other people were doing in the field. Clearly the overwhelming problem was the cost of the collector and I did not come up with a major improvement to existing designs for over four years. I did figure out as a mental exercise that in all existing systems the concentrators are packed closer together than economically optimum. To prove it required running four HP-110 computers continuously for about 2 years. A few papers have been written about optimum packing. They conclude that the optimum density is much higher than my calculations show. They don't give enough information for me to tell where the difference arises. Getting that right helps, but it was not the needed breakthrough in collector cost.

I started the project by designing a concentrator that was very strong, had a low material cost, and was easy to assemble. During the 7 years that have passed since then, I have not thought of another design that is even close to the cost effectiveness of this one. The only problem was that there was no known mount that would hold it and move it through the required motion.

I avoided being led astray by exotic fluids and "new" engines. These just confuse the issue. If a better engine comes along, it will be a better engine for a coal fired plant too and will confer no particular advantage to a solar system. I designed cheaper tracking systems, more efficient receivers, and better plumbing. These all help. Together they help significantly. But I still didn't have the required breakthrough in holding the dish and surviving the high winds that occur occasionally almost anywhere.

I actually visited several solar power installations to see first hand some of their solutions to the engineering problems. I visited Solar-1 (power tower) and SEGS-1 (troughs) at Daggett, CA. I visited STEP (parabolic dishes, single engine) (also one big dish with an engine mounted on it) at Newnan, GA. I visited Solar Plant 1 (stretched membrane dishes) at Warner Springs, CA. I visited the installation of the University of South Africa, near Pretoria, (a single parabolic dish made of fiberglass with a stirling engine not yet installed on it). And I visited a photovoltaic generator at Borrego Springs, CA. That one used Fresnel lenses as concentrators. They mounted the array on styrofoam blocks which they floated on a shallow pond of water. They drove the whole floating assembly, about a half hectare of it, around a vertical axis. Within the array, they drove whole banks of lenses and diodes, mounted on a pipe carrying cooling water, around horizontal axes (the pipes). The entire assembly was only about 30 cm high, so wind load was not a major problem. This was the only installation I've seen where any serious attention was paid to keeping the cost down to a reasonable level.

For the dish to be strong and simple, there has to be ample space behind the dish for structure. (Structure in front of the dish blocks sunlight and should be avoided.) Clearly the simplest dish mount is the monopod. A dish with reasonable structure cannot be mounted on a monopod and still be moved through the needed daily and seasonal motions. Also, it is hard to drive the dish to follow the sun when it is mounted on a monopod. Some very complex structures have been proposed to hold well braced dishes but these mounts are also very expensive.

Early in the course of trying to figure out the cheaper dish mount, I made a wish list for the mount. There were 7 major items, in descending order of importance: (1) cheap, (2) strong, (3) ample space for dish bracing, (4) axes of rotation pass through the edge of the dish, (5) polar axis mount, (6) easy attachment for drive mechanisms, and (7) drive mechanisms mounted at long radii from axes of rotation.

Finally in early 1989 I figured out a very simple, very strong structure that would hold a well braced dish in a gimbal arrangement. I refer to this gimbal structure as the cradle. The cradle is most easily set up for operation as a polar axis mount (as opposed to the altitude/azimuth mount normally used on monopods). The polar mount inherently requires less speed and power from the drive motors. The cradle has natural attachment points for mounting very simple dish drive mechanisms for both axes of rotation. These attachment points are at a long radii from the axes of rotation so the drive motors can run at lower torques. Finally, the axes of rotation pass through the edge of the dish (rather than well behind the dish as with a monopod), so the wind induced torques on the drive system are minimized. It seems to be the ideal dish mount.

Sometime about 1987 I convinced my major professor, then my whole doctoral committee, that I should be allowed to use my solar steam generator as my PhD thesis project. In retrospect, this was a very risky proposition because at that time I had very little new to offer. In 1988 I tried to publish a paper about the optimum dish spacing. It was not well received, especially not by the people who disagreed with my results. By late 1989, I wrote a first draft of my thesis. The consensus of opinion was that it was too long and not detailed enough.

I actually started working with a patent agent in 1987, while I had improvements to only the small problems. He wrote a couple drafts of patent applications that were terrible. In 1991, after I added the cradle, and after another terrible draft of a patent application, I changed to a patent lawyer who I had met at Apple. In Sept. 1994, I was granted U.S. patent number 5,347,986, which covers most of the designs I have made. This is a surprising range of devices for a single patent. I was very busy with my consulting work in 1991-3 and did not give the thesis the attention it needed. I did finish the patent. I did submit a paper about the cradle. After several cycles of modification, the paper has been accepted by the American Society of Mechanical Engineers, Journal of Solar Energy Engineering and will be published in the August 1995 issue. This thesis is the culmination of my ten-year design effort.

DESIGN OF A SOLAR POWERED HIGH-PRESSURE STEAM GENERATOR

1. INTRODUCTION

SOLAR ENERGY IS FREE. WE SHOULD BE USING IT.

THE ABOVE STATEMENT SHOULD BE THE ONLY FALSE STATEMENT IN THIS THESIS

Solar energy definitely is not free. Direct solar energy is a diffuse resource and the cost of the equipment needed to collect it has been prohibitive except in very limited special circumstances.

The main cost of a solar thermal energy system is the concentrator and the structure to hold and move it. It is expensive because it must survive occasional, very strong winds. It does not have to operate during a high wind condition, but it must not break.

Most solar concentrator dishes in operation today are mounted on monopods. This forces design constraints onto the dish that result in a dish that is more expensive and less strong than desirable. Also, there is no convenient way to connect the two-axis dish drives from the monopod to the dish, so the drive is more expensive than desirable. To protect the dish during high winds, it is normally driven to a position where it can be safely stowed. This requires a drive that can move the dish much more rapidly than is needed to simply follow the sun and the drives must operate even during power failure conditions. Efforts have been made to design dish mounting structures that avoid these problems, but they are universally very complex and expensive.

The design presented here starts with a dish that is strong and cheap. The dish will survive strong winds in any orientation, so does not need to be driven to a stow position. That removes the requirement for a high speed, fail safe drive system. It also eliminates the need for weather prediction. This dish could not be mounted onto presently available dish mounts because the dish structure would interfere with the mount during its daily and seasonal movement.

The second step of the design is to create a strong, cheap structure for holding and moving the dish. This gimbal, or cradle, represents the biggest single breakthrough in system cost of anything presented in this thesis. The salient characteristics of the cradle are:

1. It is composed of three tetrahedra, the tetrahedron being one of the few fundamentally stable three dimensional shapes.

2. There are a total of 12 structural members in the cradle. The dish itself is one of these members.

3. Eleven of these structural members experience only axial loads. One is loaded in flexure.

4. All forces along the polar axis are delivered to the earth's surface at the end of the cradle nearest the equator.

5. The cradle contains ample space for the dish structure to move without interference.

6. The dish rotates within the cradle ±23.5° around the declination axis.

7. The cradle, and the dish contained within, rotates up to ±120° around the polar axis.

8. There are natural attachment points for drives around both axes, operating at long radii from the axes, so drive forces are minimized.

Presently available receivers have several undesirable characteristics. A receiver design is presented that minimizes these problems. This receiver has a unique cavity shape that is maximally black (to absorb the most possible sunlight) in minimum length (to minimize heat losses). It has a combination thermal shield (to protect the receiver in case of drive system failure) and secondary reflector (so the aperture can be smaller to reduce heat losses). And it has a dual steam outlet which allows the receiver to operate to a horizontal position (which allows sunlight to be collected from sunrise to sunset). These improvements are not cheaper than present receivers, although they are not significantly more expensive. They deliver more output energy, so return on investment is improved.

Two improvements in the plumbing of a collector array are presented. It is shown that by properly mounting the tubes carrying water and steam to and from the receiver, special flexible couplings operating at high pressure and high temperature can be eliminated. This is a significant improvement in cost and reliability. It is also shown that by dividing the collector array into two parts, approximately two equal halves, the amount of insulation used on the pipes in the collector field can be cut in half. Cold water from the condensed engine exhaust is pumped to half the receivers through uninsulated pipe. Hot water from the steam separator is circulated through the other half of the receivers and that water pipe is bundled with the steam return line within a single layer of insulation.

The density of dishes in the collector array affects return on investment. A massive computer analysis of the economics of dish spacing was done. Sample results are shown. The optimum dish density in a conventional installation at the latitude of U. S. desert areas is about 12% (total mirror aperture divided by total land area). This is less than half the density used in existing installations or reported in the literature.

Finally, an analysis is done that shows the optimum dish size is about ten meters in diameter. The system cost per unit area has a fairly broad minimum and little penalty is incurred as long as the dish diameter is in the range of eight to twelve meters. Beyond those limits, the system becomes considerably more expensive.

2. THE WORLD OF ENERGY

ENERGY RESOURCES

It is widely recognized that the present world energy situation is precarious and considerable effort has been expended to develop alternatives to the mass use of fossil fuels. At present, the bulk of the world's energy comes from burning fossil fuels. Other significant contributors are nuclear, hydro, and geothermal sources. Eventually the fossil fuel reserves will be depleted and the fuels will be unavailable or prohibitively expensive. With breeder reactors, nuclear fuels are practically limitless, but nuclear reactors have become politically unacceptable. When the real fossil fuel crisis comes, it is unlikely that there will be enough installed nuclear generation to forestall disaster. There is a serious limit to how much hydro and geothermal energy is potentially available and much of what is available is already being used.

Nuclear fusion is often presented as a panacea. It is commonly claimed to be a "clean" energy resource of practically unlimited size. In reality it is unavailable and would not be clean if it were. Worse, a usable fusion generator now appears to be at least as far in the future as it did 20 years ago.

There are other proposed methods of generating power such as burning biomass or garbage or fermentation of biomass and burning of the resulting alcohol or methane. There are arguments about whether these are ecologically desirable (get rid of garbage) or undesirable (make smoke). But in any case, they are rather limited resources.

It is generally considered that the most desirable alternative is direct solar energy collection. No existing solar power system can compete economically with a modern coal fired, steam turbine, electric power generator (despite the claims of some rather creative accountants to the contrary).

There are three forms of solar power collection that have received serious attention. These are wind driven electric generators, photovoltaic generators, and solar thermal generators. The first two are strictly electric generators. The latter is commonly used to generate electricity as a final product but can also generate heat for industrial processes.

Many wind generators of various sizes and designs have been built. Clearly the energy availability is sporadic so they could never provide more than a small fraction of the power in the electric grid. Even as a supplementary system, they do not seem to be competitive with burning coal. If all the technological problems were solved and an economically competitive design were produced, there are only a few places where the wind is steady enough to make wind generators useful. The resource is limited.

Photovoltaic cells have been used in special applications for many years. Their characteristics are well known. In terms of installation and use, there are no unsolved problems. The problem is the cost of the diodes themselves. It will take at least one more major breakthrough from the semiconductor industry in either cell cost or efficiency before photovoltaics will become widely used. It is likely that ultimately this will be the answer to the world's energy problems. It may be many decades before this happens.

That leaves solar thermal generators. A solar collector can be designed using no concentrator. The common roof top water heater is one example. Other examples are salt gradient ponds and using temperature differences in various layers of the tropical oceans. By nature, these collectors are very large area. As a result, they must work at low temperature differences to keep heat loss down to a reasonable fraction of the total input. There are few interesting processes that work at low temperature and to generate electricity with a small temperature difference is inherently a very low efficiency process. In addition, very large volumes of working fluid must be pumped thru an extensive plumbing system. This is expensive. Even though the the collector itself is cheap (in the case of the salt gradient ponds) or free (in the case of the open ocean), the total system is not cheap and the electrical output per unit area of collector is tiny. Considerable effort has been put into the salt gradient pond concept. However, it is most likely that economics will continue to dictate the use of a concentrator.

HOW MUCH IS AVAILABLE

In space, near the earth orbit, the solar power density is about 1390 W / m^2 $\pm$ 3.4% (as the earth goes around its slightly elliptical orbit. The atmosphere is not perfectly clear at any wavelength. In the infrared, large bands are totally opaque, mostly due to water vapor absorption. On a crystal clear, dry day near sea level, solar power density probably never exceeds 1000 Watts per square meter. In Barstow, CA, (desert, elevation 1000 m) it occasionally exceeds 1050 W / m^2. On the Bolivian altiplano (very dry, elevation 4000 m) it could approach 1200 W / m^2.

Converting solar energy into electricity is a multistep process and there are losses associated with every step. Table 2-1 contains a summary of the efficiency of each step and the final electrical output. This assumes that the system is composed of a field of paraboloidal dishes with a receiver (boiler) mounted on each dish. There are two columns in the table. The first shows the output with the brightest possible sun and everything polished and adjusted for peak performance. The size of the power generator must be based on this value. The second column shows the typical output with normal atmospheric conditions, dust on the mirrors, and other imperfections throughout the system. The net result is that optimistically the peak electrical output may approach 250 W / m^2 of mirror , but it will not average more than 150 W / m^2. In terms of land use, this converts to a typical value of 20 W / m^2 of land, or 20 MW / km^2. Since turbines do not work well in sizes smaller than tens of megawatts, this implies that typical installations will be one to two kilometers on a side.

	Peak	Ave	
Solar power density =	1050	900	W / m^2
Mirror reflectivity =	93	85	%
Mirror distortion loss =	2	4	%
Receiver blackness =	99.9	99	%
Thermal losses =	3	5	%
Theoretical efficiency =	32	28	%
Turbine efficiency =	82	78	%
Overall efficiency =	23	17	%
Electrical output =	243	**150**	W / m^2 of mirror
Optimum dish density =	13	13	%
Electrical output =	32	**20**	W / m^2 of land

Table 2-1
AMOUNT OF ELECTRICITY THAT CAN BE GENERATED

SOLAR ECONOMICS

It is commonly stated, and it seems almost universally accepted, that as the price of fossil fuels rises, solar generators will become more competitive. This is untrue. As the price of fossil fuels rises, the price of everything else rises also. That means that the price of the materials used in the solar collector rises and the wages paid to the workers rises. It all rises very close to the same ratio, although there are often delays of a few years between events. In the end, if a solar electric system is noncompetitive today, it will still be noncompetitive in 10 or 20 years when the cost of fuel is higher. It is a mistake to talk of the cost of a solar collector in terms of today's dollars and the cost of a coal fired generator in terms of tomorrow's dollars.

In the United States, half of the cost of a coal fired electric generator is pollution controls. This fraction is constantly rising. This does tend to make solar systems more competitive, but only in the U. S. Most countries with any significant pollution control requirements have no desert areas, so solar power is not a realistic option. Conversely, most countries with significant desert areas have no pollution regulations, so solar power is not an economic option.

The cost estimates for building new coal fired electric generators vary considerably. The most common estimate is $5 / Watt peak output. Common estimates for nuclear power plants are in the range of $4 / Watt. However, PG&E figures $1.5 / Watt for a coal fired plant [Wallace, 1988]. They spent $2.5 / Watt on the Diablo Canyon reactors [Pacific Gas and Electric, 1984] and they figure they could duplicate that. With their amortization schedule, construction costs come to 3.8¢ / kWh for a coal fired plant.

Operating costs aren't much better defined. It was reported in 1989 that the operating cost for a coal fired plant dropped below that of a nuclear plant for the first time [Horgan, 1989] at 2.0¢ / kWh vs. 2.1¢ / kWh. On the other hand, PG&E estimates [Wallace, 1988] that the costs are 3.8¢ /

kWh and 1.3¢ / kWh respectively. That brings the cost for electricity produced from coal to 7.6¢ / kWh according to the PG&E estimate or 14.7¢ / kWh by the other estimates.

Make some optimistic assumptions. A competitive solar generator must generate electricity for 15¢ / kWh. It requires no maintenance. It generates at full power for 10 hours a day. It must be paid off in 5 years, or 18250 hours of generation. Then the whole system has to be built for $2.74 / Watt. If the power plant costs $0.50 / watt, the collector field has to be installed for $2.24 / Watt. If the system will deliver 160 Watts of electricity per square meter of mirror, the collector must be built for $358 / m^2. This is an absolute maximum that the collector could cost under the most optimistic possible assumptions and still be competitive with coal. The best existing systems do not meet this requirement.

Make some pessimistic assumptions. A competitive solar generator must generate electricity for 10¢ / kWh. It requires 2¢ / kWh for maintenance. It generates at full power for 8 hours a day. It must be paid off in 5 years, or 14600 hours of generation. Then the whole system has to be built for $1.17 / Watt. If power plant costs $1.00 / Watt, the collector field has to be installed for $0.17 / Watt. If the system will deliver 130 Watts of electricity per square meter of mirror, the collector must be built for $22 / m^2. This is a pretty pessimistic estimate. It does show that it is critical to keep operating hours up and maintenance costs down. It is inconceivable that a solar collector could be built for $22 / m^2.

Make some medium assumptions. A competitive solar generator must generate electricity for 12¢ / kWh. It requires 1¢ / kWh for maintenance. It generates at full power for 9 hours a day. It must be paid off in 5 years, or 16425 hours of generation. Then the whole system has to be built for $1.81 / Watt. If power plant costs $0.75 / Watt, the collector field has to be installed for $1.06 / Watt. If the system will deliver 150 Watts of electricity per square meter of mirror, the collector must be built for $159 / m^2. This should be a reasonable estimate of what a cost competitive solar collector could cost.

3. REVIEW OF CONCENTRATING SOLAR THERMAL SYSTEMS

There are four basic forms of optical concentrators that can be designed. These are known as (1) the parabolic trough, (2) the spherical fixed mirror, tracking receiver, (3) the central receiver or power tower, and (4) the point focus distributed receiver. In this chapter, a very brief description of each is given, then the systems that have been built are described. The next chapter presents an engineering analysis of each optical system.

THE PARABOLIC TROUGH

The parabolic trough concentrates the sunlight in one axis, whereas all other concentrators focus in two axes. It focuses to a line instead of a point. As a result the trough need be moved in only one axis. To properly focus the sunlight on the focal line, the trough must be aimed such that the sun lies in the plane defined by two lines: the focal line and the axis of the parabola. In theory, this can be accomplished no matter how the trough is oriented. In practice, the trough axis is always mounted either in the north-south direction or the east-west direction. In chapter 4 it is shown that the N-S axis of rotation gives much more daily energy per unit of mirror area.

The receiver for the trough concentrator is a tube passing along the focal line. Chapter 4 shows that for the trough, concentration ratios of about 20 are expected. Heat loss is a critical problem and controlling it is essential.

By 1982, fairly modern troughs were being proposed [Almanza, 1982]. By then the Johnson & Johnson process steam plant was in operation [Brink and Youngblood, 1982]. It was fairly unsuccessful in that the parasitic losses (power required internally to run the solar generator) were high and operating time was low. Another early system at Getafe, Spain [Koehne, Kraft, and Vidal, 1982] captured only 51% of the incident light, largely because the absorber pipe was too small for the mirror quality. Improved systems followed. These include the electricity generators at Willard, NM, [Krivokapich, et al, 1983], Coolidge, AZ, [Larson, 1987], the SEGS systems, [Electric Energy Information Center, 1985][Luz International, no date given], and two trough systems at Almeria, Spain [Wettermark, 1988]. The Almeria systems are both unusual. One is an east-west trough, insuring poor total daily energy collection. The other is composed of a set of troughs mounted on monopods with two-axis drive. That manages to combine the great disadvantage of troughs (high heat loss) with the great disadvantage of two-axis drives (expense).

Of all these, the SEGS units are clearly the most successful. The SEGS-II systems are 30 MW modules. The early units are located at Daggett, in the southern California desert. Later units were built nearby at Kramer Junction. The troughs are nearly 5 meters wide and 50 meters long. The mirrors are formed of sagged glass, silvered on the back side. Full power operation can be achieved in 16 m/s wind. Operation at reduced power, due to mirror flexure, is possible to wind speeds of 20 m/s. Tolerable wind speed in the stow position (nearly face down) with windbreaks installed is 35 m/s.

Concentration ratio for SEGS-I is 19. SEGS-II is probably similar. The receiver is wavelength selective and is mounted in an antireflection coated, evacuated, glass tube. The absorbing surface is said to be 95% black to sunlight and 21% black to a 300C black body. They claim the glass vacuum jacket functionally transmits about 97% of incident light. From pure physics, it would seem these claims are extremely optimistic. To accommodate thermal expansion of the receiver, the glass vacuum jacket sections are separated by metal bellows. Oil is pumped through the receiver to a heat exchanger where water is boiled. The steam can be superheated in a natural gas fired furnace. Cost of the first SEGS-II unit was $95M, or $3.2 / peak Watt. They claim that later units are cost competitive with new coal fired electric generators.

THE FIXED MIRROR TRACKING RECEIVER

The FMTR is the only concentrator for which the optical function is not obvious. The geometry of the concentrator is shown in Figure 3-1. A spherical bowl is fixed to the surface of the earth. The receiver is suspended from the center of the sphere. It is a characteristic of a single spherical surface that there is no such thing as an off axis ray. In effect, this is equivalent to saying that it is possible to draw a line through the center of the sphere that is parallel to any arbitrary ray. That being the case, there is no off axis aberration. That leaves only spherical aberration. (There is no chromatic aberration in a reflective system.) All on axis rays will be focussed at some point on the line passing through the sun and the center of the sphere. Rays entering close to the axis will be focussed on the axis halfway between the center of the sphere and its surface. Rays entering further from the center of the sphere will be focussed closer to, or even behind, the surface of the sphere. A ray far enough from the center to be focussed behind the spherical surface, will undergo multiple reflections, but will ultimately pass through the line passing through the sun and the center of the sphere at some point between the surface of the sphere and halfway to the center of the sphere. Note that for the above to be true, the surface must be spherical, not paraboloidal or any other shape.

For use as a solar concentrator, the spherical bowl is anchored to the surface of the earth. The receiver is mounted on an arm which pivots around the center of the sphere. The receiver extends from near the surface of the sphere to a point halfway to the center of the sphere. The receiver is moved in such a way that the mounting arm always points away from the sun during its daily and seasonal motion. This requires two-axis tracking, but the weight and wind loading forces to be overcome are much smaller than in systems moving the entire concentrator. Hence the drive is much cheaper. Note that at those times when the sun is near the horizon, the mounting arm will not be aimed at a point on the surface of the dish. In that situation, some rays may pass beyond the end of the receiver and not be collected. The loss is small because the sunlight intercepted at the ends of the day is small in any case. While the bowl is fixed to the earth, it is not necessary that it be fixed with its edge, or lip, parallel to the plane of the local horizontal. As is shown in chapter 4, considerably more energy can be collected if the plane of the lip is perpendicular to the sun's rays at solar noon on an equinox. This condition is satisfied if the north edge of the bowl is raised above the south edge (in the northern hemisphere) to an angle equal to the local latitude.

The receiver for an FMTR concentrator will be a tube shape. In chapter 4, it is shown that the concentration ratio is about 30. It is also shown that in any system with a concentration ratio under about 100, the control of heat losses from the receiver is critical. The FMTR clearly falls within the critical heat loss category. The same expensive measures to control heat loss that are used with trough collectors must be used with the FMTR.

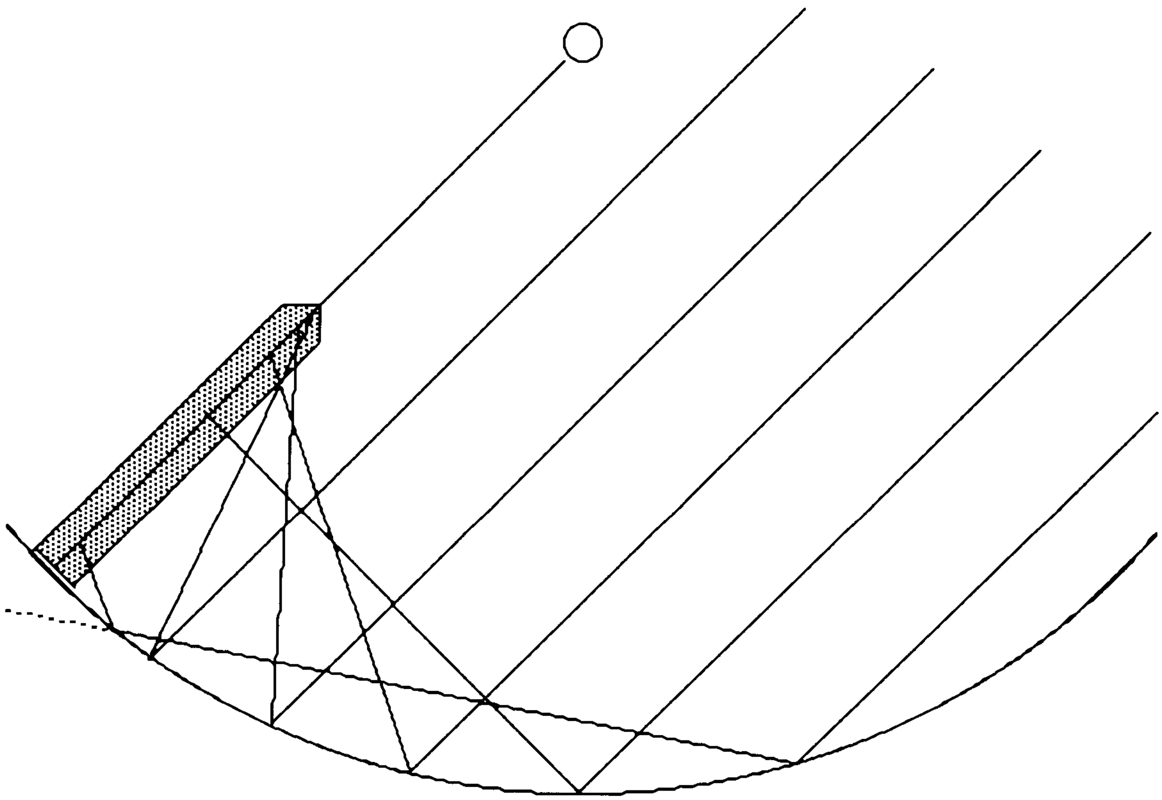


Figure 3-1
RAY TRACE FOR AN FMTR CONCENTRATOR

Several FMTR systems have been built for steam generation. The first was the Pericles installation, in France [Authier, 1977]. It was a relatively small bowl, only 10 meters in diameter. Next was an experimental 2.5 meter bowl [Fruchter, Grossman, and Kreith, 1982] in the U.S. The biggest and best known is the Solar Gridiron at Crosbyton, Texas [Reichert and Watson, 1982][Jarnish and O'Hair, 1986][O'Hair, Simpson, and Green, 1986]. The bowl is 20 meters in diameter, composed of 1 m^2 sections. The mirrors are glass mounted on honeycomb. Many broke. The edges did not conform sufficiently to the spherical surface so only 60% to 70% of the incident light hit the boiler "at best", despite 83% mirror reflectivity. Water is pumped through the receiver and boiled therein. The lip of the bowl is somewhat tipped but not by as much as the latitude. Their economic analysis suggests that the optimum size bowl would be 61 meters in diameter. That would collect a peak power of 2 MW_t. The estimated cost to produce electricity is 15 to 18 ¢ / kWh.

There is a system built in Corsica that is a hybrid system, an FMTR in a trough [Bacconet, Dancette, and Malherbe, 1982]. There has also been a U.S. patent granted on this idea [Boy-Marcotte, 1985]. To collect most of the available energy at the ends of the day with a north-south trough would require an absorber tube with a diameter of one half the radius of the trough. This implies a concentration ratio of about one, which is useless. The east-west trough is a lousy collector at the ends of the day anyhow, so using a smaller absorber is not so great a penalty. However, concentration ratio will be under 20 at best, so thermal losses will be higher than the spherical system, and daily energy intercepted will probably be lower too. This approach cannot compete with the spherical bowl.

THE CENTRAL RECEIVER

The central receiver, or power tower, seems to have become the standard configuration of solar collector in the mind of the interested layman. Perhaps this is because the tower and receiver make a much more spectacular sight, especially in operation, than any of the other installations. The intensely illuminated receiver gives an other-worldly impression that is not comparable to any other view. The basic concept is very simple. Mount a receiver on a fixed tower. Surround the tower with a field of mirrors that are nearly flat (or even flat [Sun World, 1981]). Aim each mirror at a point half way between the sun and the receiver, as viewed from that mirror. The solar image from each mirror then falls on the receiver. Herein lies the first problem. There is no object for the mirror to track. Each mirror has to be driven open loop. If it is out of position, there is no way to generate a correction signal. In fact, if an error is detected, there is no way to know which mirror is out of position.

The receiver is equivalent to a cylinder atop the tower. In most installations, the radiation comes in from all sides, so insulation is impossible. Internal (cavity) receivers have been proposed

[Wu, Naraganan, and Gorman, 1983], but it is hard to visualize how any real advantage could be gained and no large systems have been built that way. Concentration ratios near 200 are usual. For any given mirror design, a higher concentration ratio can be obtained by packing the mirror field tighter. However, this leads to additional shadowing. Studies show that the mirror and two axis drive is the most expensive part of the power tower system [Brown, 1987][Brown, 1989]. Since the concentration ratio is well above the 100 level, It is more important to reduce mirror shading than to increase concentration ratio.

Several large power towers have been built. Even larger ones have been proposed, extensively studied, and largely designed [Durrant, Capozzi, and Best, 1982]. Among the early power towers were the Central Receiver Test Facility [Holmes, 1982] at Albuquerque, NM, the Eurelios unit [Cefaratti and Gretz, 1981] at Adrano, Sicily, and CESA-1 [Muñoz, 1982][Grasse, 1981] at Almeria, Spain. In power towers, power density is high enough to consider using molten salts or metals as the working fluid in the receiver. Examples are the molten salt experiment [Delameter, 1987] and the Almeria power tower [Wettermark, 1988] with liquid sodium. Both of these suffered seriously because the power required to keep the materials molten during the night was a large fraction of the electricity that was generated during the day. At Almeria, parasitic energy exceeded the solar electric energy generated.

Easily the best known power tower is the Solar 1 [Bartel and Skuarna,1983][Bartel, 1983][Sandia, No Date Given] at Daggett, near Barstow, CA. The tower is 91 meters high. The receiver is 13.7 meters high by 7.0 meters in diameter. The concentrator field has 1818 mirror assemblies of 39.9 m^2 each. Each assembly has 12 mirrors, about 3056 mm by 1100 mm, mounted in a 2 wide by 6 high array. The back silvered glass mirrors are epoxied to a metal honeycomb which is epoxied into a sheet metal tray, giving weather protection to the metalized surface. The mirror assemblies are designed to operate in a 22 m/s wind and withstand a 40 m/s wind in the stow (horizontal, face down) position. The apparent concentration ratio is 240. However, because most mirrors are working significantly off normal, the cosine factors reduce the effective concentration to little, if any, more than 200. Water is boiled and superheated within the receiver.

I visited Solar 1 again in August, 1994. At that time it was shut down for modifications. The boiler was obviously badly damaged. The worst damage was in the section that produced saturated steam, not the region where the steam was superheated which normally operates at higher temperatures and lower power densities. I suspect there had been a failure in the water circulation system. They are adding two rows of mirrors around the outside of the present mirror field. In addition, they are rebuilding the receiver to work with liquid sodium circulating through the receiver. If the fluid circulating system ever fails again and the fluid freezes in the receiver and pipes, it will be very expensive to recover. Also, much of the luster seems to be gone from the idea of solar power generation. The visitor center has been closed.

THE POINT FOCUS DISTRIBUTED RECEIVER

The point focus distributed receiver system consists of an array of paraboloidal dishes with a receiver mounted at the focal point of each dish. The receiver is mounted on the axis of the paraboloid and the dish is driven in two axes to keep the sun on the axis of the paraboloid also. Ideally, there are no aberrations and the power density at the focal point theoretically can approach 6000 W/cm^2, the radiant power density of the surface of the sun. Real systems don't do that well. At the 1 MW$_t$ Solar Furnace at Odiello, France [Kreider, 1981], power densities of 16 MW/m^2 (1600 W/cm^2) can be achieved, resulting in operating temperatures of 3825C. This implies a geometric concentration ratio approaching 20000. For purposes of steam generation, this is higher than necessary, or even desirable. There is a compromise between mirror quality (expense) and heat losses. Better mirrors mean higher concentration ratio, smaller receiver aperture, and lower loss. Chapter 4 shows concentration ratios over 1000 are reasonable. Two axis tracking is essential. Normally, the sun is tracked with a closed loop electro-optical system.

The receiver can be either an internal (cavity) receiver or an external receiver. In an internal receiver, the sunlight is directed through an aperture into a cavity. The receiver contains the cavity. The outside of the receiver is insulated. This form minimizes heat loss. An external receiver absorbs the sunlight on its outside surface. Concentration ratio is lower and heat loss is higher. But the heat loss is small in any case and the internal receiver is more expensive.

There have been several large distributed receiver systems built. These include the Solar Total Energy Project (STEP) [Stine and Heckes, 1987][Ney, 1982][Georgia Power, no date given][Casbaro, 1989], a Kuwaiti installation [Moustafa, et al, 1984][Zewen and Moustafa, 1981][Moustafa, 1989], LaJet [Carroll, 1985], and several single dish generators. Each of these has some unique characteristics. The single dish generators are somewhat different from the others and are discussed in the next section.

The STEP system was a commercial installation operated by Georgia Power. (It is now mothballed.) The concentrator is a 7 meter dish, designed by General Electric. This dish is formed sheet metal in 21 radial segments mounted into a radial rib structure. The optical figure is not good, as is obvious from photographs, [Georgia Power, no date given]. The figure is particularly bad near the ribs and even worse near the points where the reflector panels are mounted to the ribs. As a result, concentration ratio is only 235. The concentrator is mounted on a trio of steel and concrete piers. Concentrators are so densely packed that they almost hit each other. Packing factor is 0.41. An internal receiver is used. A silicone oil is circulated through the receivers and can be heated to 400C. 330C is normal. Thermal losses from the receiver and plumbing are over 20% of the energy collected [Stine and Heckes, 1987]. Furthermore, over 10% of the day's energy goes to warm up the system in the morning. That is excessive. A reasonable warmup loss would be under 5% [Moustafa, 1989] and SEGS-1 has only a 1.5% inertial loss [Electric Energy Information Center, 1985]. Because the STEP installation is in hurricane country, it is designed to withstand winds of 45 m/s. Peak winds from Hugo (which passed nearby in Sept. 1989) were in the range of 30 m/s at the STEP site and there was no damage. At the time it was shut down in August 1989, STEP had one year service from some new silver on mylar mirrors. They were 97% reflective when new and they still were after a year. This compares with the 85% reflectivity of the older aluminum on mylar mirrors.

The Kuwaiti installation is a cogeneration project with waste heat used for desalination of sea water. The dishes are on polar axis mounts. In the Kuwaiti installation, the receiver is external and is fixed to the earth. By not moving the receiver, there is no worry about the working fluid (oil) leaving an air bubble inside the absorber surface. This can be a major problem. It also eliminates flexible couplings between the receiver and the load. Fluid leaks are the major maintenance item at most installations. The tradeoff is that the dish rotates around a point well in front of the dish, making the drive more difficult and increasing the wind induced torque on the gears. By using a polar mount, only one axis of sun tracker and dish drive is needed. In the other axis, adjustment is done by hand every couple days. The dish itself is a fiberglass-foam sandwich. It is very stiff, considerably stiffer than necessary. The mirror is metalized plastic.

The LaJet facility, also known as Solar Plant 1, (not to be confused with the Solar 1 power tower) is at Warner Springs, CA. It has another unique set of innovations. The mount, although entirely different from the Kuwait installation, is on a polar axis. The mount is functionally a monopod but is built of a web of metal pieces. 24 mirrors, each 1.5 meters in diameter, are mounted to a steel structure. Each mirror is a metalized plastic membrane stretched over a steel hoop. Another plastic sheet is stretched over the backside of the hoop. A partial vacuum is drawn on the chamber formed by the hoop and two plastic sheets. The vacuum causes the plastic sheets to take a spherical shape. The vacuum is actively controlled by a simple valving arrangement behind the mirror. The concept seems simple, light weight, and cheap. Weight is much smaller than wind loading in any case, so is unimportant. The hoop must be very strong and the plastic much thicker than normal mirrors, stretched very tight and evenly, and anchored securely to the hoop [Murphy, 1986]. Altogether, it is not particularly cheap. Also, it is more wind sensitive than most mirrors [Alpert and Housner, 1989] with an operating limit around 10 m/s. The receiver is internal. Water is boiled in some receivers, superheated in others. There is an intermediate fluid of molten salt between the backside of the absorber and the water. The molten salt does not leave the receiver but can absorb the high power density there and deliver it to the steam for superheating at a much lower power density. In this way, thermal losses are kept low.

THE DISTRIBUTED ENGINE

A special case of the distributed receiver system is the dish with the receiver and heat engine both mounted at the focus. In a large scale installation, this would become a distributed engine system and all the analyses of the distributed receiver system are equally applicable to the distributed engine system.

Several single dish prototypes of this type has been built and tested. The most successful of the distributed engine systems, (albeit with only one dish and engine) is the one at Rancho Mirage, CA [Washom et al, 1984][Jaffe, 1988a]. The concentrator is a 10.6 meter dish, one of a group of designs known collectively as "the Georgia Tech design". The concentrator was built of back silvered glass facets, each 45.1 by 60.3 cm, individually mounted into a metal structure and hand aligned. The structure and mirror assembly and alignment "only" required 5 men for 15 ten hour days. That comes out to 8.5 man hours/m^2. At \$40/hr, that is \$340/m^2 just for assembly. If unwashed, mirror reflectivity dropped from 92.5% to 74% in 25 days. Washing requires 2 hours, (about 44 m^2 / hour or \$1/m^2 or 1.3 ¢/kWh). High temperatures (750C) were important for efficient operation of the Stirling engine, so the concentration ratio is 2700. The aperture vignettes a significant amount of light and only 79% of the solar energy passes through. Furthermore, at a wind speed of 7 m/s, mirror flexure reduced output to 83% of its zero wind output. The concentrator would survive a 22 m/s wind in any orientation and a 40 m/s wind in the stow position. The dish is mounted on a pedestal 75 cm in diameter, 1 cm wall thickness. This is mounted to a concrete and steel pier set 3.7 meters into the ground. The unit will produce a peak gross output of 25.6 kW and a net energy output of 238 kWh / day. Total gross efficiency is 29%, which is very good.

The advantage of the distributed engine is that it eliminates plumbing. The disadvantage is that the output from any one generator is small, so the cost of generators per kW is high. To minimize the generator cost penalty, the optimum dish size is larger than that for any other system configuration. It will be shown later that large dishes are relatively expensive. So, the savings in plumbing comes at the cost of concentrator and engine expense. The choice of a Stirling engine also has system impact. To be competitive with a steam turbine, the Stirling engine must work at a high temperature. This implies a large concentration of solar energy, and consequently, a higher quality optical surface on the concentrator. That also raises the cost of the concentrator. Small turbines do not work well, so are inconvenient to use in distributed engine systems. Tests with similar dishes and Brayton and Rankine engines were less successful [Jaffe, 1988a][Jaffe, 1988b].

4. ENGINEERING DECISIONS

Solar thermal generators have been around for decades. This is a relatively mundane field. Very little is available for use now that was not available 50 years ago. That will not change. The breakthroughs needed to make solar thermal generators competitive with burning coal are in the area of engineering design, not materials science. To date, a couple billion dollars have been spent world wide to build prototype systems. Most are not even close to being cost competitive. In fact, most were obviously designed in accordance with Parkinson's law [Parkinson, 1957] rather than good engineering principles.

To design a solar thermal system, many decisions have to be made about the basic approach to be used. These decisions all have economic impact, often major economic impact. The following sections discuss some of these fundamental decisions.

CONCENTRATION RATIO

One of the most important characteristics of a solar concentrator is the concentration ratio. For purposes of solar collectors, the most useful definition of concentration ratio is the area of the mirror aperture divided by the surface area of the receiver. A higher concentration ratio produces a lower percentage heat loss. Consider a system working at 300C. With a concentration ratio of 100, the typical noontime solar power density absorbed by the receiver will be in the range of 70 kW / m^2. The radiated power density from a black body at that temperature is over 6 kW / m^2. Adding convection losses raises the total loss above 10 kW / m^2, or about 15%. In any system where the concentration ratio is less than about 100, heat losses will be a serious concern in the overall system efficiency. At concentration ratios over 100, heat losses are a much smaller factor.

The angular diameter of the sun as seen from the earth is about 9 mr. The form of the mirror can be made essentially perfect, as in a telescope, but that is prohibitively expensive. As a practical matter the mirror will have errors that blur the solar image considerably. There are several potential sources of error in the mirror. These include small irregularities in the mirror surface, errors in the slope of the mold surface, warping of the mirror backing after it comes off the mold, twisting of the mirror due to imperfect mounting structures, and deflections due to wind and gravity. Each of these are typically several milliradians. Since the error sources are independent, the total error is the RMS of all the individual errors and the energy distribution approaches a Gaussian. To make the receiver large enough to intercept the entire fringe of the imperfect solar image would mean unreasonably large heat losses from the receiver. Typically, the receiver is made large enough to intercept the part of the image that lies within ±15 mr of the center of the image. This should deliver about 98% of the solar energy to the receiver.

CONCENTRATOR FORM

There are four basically different configurations that can be used. These are the parabolic trough, the fixed mirror tracking receiver (FMTR), the central receiver (Power Tower), and the point focus distributed receiver. These are listed in increasing order of the concentration ratio that can be achieved in a practical system. Large systems have been built using each of these configurations.

Any time the axis of a solar concentrator is not aimed directly at the sun, the solar power intercepted is reduced by a factor of the cosine of the angle between the concentrator axis and the direction to the sun. For any concentrator geometry at any given hour and day of the year, this angle can be computed. I define the effective aperture, A_{eff}, to be the cosine of that angle and the average effective aperture, Ave A_{eff}, to be the average of this value over all daylight hours of the year. This is a figure of merit for each concentrator geometry.

The Parabolic Trough

The parabolic trough focuses the sunlight to a line and a black pipe is mounted on that focal line. The trough is rotated about one axis to track the sun. The axis of rotation can be either North-South or East-West. In either case, the trough has to be moved through a full π radians to follow the daily motion of the sun. (It is a common misconception, even in print, that the East-West axis trough only has to be moved through $\pm 23.5°$ on a seasonal basis.)

It takes a computer program to calculate the effective aperture of the mirror for each axis of rotation. However a close approximation can be made as a mental exercise. The E-W trough, as seen by the sun, appears to have an aperture of about

$$A_{eff} = A * \cos(\pi t/12)$$

where t is the time after noon. Averaged over the year, this gives an average effective aperture of

$$\text{Ave } A_{eff} = A * 2/\pi$$

On the other hand, the N-S though has an effective aperture of about

$$\text{Ave } A_{eff} = A * \cos(\text{latitude})$$

The cost of the system is independent of the direction of the axis of rotation, so clearly the E-W trough can be eliminated from consideration (despite the fact that some systems are built that way). Note also that the N-S axis of rotation gives a fairly constant output throughout the day whereas the output of the E-W axis trough drops dramatically toward the ends of the day.

It is easy to calculate the concentration ratio. If the optical speed of the trough is 0.5, a commonly used value, then the trough width is twice the focal length. If the tube has a radius sufficient to intercept all rays within ± 15 mr of the center of an ideal solar image, then the tube circumference is about:

$$\text{Circumference} = 2 * \pi * 0.015 * \text{focal length} = 0.1 * \text{focal length}$$

and the concentration ratio is:

$$\text{Concentration ratio} = (2 * \text{focal length}) / (0.1 * \text{focal length}) = 20$$

Clearly, heat losses are on the verge of prohibitive and any successful system will depend on heroic efforts to control them.

The big advantage of the trough is that it tracks the sun in only one direction, so the mount and drive system are much cheaper than something that needs to follow the sun around two axes. However, these savings are at least largely offset by the cost of thermal loss control and reflection losses from the glass tube surrounding the receiver pipe. These are real physical limitations and cannot be changed by intelligent engineering design.

The Fixed Mirror Tracking Receiver

The FMTR uses a stationary spherical mirror and moves the receiver to follow the image of the sun. The receiver is driven around the center of the sphere such that it always lies opposite the sun as viewed from the center. Inasmuch as the sun is a small angular source, the spherical surface of the mirror has no off axis aberrations, independent of the solar position. The small aperture focal point of a spherical surface is half way between the center of the sphere and its surface. In a useful geometry, the mirror aperture is not small and the spherical aberration is huge. The image of the sun can lie along the entire length of the line extending from the mirror surface to the nominal focal point. Again the practical concentration ratio of the system can be calculated. The surface area of the receiver will be the circumference, as above, times the length of the receiver, which is essentially the same as the focal length of the mirror. So:

$$\text{Receiver area} = 0.1 * (\text{ focal length })^2$$

In a typical concentrator, the mirror radius is about equal to the focal length, so:

$$\text{Mirror area} = \pi * (\text{ focal length })^2$$

and

$$\text{Concentration ratio} = 31$$

This is better than the trough concentrator but it is still far from the 100 or more that is desirable.

Again a close approximation to the average daily energy collected can be calculated as a mental exercise. Seen from the sun, the area of the bowl appears to vary sinusoidally during the day. If the edge of the bowl is parallel to the local surface of the earth, then the effective aperture of the bowl will be

$$\text{Ave } A_{eff} = A * 2 / \pi * \cos(\text{latitude})$$

If the bowl is tipped so it points in a direction parallel to the earth's equatorial plane, then the cosine factor is eliminated. Note that the intercepted energy drops toward zero at the ends of the day, while the heat losses remain constant. Thus this collector becomes utterly useless while the sun is still well above the horizon.

It is necessary to use similar measures to control heat losses in an FMTR as Luz applied to the trough collectors. In fact, it would be significantly easier in the FMTR because the receiver is not so long that the bellows would be needed to accommodate the thermal expansion of the receiver.

The great advantage of this optical system is that the mirror does not move. Moving the receiver is relatively easy, and cheap. The low concentration ratio is a major problem, a major expense. The killer problem for this system is the low average effective aperture. The power house, which is also a major cost item, must be sized to handle the power delivered at noon with the sun essentially centered over the bowl. After accounting for thermal losses, it is probably impossible for a system to deliver half that much power averaged over all daylight hours. The implication of this is that if the power house cost half the total investment in a point focus distributed receiver system, and the FMTR delivers only half as much heat as the distributed receiver system, then, to be competitive, the FMTR collector would have to cost nothing.

The Central Receiver

The central receiver, or power tower, is equivalent to a cylinder atop a tower surrounded by a field of mirrors. The power tower is less amenable to analysis than other optical geometries. There is no fixed geometry associated with the ratio of the tower height to mirror field radius. There is also no fixed density of mirrors within the mirror field. Typically, the radius of the mirror field is about twice the tower height. Mirrors at the edge of the field suffer more mutual shading. If the field is a smaller radius, the concentration ratio is smaller and the percentage of thermal loss increases. An optimum mirror field radius exists. There is a hole in the center of the mirror field. The inside mirrors suffer less mutual shading but the receiver (not the tower) must be taller to intercept the light from them. Again, there is an optimum radius to the inside mirrors. The hole in the center of the mirror field is a small part of the area of the mirror field.

From this geometry, the receiver radius has to be about

$$\text{Receiver Radius} = 0.033 * (\text{tower height})$$

The receiver height is typically about four times the radius, so the light from the mirrors close to the tower does not pass above and below the receiver. The resulting surface area is

$$\text{Receiver Area} = .009 * \pi * (\text{ tower height })^2$$

Ignoring the hole in the center of the mirror field, the mirror field covers an area of

$$\text{Mirror Field Area} = 4 * \pi * (\text{ tower height })^2$$

Thus, if the mirror field were covered solid with mirrors and there were no mutual shading, the concentration ratio would be 444. The mirror field is not covered solid. The mirrors and mounts are expensive and to get reasonable use from that expense, it is necessary to space then widely enough to reduce the mutual shading. In practice, the mirror field is about one third covered by mirrors and the concentration ratio is in the range of 150. This is within the realm of a reasonable value. (The concentration ratio of 250 at Power 1 was achieved by spending a lot of money to get high quality mirrors and mounting them in stiff housings).

The effective average aperture of the mirror is very hard to estimate and impossible to calculate for a "typical" situation. Untold hours of CPU time have been burned up searching for mirror arrangements within the mirror field that produce less shading than any known pattern. There are still dreamers who think a significant improvement remains to be discovered. At any given moment, there is a cosine effect because most of the mirrors in the field are pointing at a spot significantly away from the sun. Towards the ends of the day, this effect is large. A much larger problem is that at most times, possibly at all times, some mirrors are shading other mirrors. Worse, of that light that does strike a mirror, some is reflected onto the back side of an adjacent mirror and lost. The shading and vignetting problems are particularly severe toward the ends of the day, but they generally occur to some extent at all times.

Consider the mirror field as a unit. This unit is stationary and is parallel to the surface of the earth at the site of the installation. The unit has a certain mirror area and the rest is nonreflective areas between mirrors. As a crude approximation, the effective average mirror area is

$$\text{Ave } A_{eff} = A * 2/\pi * \cos(\text{latitude})$$

just as it was with the horizontal FMTR bowl. A is still the total mirror aperture, not the land area covered. There are two obvious errors in this approximation. First, the mirrors within the field move and will intercept more sunlight than this model predicts. Second, some of the intercepted sunlight is reflected against the back side of adjacent mirrors and less energy is delivered to the receiver than might be expected. These two errors tend to cancel and real installations deliver average energies very close to what this simple minded model predicts.

In the final analysis, the only real advantage of the power tower is that it saves a lot of plumbing. The disadvantages are that it needs two-axis movement of the mirrors (costs the most) and it collects the least average energy per unit area of mirror (pays the least). This is the easiest of the four optical systems to eliminate from serious consideration.

The Point Focus Distributed Receiver

The point focus distributed receiver system consists of an array of paraboloidal dishes with a receiver mounted at the focal point of each dish. The receiver is mounted on the axis of the paraboloid and the dish is driven in two axes to keep the sun on the axis of the paraboloid. Since the dish always points directly at the sun, the effective aperture of the mirror is equal to the real aperture. The concentration ratio is very high, especially when an internal receiver is used. In a dish with the radius equal to the focal length, the radius of the receiver aperture will be about:

$$R_a = 0.015 * (\text{focal length}) * 1.6 = 0.024 * (\text{focal length})$$

the factor of 1.6 being due to the fact that rays from the edge of the dish have to pass through the aperture at an angle of a bit more than 45° from the normal. The resulting concentration ratio is:

$$\text{Concentration ratio} = 1 / 0.024^2 = 1736$$

which practically eliminates thermal losses.

The great advantage of the point focus distributed receiver is the large average effective aperture (1.0) and the low thermal loss (a few percent). The disadvantage is the cost of building a mount and drive system that will track the sun in two axes. This problem can be attacked by engineering cunning. It is not limited by the laws of physics.

Summary of Optical Systems

Table 4-1 shows the effective aperture of the various optical systems that can be used as solar collectors. These numbers are the result of detailed computer analysis, not the approximations used above. This represents the size of the aperture of an isolated collector, as seen by the sun, averaged over all hours of the day and all days of the year.

Latitude Degrees	E-W trough	N-S trough	horiz FMTR	tipped FMTR	dist rcvr
0	0.690	0.958	0.610	0.610	1.000
5	0.690	0.957	0.608	0.610	1.000
10	0.690	0.952	0.602	0.610	1.000
15	0.690	0.944	0.591	0.609	1.000
20	0.690	0.932	0.577	0.608	1.000
25	0.690	0.918	0.558	0.607	1.000
30	0.690	0.901	0.536	0.606	1.000
35	0.690	0.882	0.511	0.603	1.000
40	0.690	0.861	0.482	0.600	1.000
45	0.690	0.838	0.451	0.596	1.000
50	0.690	0.814	0.418	0.590	1.000
55	0.690	0.790	0.383	0.580	1.000
60	0.690	0.765	0.348	0.563	1.000
65	0.690	0.743	0.315	0.529	1.000
70	0.690	0.723	0.291	0.458	1.000
75	0.690	0.708	0.275	0.413	1.000
80	0.690	0.698	0.264	0.374	1.000
85	0.690	0.692	0.258	0.339	1.000
90	0.690	0.690	0.256	0.305	1.000

Table 4-1
AVERAGE EFFECTIVE APERTURE OF VARIOUS OPTICAL SYSTEMS

Using the data in Table 4-1, it is possible to calculate the cost for which each optical system would have to be built in order to compete with the distributed receiver system. The results of this calculation are shown in Table 4-2. Since the aperture of the power tower cannot be computed precisely unless the position of each individual mirror is known, the average aperture is assumed to be the same as the horizontal FMTR. This was shown earlier to be a reasonable assumption.

Assume that a distributed receiver system that is cost competitive with burning coal can cost 2.0 units. Further assume that this cost is divided evenly between the power house (1.0 unit) and the collector array (1.0 unit). For that 1.0 unit cost, the collector field delivers an average output of 0.98 units of heat to the power house (the rest being thermal losses). Assume the cost of the power house is proportional to the peak power out of the collector. The money that can be spent on the total system is proportional to the average power generated. Subtract the cost of the power house from the total money available and it leaves the money that can be spent on the collector field. It is pretty obvious that nothing can compete with the parabolic concentrator except possibly the N-S trough. After considering the expense involved with heat loss control, even the N-S trough is very unlikely to be a competitive system. The only real question is whether the parabolic dish system can be built cheaply enough to compete with coal.

	E-W trough	N-S trough	horiz FMTR	tipped FMTR	power tower	dist rcvr
Concentration Ratio	20	20	31	31	150	1500
Thermal Losses	20%	20%	15%	15%	10%	2%
Receiver Emissivity	0.90	0.90	0.90	0.90	0.93	1.00
Vacuum Tube Loss	5%	5%	5%	5%	none	none
Average Aperture	0.689	0.882	0.511	0.603	0.511	1.000
Maximum Aperture	1.000	1.000	0.980	1.000	1.000	1.000
Peak Power Out	0.684	0.684	0.712	0.727	0.837	0.980
Average Power Out	0.471	0.603	0.371	0.438	0.428	0.980
Money Available	0.972	1.244	0.766	0.903	0.873	2.000
Cost of Power House	0.705	0.705	0.734	0.749	0.854	1.000
Cost of Collectors	**0.27**	**0.54**	**0.03**	**0.15**	**0.02**	**1.00**

Latitude = 35°

Table 4-2
RELATIVE COST OF COLLECTORS TO BE ECONOMICALLY COMPETITIVE

DISTRIBUTED ENGINE SYSTEMS

Mounting the engine directly on the concentrator has the advantage of saving heat losses and plumbing cost. It has two big disadvantages. First, it uses a lot of little engines and generators instead of one big one. One big one is much cheaper. Second, small turbines do not work well. A distributed engine system generally uses some other type of engine. Stirling engines are used most commonly, but others (including turbines) have been tried.

The turbine is the engine of choice where the power source is high pressure steam unless there are other overwhelming considerations. All power companies use turbines to drive their generators. Small power generators use diesel engines. Stirling engines are still in the realm of scientific curiosities. If Stirling engines were cheaper in the long run, power companies would be using them already. The double penalty of more expensive engine types and more expensive engine sizes makes the distributed engine system unattractive.

SUPERHEAT

Superheating the steam makes the efficiency of the engine higher. The theoretical efficiency of an engine working with saturated steam at 300C input and 60C output is 31.0%. Raising the temperature to 600C at the same pressure raises the efficiency to 39.4%. That means any given mirror will provide 27% more electricity if the steam is superheated to that extent. This increase is not free. Radiation losses in the system increase by a factor of 5 due to the higher operating temperature. If the radiation loss from the receiver and plumbing is 4% at 300C, it would be 20% at 600C and most of the gain in engine efficiency would be lost. In addition, heat can be safely pumped from a metal surface into liquid water at a power density of about 500 kW/m^2. The maximum practical power density that can be transferred into steam is two orders of magnitude lower. That means the receiver would be much bigger, and would have much higher heat losses.

The SEGS systems use a natural gas fired superheater. The theoretical efficiency of the natural gas part of the system is 50%, which is very high. That makes it sound attractive. If it really is attractive, the idea should be in use in geothermal power plants. I wrote to the Electricity Corp. of New Zealand [Thain, 1988]. They said they had investigated fossil fuel superheaters and had concluded that it was not economically advantageous. My conclusion is that, at best, the idea is of questionable value.

The La Jet system uses a pool of liquid salt in contact with the receiver surface. The steam can then be circulated through a heat exchanger within the salt. In this way, the receiver can be built so it is little bigger than the receiver that produces saturated steam. The receivers that superheat could be mounted on dishes that are close to the power house which would minimize the heat loss from the very hot pipes carrying superheated steam. It is possible that this idea has merit. The receiver would cost more, but the receivers are a small part of the system cost. I have not yet done the detailed investigations on the cost and characteristics of high temperature insulation to determine if superheating is economically viable.

WORKING FLUID

Most heat engines use a liquid/vapor system. Usually the fluid is water although other fluids have been used. Water is not perfect. It is corrosive and it works better if superheated, which is difficult in a solar system. The great advantage is that it is cheap. It is not necessary that the working fluid be the same fluid that is pumped through the collector field, which I will refer to as the collector fluid.

Collector fluids used in solar systems include water, other boiling liquids, a variety of oils, liquid metals and salts, and chemical systems. The last store the energy in the form of some chemical change rather than heat. The chemical energy is changed to heat in the power house, where it is used to drive a heat engine. These have an appeal in that they could make it so the entire solar collector field could be operated at a relatively low temperature and pressure, which would save heat losses and insulation costs. Unfortunately, no material is known that is cheap or works very well.

Circulating oils or liquid metals or salts through the collector field allows the field to operate at low pressure but it must operate at a temperature at least as high as if the working fluid is also the collector fluid. Also there is an additional heat exchanger needed. The maximum operating temperature of existing oils is no higher than the temperature of high pressure saturated steam, so they cannot be used to superheat the steam. Therefore oils have little advantage. Liquid metals and salts can be much hotter. That increases heat losses, makes insulation difficult (common materials are limited to about the temperature of saturated high pressure steam), and adds a requirement that the system be kept hot at night. The liquid cannot be allowed to solidify while in the collector field. This added loss makes liquid metals and salts very unattractive in a distributed receiver system. Some other liquids, such as freon, with better thermodynamic characteristics as a saturated vapor have been used. These are expensive and have other failings.

Almost all fuel fired electric generators use water as a working fluid. So do steam locomotives. Power companies learned how to control the corrosiveness of water in the last century. Basically the water must be kept very pure and free of oxygen. This is done by using pure water to start with and by constantly circulating a fraction of the water through a deaerator.

Most geothermal fields produce hot water. The rest produce saturated steam. The power companies have learned to deal with this condition. If there were some great advantage to using some other fluid in the heat engine, then all geothermal generators would be circulating this fluid through a heat exchanger and the heat engine. None do this.

A question has been raised about problems in pumping a steam/water mixture through the pipes. Again, the geothermal generators have abundant experience in this field. It has not been a problem for them [Thain and Stacey, 1984]. Nor has it been a problem in solar generators where the condition exists [Gee and Murphy, 1983][May and Murphy, 1983]

THERMAL STORAGE

Most solar power installations have some means of storing a fraction of the acquired thermal energy as heat rather than converting it all to electricity instantaneously. There are three reasons for doing this. The power house can be built a bit smaller and cheaper because peak power is lower; the electric utility that is buying the electricity will often pay more for electricity generated in the late afternoon and early evening when solar input is low or zero; and it reduces fluctuations, especially fast fluctuations, in the solar electricity supply delivered to the electric grid as clouds come over.

Thermal storage is very expensive. The savings in power house cost are minuscule compared to the cost of thermal storage. Hydroelectricity is cheap. It makes much better economic sense to turn down the hydrogenerators during the day and turn them up again in the evening [Metz and Hammond,1978]. Even when the quantity of solar generated electricity exceeds the capacity of the present hydroelectric system to compensate, water could be pumped up the dams during the day and allowed to run down again at night. It is almost possible to pump water up the main stem of the Columbia and Colorado rivers right now. A few more relatively small dams would make it entirely possible. A hydro - solar combination is both cheaper and more efficient than thermal storage. Power companies are using such pumped storage systems already to provide peaking power to supplement their fuel fired, base load generators.

Once a significant solar electric capacity is installed, fast changes to the power generation level will not occur. Any one dish can be blocked by a cloud in a few seconds. Any one collector field can be blocked in a few minutes. The solar arrays serving any one utility cannot be blocked in less than a period of hours. And the prime collection area in the U. S. covers a couple thousand kilometers. It would take days to cover that whole area with cloud. That is certainly not a fast fluctuation. Thermal storage is very expensive and inefficient. It makes no sense.

5. CONCENTRATOR DESIGN

Having shown that the only practical way of collecting solar thermal energy for electricity generation is with a paraboloidal dish and attached receiver, the next step is to define the shape of the dish. The optics of the concentrator dish are well understood. It is fairly easy to show that the maximum concentration ratio is achieved if the optical speed of the dish (focal length / diameter) is 0.6. Essentially all existing designs use dishes with a speed of very near 0.6. The unsolved problems in dish design lie in the realm of structural design.

It is first necessary to select from among several possible approaches to the dish design. The dish is composed of three parts, the reflective surface, a rigid backing for that surface, and a structure that supports the the backing and provides mounting points. The reflective surface is generally either a metalized plastic membrane or metal deposited on glass. There are at least four different styles of dishes. These are the stretched membrane, fiberglass backed plastic mirror, sheet metal backed plastic mirror, and glass mirror sections anchored into a structure of some sort. All have been used in existing systems and all work. There is an infinite variety of structures that could be used to support the mirror and its backing.

THE MIRROR AND BACKING

A glass mirror set into a metal mount which, in turn, is held in a support structure, has the potential of being the best optical quality, but it is more expensive than the others. The mirror is expensive and the labor required to mount and align all the mirror sections is prohibitive. It is economically impractical unless there is a need for a very high concentration ratio.

The LaJet installation uses stretched membrane mirrors. At first, it appears to be easily the cheapest concentrator. Plastic sheets are stretched across both ends of a metal hoop, like a very wide, thin drum. The inside of the drum is partially evacuated so the plastic membrane assumes a spherical shape of the proper radius to focus the sunlight on the receiver. Under analysis of the design details, the apparent advantage disappears. The plastic has to be much thicker than is needed when the plastic has a rigid backing. The hoop over which the plastic is stretched has to be strong and rigid. A rigid hoop is a heavy structure. The plastic comes in 1.5 meter maximum width, so that limits the diameter of any individual mirror element. Sealing the membrane to the hoop has been a problem. To mount a group of mirrors on a single drive requires a fairly elaborate structure. Each element in the group has to be individually aligned to focus into the receiver. At best, the stretched mirror has no clear advantage.

The STEP facility has a sheet metal backing for the mirrors. The quality of the mirror shape is not as good as would be desired. They have a concentration ratio of only 235 despite using an internal receiver. There is a metal dish at Cal Poly, San Luis Obispo. Its surface has an orange peel texture and obviously does not focus as well as would be desired. Based on these examples, it is apparent that making a metal dish is not an easy job.

The installation in Kuwait uses fiberglass dishes and they work well. The concentration ratio is 200, despite using an external receiver. It would normally be three times as high with an internal receiver on the same mirror. The structure was built as a fiberglass/foam sandwich, which, in practice, was found to be much stiffer than necessary [Moustafa, 1989]. Fiberglass has its own problems. It can seriously warp, especially if the resins are over catalyzed. To minimize warping, curing time is long and the material is left on the mold until it is well cured. Hence, output per mold is small and the investment in molds is significant.

New fiber loaded, injection molded plastics are constantly being introduced. It may become possible to make injection molded plastic backings for plastic film reflectors. These would be similar to the car body panels now being used instead of fiberglass pieces. The investment in molds is much larger than for the simple molds needed for fiberglass parts, but the manpower needed to produce a part becomes minuscule.

The plastic mirror is the nearest thing to a high tech item in the whole system. There are presently several manufacturers and considerable research effort, despite the low priority generally given solar power at the moment. The mirror is a multilayer system. A plastic layer is metalized. The plastic is commonly a polyester, although better materials are now available. The material of choice at the moment seems to be tedlar, but several others are being tested.

The metalization is aluminum or silver. Silver has been severely limited in lifetime, but the latest silver mirrors seem to be lasting well. Silver has a higher reflectivity. The plastic layer must contain an ultraviolet absorber to protect the metalization. The back of the metalized plastic is covered by a second layer of plastic for weather protection. An adhesive is commonly added to the mirror to attach it to the dish.

The South African group [Cawood, 1991] has built their dish using strips of very thin glass mirrors. The glass is so thin that it can be deformed to fit the curve of the fiberglass back. Glass mirrors have historically given better performance and lifetime. If they are thin enough to conform to the backing (as opposed to flexing the backing to conform to the glass), then they may be economically competitive. The best answer may be to make the glass strip with a slightly spherical shape. This would easily conform to the paraboloidal shape of the dish.

Fiberglass backed plastic mirrors can be made today. Their properties are known and a design can be made using these properties. Making the choice to design a structure using a plastic mirror mounted on a fiberglass backing allows future changes to be made in material selection with minimal effect on the design of the rest of the structure.

THE BRACING STRUCTURE

Fiberglass mat is cheap but it is neither strong nor rigid compared to steel. More rigid high tech composites are available but they are expensive and the production processes are difficult. Fiberglass from a chopper gun (the most obvious production process) has a strength of about 70 MPa and a Young's Modulus of about 7 GPa, [Puls, 1989]. This compares to typical values of 350 MPa and 200 GPa respectively for steel. Attempting to design an all fiberglass dish soon makes it clear that an all fiberglass design is impractical. It is necessary to build a steel structure into which the fiberglass dish or dish sections are mounted.

The simplest, most rigid bracing for the dish takes the form of a teepee frame with a center pole [Cordy, 1994]. The bracing could be installed either behind or in front of the dish. Braces in front of the dish cause shadows across the dish and the center pole interferes with the receiver. Braces behind the dish would hit a monopod mount and the dish could not be moved through its required range of motion. The solution is to devise a mount into which a strong dish with braces behind the dish can be mounted. That is done in the next chapter.

A picture of a strong, simple dish is emerging. It is a thin paraboloidal fiberglass shell nested in steel with a teepee shaped steel frame extending a considerable distance behind the dish. The simplest nest for the dish is a set of radial ribs, each connected to one leg of the teepee frame. This structure is shown in Figure 5-1.

STRUCTURAL ANALYSIS

The Mirror Backing

The dish, being a compound curve, does not yield to simple analyses of stress and flexure. In 1988 a finite element analysis was done on a 4 meter diameter dish built in 8 sections [Blythe, 1988]. Several possible dish structures with radial steel ribs and various lesser supporting ribs in the fiberglass were analyzed. Although the simplest case of no other supporting ribs was not analyzed (and the computer program was lost immediately afterward), the results made it pretty obvious that the best situation would be to use only the radial steel ribs. The computer plot of the results of the finite element analysis is almost unreadable on the original and is useless if reproduced. The results for a single dish section are paraphrased in Figure 5-2. The analysis was done with a rib across the outer edge of the dish panel. That caused major distortions at the edge of the dish, especially in the radial direction. So nothing can be extrapolated from the existing data about radial deflections near the dish edge. The large distortions at the edge also affected the way the computer plotted the data and resulted in less resolution than desirable in the deflections over the bulk of the dish area.

The above analysis shows that the fiberglass itself can be surprisingly thin. If the dish sections are no more than 1.5 meters wide at the outside of the dish (the width of available mirror material), then a fiberglass thickness of 1.5 mm is sufficient for operation in 15 m/s winds and survival in 50 m/s winds. At that thickness, the glass and resin in a 20 section dish (nominally 10 meter diameter) would weigh about 1400 N.

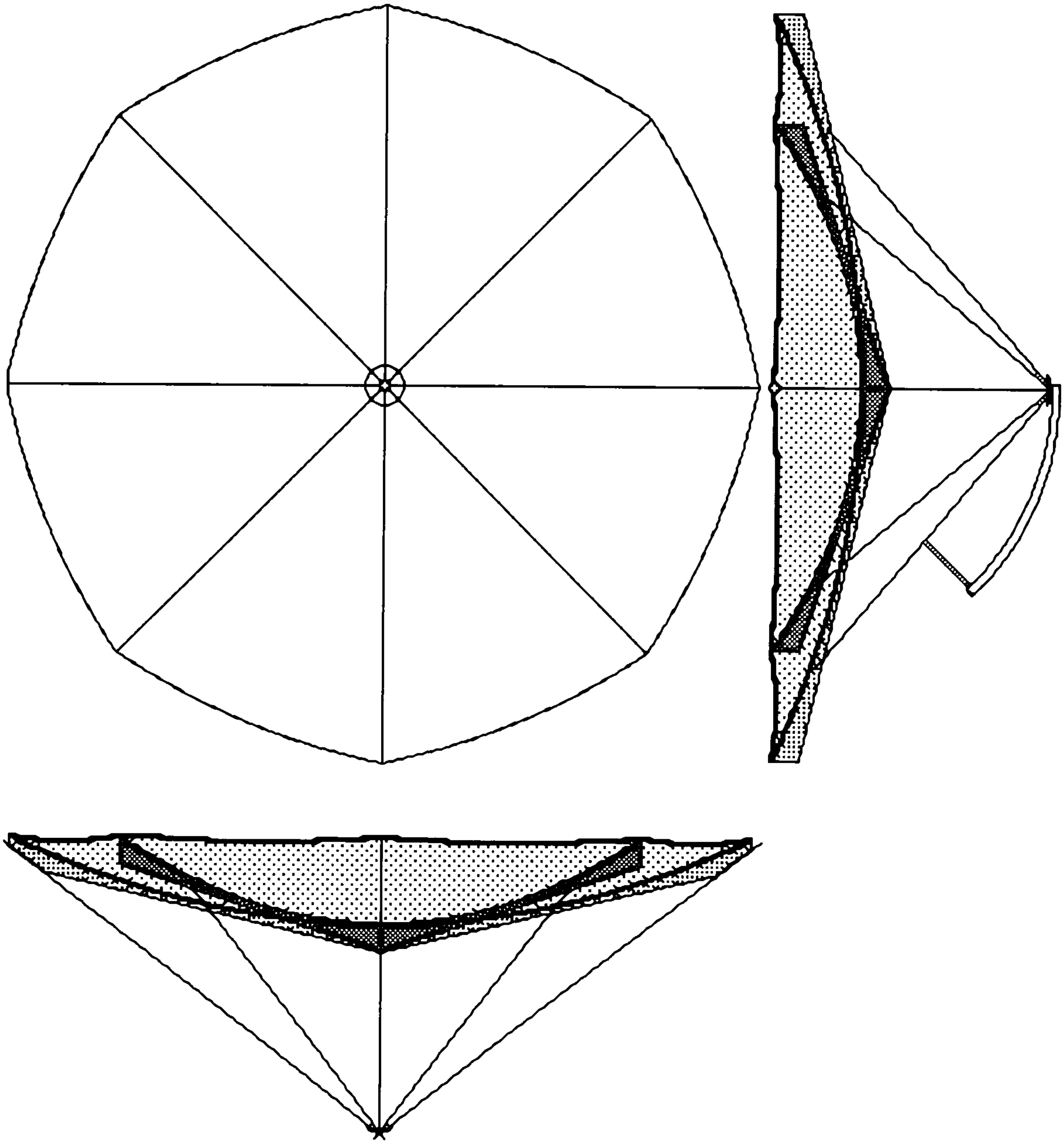
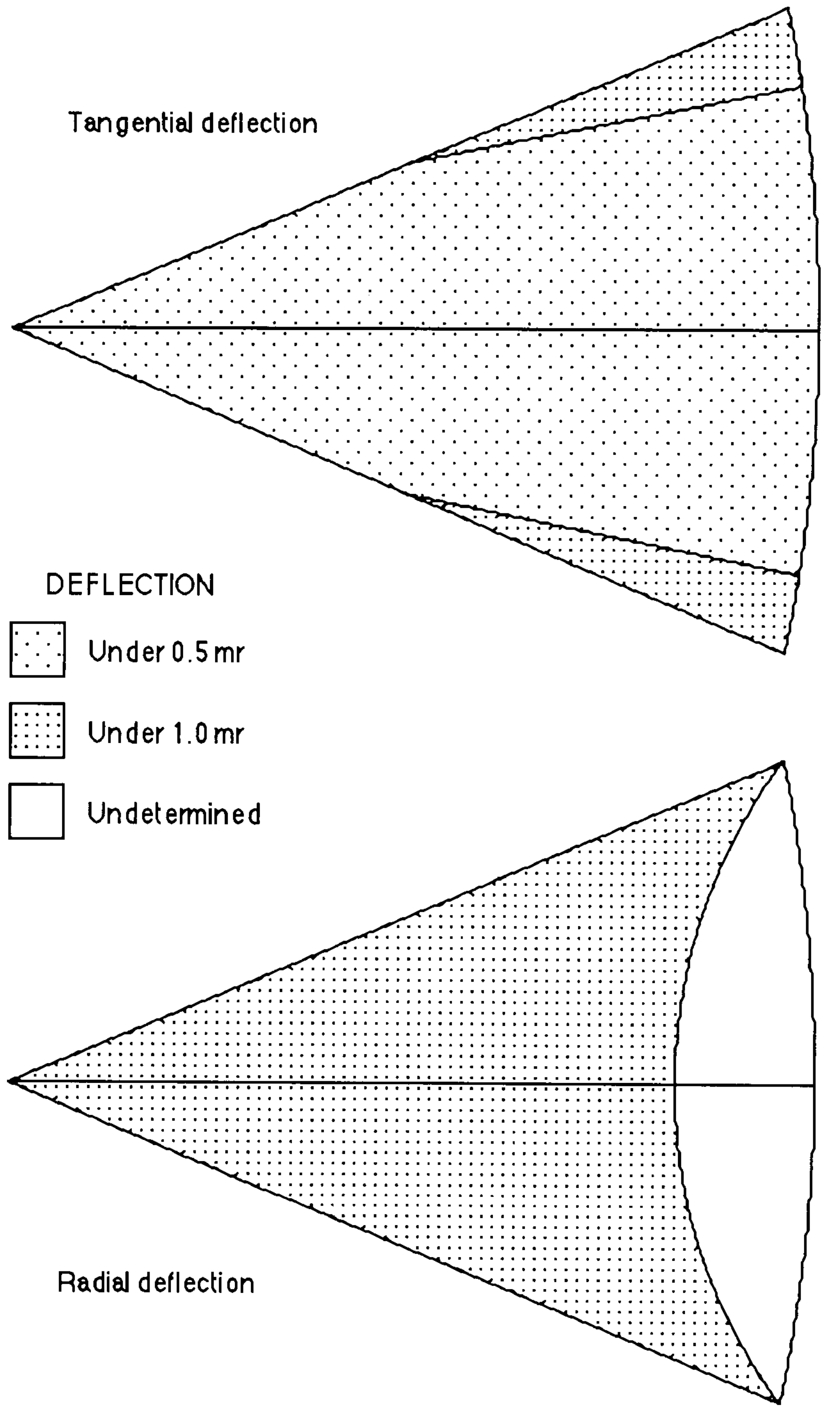


Figure 5-1
CONCENTRATOR DISH



dish radius = 2 m. fiberglass thickness = 1.6 mm. wind speed = 15 m/s

Figure 5-2
WIND INDUCED MIRROR DEFLECTION

The Ribs

Assume for the moment that it is possible to design some sort of gimbal mount for the dish. It has a pair of dish mounts that are diametrically opposed. The dish can rotate within the gimbal around one axis, located in the plane of the lip of the dish. This is one of the design goals. The drive around that axis can be tied into the apex of the teepee frame. Drive forces to overcome wind loads are minimized because there is a long lever arm connecting the drive to the dish. A track for that drive mechanism is also shown in Figure 5-1.

The steel ribs are a length of the dish radius, a height of something greater than 1/4 dish depth (so they are held between dish sections for their whole length), and a thickness suitable to prevent buckling. Timoshenko [1936] analyzed buckling problems of various structures early in this century. For all sorts of long thin beams, the maximum allowable stress is:

$$\sigma_{cr} = \pi EKT^2 / 12(1-\nu^2)H^2$$

where K is a constant dependent on geometry, E is Youngs modulus, H is rib height, T is rib thickness, and ν is the Poisson ratio. There are two sources of stress in the ribs. The rib is a loaded beam and, as such, has a moment around any given point. In addition, the ribs are part of the teepee structure. When a leg of the teepee experiences an axial force, its associated rib will also have an axial force. All these forces can be calculated as will be discussed later. One note on the critical stress formula deserves mention. The peak stress in a beam is:

$$\sigma = mH / I$$

where m is the moment at that point, and I is the moment of inertia. For a rectangular beam,

$$I = TH^3 / 12$$

and

$$\sigma = 12\, m / TH^2$$

The ratio of stress to buckling stress is:

$$\sigma/\sigma_{cr} = [144\,(1-\nu^2) / \pi E] * [m / K T^3]$$

Once a material is selected, the quantity in the first bracket is a constant. To avoid failure of the rib, this ratio must be less than unity. Note that while the stress in the rib is related to rib height (and this must not exceed the strength of the material), the safety factor for buckling is related only to rib thickness. The critical thickness, which just avoids buckling, is:

$$T_{cr} = (\, 144\,(1-\nu^2) / \pi E * m / K\,)^{1/3}$$

and the corresponding critical height, that just avoids over stressing the material, is

$$H_{cr} = (\, 12\, m / T_{cr}\,\sigma_{max})^{1/2}$$

Depending on the geometry of the beam and the nature of the load, the value of K ranges from less than 0.5 to over 25. This is a wide range. Timoshenko discusses the value of K for several situations. Some are relevant here. In a plate with no lateral support where the stress is a pure moment, K=25. If there is a compression stress that equals the torsion stress, K=8. He does not discuss the case of a plate with a pure moment and lateral support, but clearly the K for such a case would exceed 25. Also, for a plate with moment and an axial load in tension, K would be higher.

The situation of the stress in the rib is shown in more detail in Figure 5-3. The rib is clamped for most of its length as shown in further detail in Figure 5-4. Notice that in the midspan of the rib, the lateral support from the fiberglass dish is near the center of the rib.

There are three points where the stress in the rib is at a local maximum. One is where the brace attaches. At that point, the stress is a pure moment and the rib is laterally supported in addition. So the value of K at that point must be in excess of 25. With wind into the face of the dish, the back of the rib is in compression. With the brace welded to the rib at that point, it could not buckle in any case. There is another stress maximum near the midspan of the rib. At that point the rib is clamped toward the back of the rib. If the wind blows into the back of the dish, the front of the rib is in tension and there is no problem. The back edge is under compression but is well supported there by the dish and by the fiberglass flange, so it cannot buckle. If the wind blows from in front of the dish, the free edge of the rib is in compression. Now consider the bulk forces in the structure. With a wind into the face of the dish, the brace will be in compression with the result that the rib is put into tension. The sum of the stresses from axial load and moment still leave the front edge of the rib in compression. At this point the rib is laterally supported and is axially loaded in tension, so K must be well in excess of 25. The third point where the stress is at a local maximum is at the center pole. The rib is welded to the center pole, so it cannot buckle near that end. The most critical point is where the brace attaches to the rib. A value of K = 25 is used in the design analysis here, but that may yield a design that is unduly conservative.

To calculate the value of stress along the length of the rib is a difficult problem. It can be decomposed into three easy problems, the results of which can be added together by linear superposition. First, consider only the load beyond the brace. There is no need to know the distribution of the stress beyond the brace. The load beyond the brace can be integrated (or summed on a computer) to give the resulting moment and shear at the brace. That shear is one part of the answer. Consider just the rib between the center pole and the brace. The moment from the end load is applied to the supported end of a beam that is clamped at the other end. This configuration is a common enough condition that the formula for moment along the beam is published [Roark, 1963]. That leaves the load across the span of the rib. This approaches a linearly increasing load from zero at the clamped end to a maximum at the supported end. The load is actually zero for some distance from the clamped end (there is no dish in the shadow of the receiver) and it does not quite increase linearly to the supported end (because the wind pressure drops toward the edge of the dish). However, these small differences in load near the ends of the beam have very little effect on the moments throughout the beam. Again, this situation is common enough that the formula for moment along the beam is published. Adding the two sets of moments and three sets of reactions gives all the information necessary to properly size the rib and braces. The optimum attachment point for the brace is at 79% of the dish radius.

The highest stress in the span of the rib is at the weld to the center pole. If the rib were supported at the center pole, instead of clamped, (by a bolt instead of a weld, for instance) there would be no moment there. In this case, the stress in mid span is very slightly higher than the stress at the weld in the clamped case. This means the ribs must weigh a tiny bit more. The optimum brace point moves in to 77% of the dish radius, also a very small change.

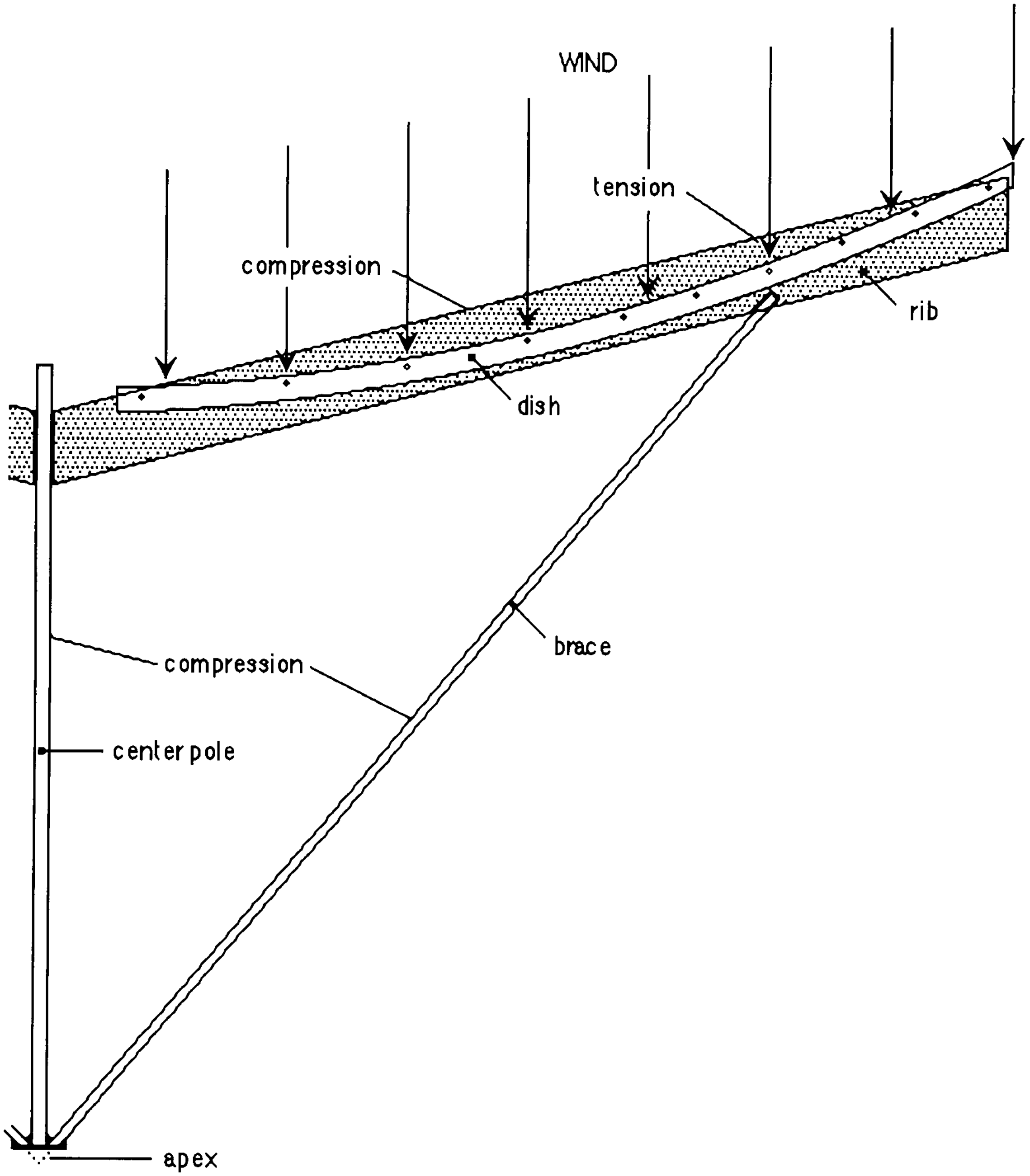


Figure 5-3
DETAIL OF STANDARD RIB AND BRACE

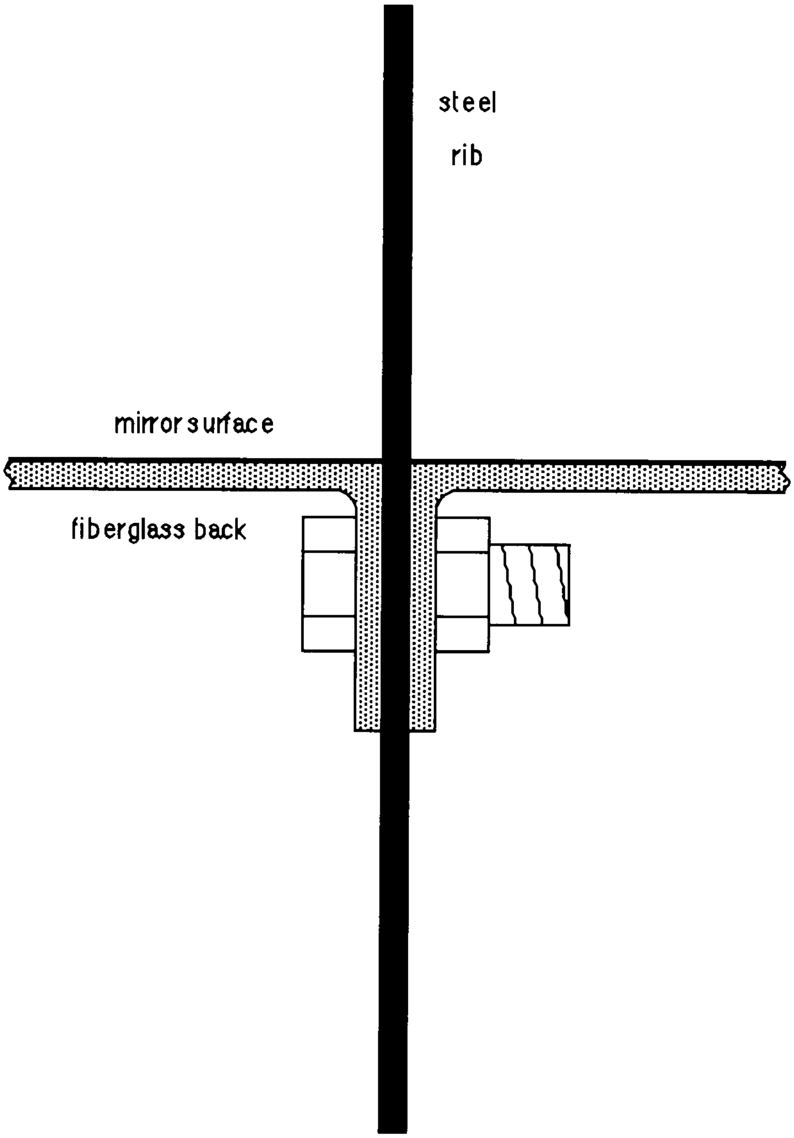


Figure 5-4
CLAMPING OF THE RIB

The Teepee Frame

The teepee frame design is another buckling problem that Timoshenko solved. This is the now standard problem of critical load in a column. As usual, the situation with the dish does not fall into one of the standard categories. The basic formula is:

$$P_{cr} = \pi^2 EI / X^2$$

where P_{cr} is the maximum sustainable axial end loading force, E is Youngs modulus, I is moment of inertia, and X is the effective column length. This is related to the actual column length and is dependent on the mounting of the column. The formula can be rewritten as:

$$P_{cr}=\pi^2 EIN^2 / 4L^2$$

where L is the actual length of the column and N is the number of quarter waves of bending in the length of the column. N is 1.0 if the column has a clamped end and a free end, 2.0 if it has two pinned ends, and 4.0 if it has two clamped ends.

The center post of the teepee falls neatly into category of N = 4.0. It is held securely at both ends. The rest of the frame is held firmly at the apex, but is relatively hinged at the dish end (at least in one plane) where it is attached to the thin rib material. In that case, a more realistic value would be N = 3.0 or a bit more.

Table 5-1 shows the dimensions of the teepee frame components and the dish weight. Steel tube is used. This is for economic reasons. Steel rod is cheaper per pound than tube. However, the teepee frame is so much lighter when built of tube that the cost is lower also.

Notice that the teepee frame gives a natural attachment point for a track to drive the dish around the declination axis. This is shown in Figure 5-1. This track is at a long radius from the declination axis, so drive forces are minimized.

Wind Load

The stresses in the dish structure are generated almost entirely by wind loading. The maximum stresses occur when the dish is facing directly into the wind. Wind loading is discussed in detail in the next chapter. Measurements show [Peterka and Derickson, 1992] that in this condition, the wind load is

$$Drag = 1.37 * 0.4815 * V_{max}^2 * D^2$$

where:

D = dish diameter in meters

V_{max} = maximum wind velocity in m/s

From this formula, with some minor corrections for pressure distribution over the face of the dish, the loading on the ribs and braces can be calculated. The results of this calculation are shown in Table 5-1.

Dish Dimensions			Max Wind Load			Operating Wind Load		
Dish Dia=	10	m	Wind Speed=	40	m/s	Wind Speed=	10	m/s
Focal Length =	6	m	Elevation=	0	m	Elevation=	0	m
Depth =	1.04	m	Max Drag Coef=	1.37		Max Drag Coef=	1.37	
Sections=	20	m	Ave Pressure=	1344	Pa	Ave Pressure=	84	Pa
Section Angle=	0.314	rad	Total Force=	105.5	kN	Glass Thickness =	2.0	mm
Brace Anchor =	3.8	m rad	Back Drag Coef=	1.09		E glass =	7	GPa
Brace Anchor =	0.60	m high	Glass Thickness =	2.0	mm	f=	6.0	m
Apex Height =	3	m	Sp Gr Glass=	1.1		w=	1.5	m
			Weight of Glass=	1693	N	R0=	12.0	m
Receiver Dimensioms			Glass Stress =	8.1	MPa	Glass Stress =	0.50	MPa
			Allowable Stress =	70	MPa			
Aperture Dia=	0.15	m	Tube ID/OD=	0.95		Stretch =	72	ppm
Cavity Dia=	0.2	m	E steel =	210	GPa	Angle of flexure =	6.72	mr
Insul Thick=	0.1	m	max stress=	350	MPa			
Housing Dia=	0.4	m	Sp Gr Steel=	7.3				

Teepee Frame

	Compr kN	N	Length m	O.D. mm	Wall mm	Stress MPa	Weight N
Center Pole	25.5	4	1.96	34	0.84	293	12
Regular Brace	7.62	3	4.49	44	1.09	52	47
Boiler Edge Brace	4.92	3	5.83	45	1.11	32	63
Mount Edge Brace	76.0	3	5.83	88	2.21	127	250

Max Horiz Compression Mount Brace= 65 kN

total weight of tubes= 1355

Ribs

	moment Nm	K	T_{cr} mm	H_{cr} mm	H_{min} mm	Rib Length m	Axial Stress MPa	Straight Ribs Weight N
Regular Rib	1004	25	2.0	131	260	5.1	12.35	190
Edge Rib	3456	25	3.0	198	260	5.1	5.35	287

total weight of ribs= 4000
total weight of steel= 5354
Total weight of dish= 7048

Table 5-1
SUMMARY OF DESIGN OF 10 METER DISH

<u>Braces Going to the Pivots</u>

Ultimately, the dish will have to be mounted. The rib shown in Figure 5-3 is connected to its brace about 79% of the dish radius. The dish must be mounted slightly beyond the radius of the dish, and the brace that goes to the mount is connected to its corresponding rib at the end of the rib. A detail of this connection is shown in Figure 5-5. The two ribs connected to the dish mounts must be thicker than the others, as shown in Table 5-1

Consider a wind blowing into the face of the dish. The entire loads from all but two of the dish sections are delivered to the apex along with the center loads from the remaining two panels. Half of this total is delivered through each of the mount braces to the pivots. The loads delivered to the braces near the pivots cause a large moment in the distance between the end of the rib and the pivot point. The rib must support the brace to near the pivot point. The force in the rib associated with a pivot is indeterminate until the gimbal structure is included in the calculation. It will be shown in the next chapter, dealing with the cradle design, that it is entirely practical to mutually design the cradle and dish so that the axial force in the ribs going to the pivots is near zero. Doing so leaves the stress in the rib span being a pure moment. The rib has lateral bracing, and a K greater than 25.

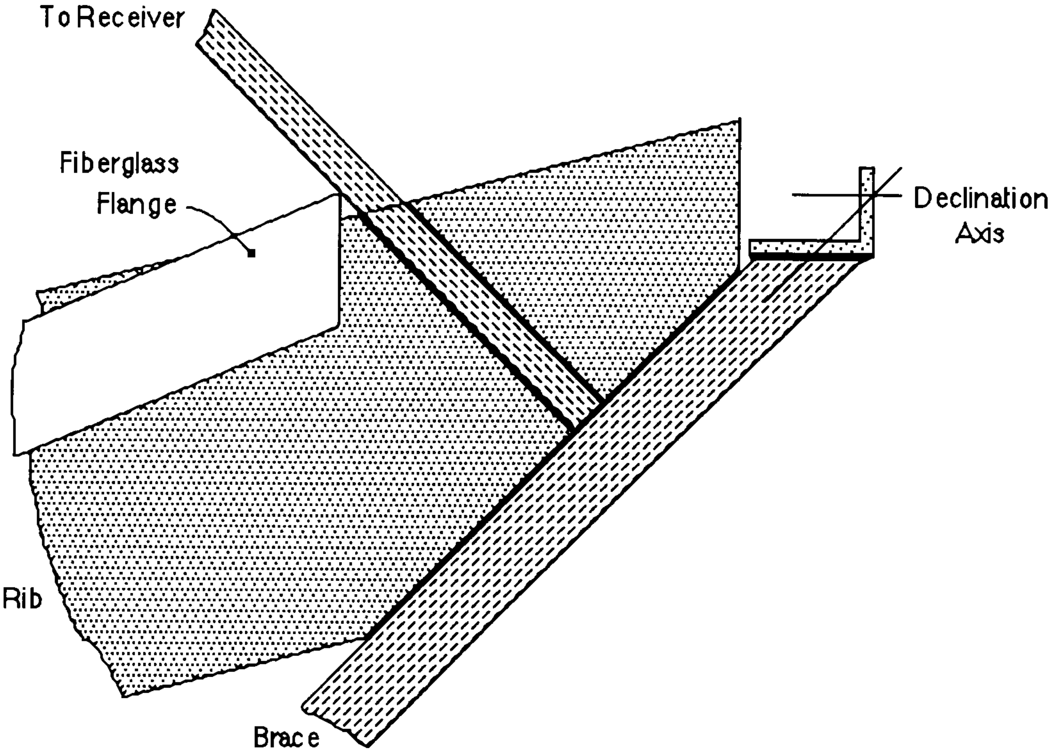


Figure 5-5
DETAIL OF THE DISH MOUNT

6. CRADLE DESIGN

Studies have been made of how to mount a solar concentrator in the most economical way. The conclusion has invariably been that it should be mounted on a monopod [Skinrood, 1981] or something very similar [Ney, 1982]. There are two major problems with using a monopod mount. It tends to interfere with the dish bracing and there is no easy way to connect simple drive systems to the dish. While the monopod mount probably is the cheapest mount that can be devised, it does not result in the lowest cost system. A dish designed for a monopod mount is considerably more expensive than that described in Chapter 5. In addition, the dish is not as strong and must be driven to a stow position to survive a high wind condition. This puts additional burdens on the drive system.

THE CRADLE CONCEPT

The design described here is a structure in which the solar concentrator is mounted much like a gyroscope is mounted in a gimbal [Cordy, 1994][Cordy, 1995]. There are two major differences between the cradle for a solar collector dish and a conventional gyroscope gimbal. First, the cradle must be able to sustain large forces. Second, the range of motion of the solar concentrator is considerably smaller than the motion that a gyroscope may encounter.

In a point focus distributed receiver on a polar axis mount, installed at the equator, the concentrator must be rotated around the polar axis ±90° from the zenith. The required range of rotation around the polar axis increases as the installation site is moved away from the equator. Essentially all interesting sites for solar concentrators are within 40° of the equator. At 40° latitude the concentrator must be rotated around the polar axis nearly ±120° from the zenith. At any latitude, the concentrator only needs to be rotated around the declination axis by ±23.5° from its equinox position. The fact that the concentrator need be rotated only ±23.5° around the declination axis allows significant simplifications in the design of the cradle.

Orthogonal views of the cradle are shown in Figure 6-1. The polar axis passes through points A and F. The declination axis passes through points B1 and B2. These axes pass essentially through the plane of the edge of the dish, minimizing wind induced forces in the drive system. The dish is rotated within the cradle around the declination axis. The entire dish and cradle structure is rotated around the polar axis. The drive system works on a large diameter track, giving the advantage of an inexpensive, low force drive. The cradle leaves an open space behind the dish of about 1.0 dish radii in which dish bracing can be housed without interference. There are a total of 12 structural members in the cradle. Using the dish design discussed in chapter 5, the wind induced force in member B1-B2 cancels the wind induced force across the face of the dish and member B1-B2 can be eliminated.

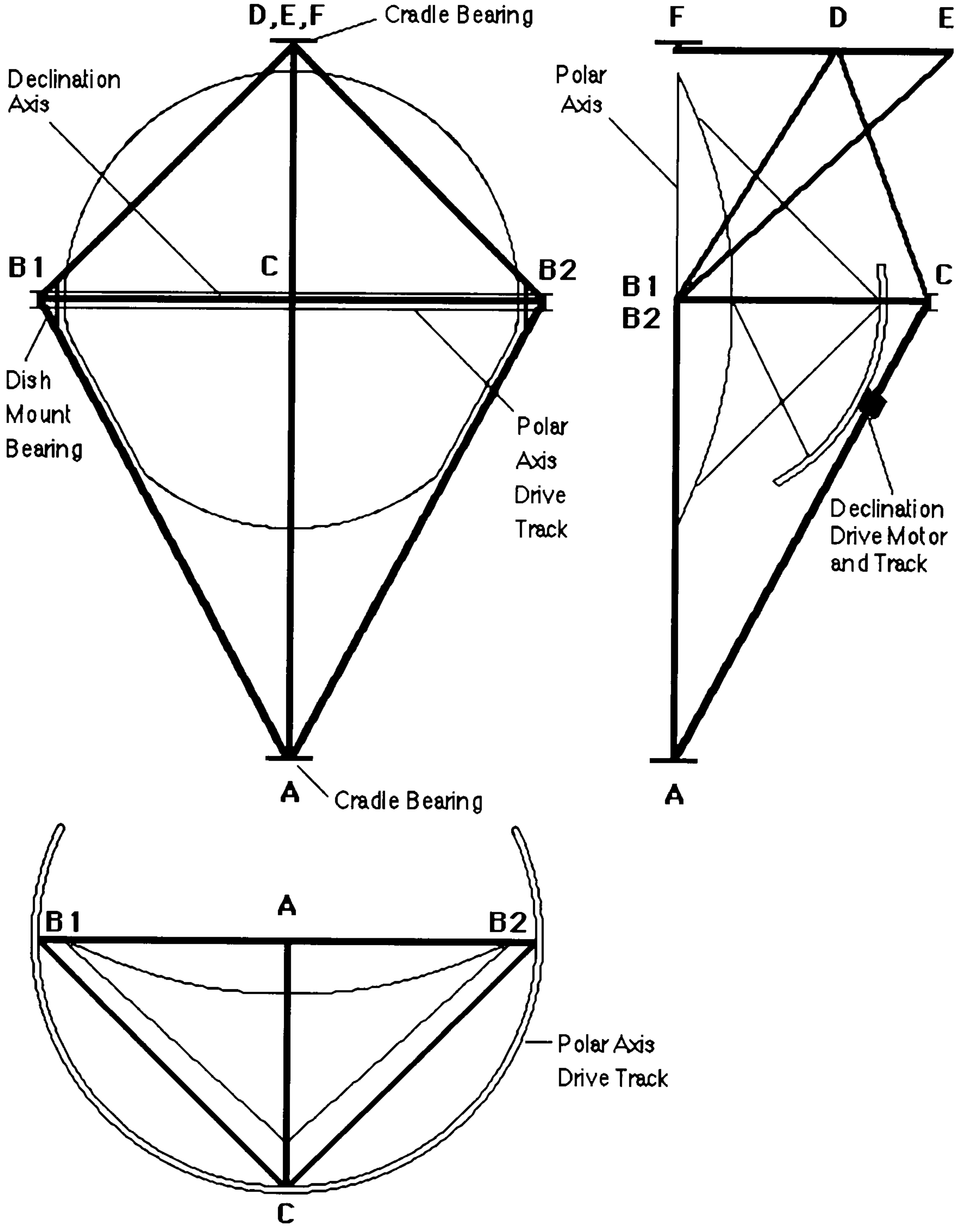


Figure 6-1
ORTHOGONAL VIEWS OF CRADLE

The size of the beam E-D-F is minimized if there is no force along the polar axis at point F. To accomplish this it is necessary that: (1) all forces along the polar axis are delivered to the earth at the equatorial end of the mount, (2) the beam E-D-F is perpendicular to the polar axis, and (3) all members of the polar end mount, either a guyed pole or bipod, lie in a plane perpendicular to the polar axis.

DESIGN DETAILS

The cradle consists of three tetrahedra. At the end nearest the equator is the tetrahedron labeled A, B1, B2, C in Figure 6-1. The exact dimensions of the cradle depend on the dish design and latitude of the installation. The distance from the declination axis to apex A will normally be about 2.0 dish radii and the distance from B1 to B2 is about 2.2 dish radii. The dish must be able to rotate between members A-B1 and A-B2. With the above dimensions, a round dish will not clear the cradle.

The second tetrahedron has a base of C, B1, and B2 with a fourth apex, point D. D must be far enough below the polar axis that the dish with its bracing can be moved into its summer position without hitting members B1-D and B2-D. Normally, point F will be 1.1 dish radii from the declination axis, (so point F doesn't shade the dish in summer). For a dish with an optical speed of 0.6, apex D is about 0.75 dish radii below the polar axis.

The third tetrahedron has a base of B1, B2, and D with a fourth apex of E. The total weight of the cradle is minimized if E is located about 1.15 dish radii below the polar axis. The cradle weight does not increase rapidly if point E is moved from its optimum position.

Member E-D-F is the only piece of the cradle that is loaded in flexure. There are no forces at F along the polar axis, so the beam needs no great strength in that direction. Forces in the solar direction do not flex E-D-F, so are inconsequential. The largest wind loading along the declination axis occurs when the wind is blowing against the back of the dish (and is not generating much lift). The wind drag and the weight of the dish and cradle all add to cause a moment around D. Even in this case, the moment around D is under 6% of the moment experienced by a monopod holding the dish facing into the wind.

There are two other possible configurations for the polar end of the cradle. First, point E can be located above the polar axis about 0.45 dish radii. This results in a somewhat lighter cradle, especially the beam D-F-E. However, it also results in two shadows across the dish from members B1-E and B2-E. The shadows block 1% to 2% of the total sunlight that would otherwise be intercepted by the dish and the heavier structure required to put point E below the polar axis does not cost 1% of the collector installation.

The other possibility is to reverse the positions of points D and E. This is the same as running a member from C to E (as located in Figure 6-1) instead of from C to D. This results in a heavier structure and there is no commensurate advantage gained.

To design the cradle, it is necessary to calculate the stress in each member. From the geometry of the cradle, it is easy to calculate the stresses in each member due to a unit force equally divided between mounting points B1 and B2. The calculation is done for unit forces in each of three orthogonal directions, toward A, toward B2, and toward C. The wind load in each direction depends on the relative position of the dish, cradle, and wind. The dish position can be expressed easily in global polar coordinates. Through a series of coordinate system rotations, the dish position can be expressed in a wind based polar coordinate system with the dish facing an angle, Θ, away from the source of the wind and at an angle, Φ, clockwise from the vertical as seen from the wind source. From this, the wind drag and lift can be calculated [Peterka and Derickson, 1992]. Then these force vectors can be expressed in a local rectangular coordinate system (east, south, and up for instance) at which point the weights of the dish and cradle can be added. A coordinate rotation to a global rectangular system, (east, zenith, and equatorial for instance) gives the force vectors in a form that makes the forces in the guyed pole easy to calculate. Yet another coordinate rotation to a cradle based rectangular system (toward B2, toward C, and toward A) yields force vectors that are usable for calculating the stresses in each member of the cradle.

To find the maximum force in each member of the cradle, it is necessary to search the combinations of wind direction, right ascension, and declination. To do this in any practical manner, it is necessary to develop expressions that approximate the data presented by Peterka and Derickson. This has been done [Cordy, 1995]. The smallest order polynomials (generated by a regression program) that fit the data to within about 5% (worst error) follow:

$$\text{Drag} = 0.4815 * V_{max}^2 * D^2 * (1.348 - 0.146 * \Theta - 0.470 * \Theta^2) \qquad \text{for } \Theta < \pi/2$$

$$\text{Drag} = 0.4815 * V_{max}^2 * D^2 * (-1.036 + 0.681 * \Theta) \qquad \text{for } \Theta > \pi/2$$

$$\text{Lift} = 0.4815 * V_{max}^2 * D^2 * (0.020 + 1.367 * \Theta - 0.966 * \Theta^2 + 1.968 * \Theta^3 - 1.228 * \Theta^4) \qquad \text{for } \Theta < \pi/2$$

$$\text{Lift} = 0.4815 * V_{max}^2 * D^2 * (-7.660 + 9.131 * \Theta - 3.277 * \Theta^2 + 0.365 * \Theta^3) \qquad \text{for } \Theta > \pi/2$$

where:

D = dish diameter in meters

V_{max} = maximum wind velocity in m/s

Θ = angle between wind source and dish direction in radians

In general the maximum stress in any member of the cradle does not occur at any combination of wind and dish directions that would cause a maximum load on the dish. The various combinations of wind angle and dish position are searched for the maximum stress in each member of the cradle and mount. Analysis discussed in Chapter 11 shows that the economically optimum dish diameter in this cradle mount is in the range of 10 meters. Table 6-1 shows the maximum total force that each member of the cradle will experience in a wind of 40 m/s if the cradle is holding a 10 meter diameter dish. These forces can be converted to the minimum required moment of inertia (then to tube diameter and wall thickness) using the standard column buckling formula as discussed in Chapter 5.

The cradle would be built with welded joints. At least one member at each apex is in tension. This results in all members being effectively clamped, but only weakly. Taking as an example a cradle suitable for mounting a 10 meter dish, Table 6-1 shows the size of the tubes that would be required for each member of the cradle in a 40 m/s wind with N=3 and a tube wall thickness of 2.5% of the tube diameter. Assuming a weight for the cradle, dish, and receiver, the weight of the cradle is calculated. The calculation can be repeated using the refined assumption of cradle weight. Assuming that the weight of the dish and receiver equals the weight of the cradle, the total weight of the cradle for a 10 meter dish that is designed to withstand a 40 m/s wind is 5700 N, under 6% of the maximum force exerted by the wind. Since the bulk of the stress in the cradle members is caused by wind load, the initial estimate of the weight of the dish and cradle do not have to be particularly accurate. The stress in each cradle member must also be calculated to be sure that the stress does not exceed the maximum allowable. The results of the structural analysis are summarized in Table 6-1.

This cradle will survive high winds independent of the relative positions of the dish and wind direction. With the space available within the cradle for dish bracing, it is cheaper to build the dish strong than it is to build the high speed, fail safe drive system needed to drive the dish quickly to the special position at which the system can survive a high wind. In addition, using a strong dish will probably result in improved system reliability and maintenance costs.

The cradle is not very useful without a suitable mount. The equatorial end is easy. At latitudes more than about 20° away from the equator, the equatorial end mount can be a concrete pad or low pier, as shown in Figure 6-2. The polar end is more difficult. The most obvious mount for the polar end is a guyed pole with the guy wires and the pole all lying in a plane perpendicular to the polar axis. It is also possible to use a bipod or a guyed bipod. The guy wires can be anchored to the concrete pads on which the adjacent cradles to the east and west are mounted as shown in Figure 6-3. Table 6-1 also shows the size of the guyed pole needed to mount a cradle at a latitude of 35°. In this case, the pole is likely to be pinned at both ends and the proper N to use in the column buckling equation is 2.0. The weight of the pole and guy wires depend on the east-west spacing of the dishes. Assuming the spacing is 2.5 dish diameters, the pole and guy wires will weigh about 2000 N. In Figure 6-2, each mounting pad is shown supporting the north end of one cradle and the south end of another. At the latitudes of most of the world's deserts, this is a satisfactory arrangement.

The total weight of the dish (with receiver), cradle, and mount must exceed the upward lift force of the wind. As a practical matter, if the wind is blowing into the face of the dish, the lift force has a downward component. An upward lift force occurs when the wind is blowing against the back of the dish. This force is calculated and shown in Table 6-1. Less than one cubic meter of concrete is needed to hold the dish and cradle down.

Design Parameters

dish diameter =	10	m	max force on dish =	106	kN
max wind velocity =	40	m/s	ID/OD =	0.95	
elevation =	0	m	max stress =	350	MPa
estimated cradle weight =	5700	N	E =	210	GPa
estimated dish weight =	5700	N	Sp Gr of steel =	7.30	
			Sp Gr of concrete =	2.40	

Cradle Tubes

	length	force	N	OD	wall	stress	weight
	m	N		mm	mm	MPa	N
A-C	11.41	62590	3	118	2.9	59	866
A-B	11.41	66360	3	119	3.0	61	892
B-C	7.78	42150	3	88	2.2	71	330
B-D	8.63	67490	3	104	2.6	81	515
C-D	5.77	57550	3	82	2.0	112	212
B-E	9.67	14440	3	76	1.9	35	309
B1-B2	11.00	65640	3	117	2.9	63	824

End Beam

	length	torque	height	width	thickness	weight
	m	Nm	mm	mm	mm	N
E-F	5.75	35120	200	100	5.0	825

total cradle weight= 5997 N

Guyed Pole

	length	force	N	OD	wall	stress	weight
	m	N		mm	mm	MPa	N
pole	10.85	89780	2	154	3.8	50	1407
guy	18.51	82700		17.3		350	313

total weight of cradle and guyed pole = 8030 N

max lift force = 36209 N
additional weight needed = 21179 N
volume of concrete = 0.90 m^3

Table 6 -1
SUMMARY OF CRADLE DESIGN FOR 10 METER DISH

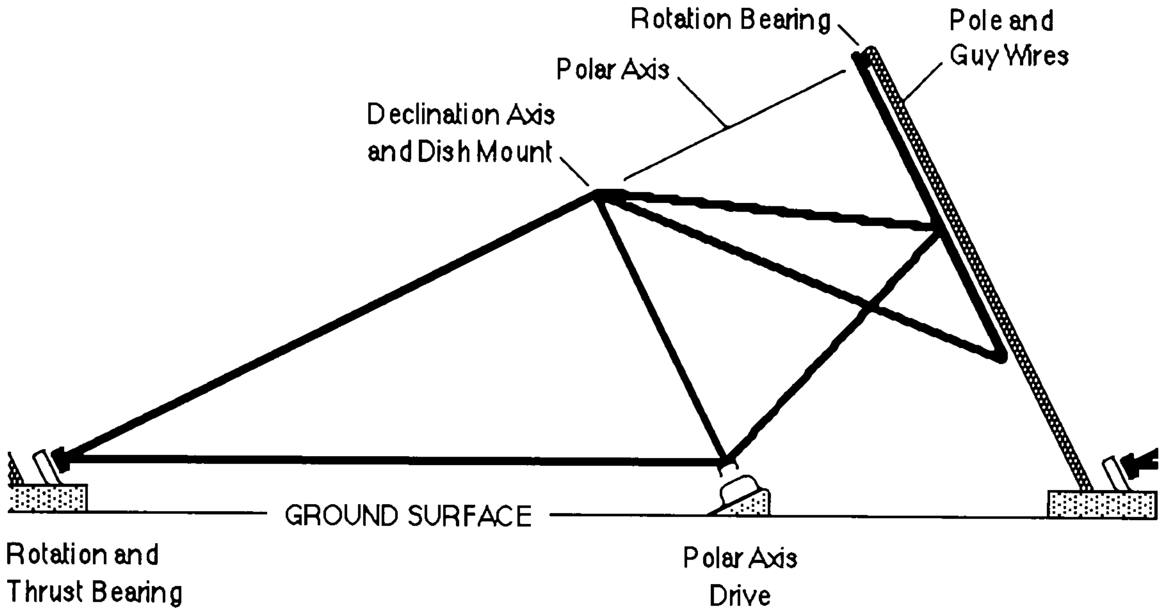


Figure 6-2
CRADLE AND MOUNT

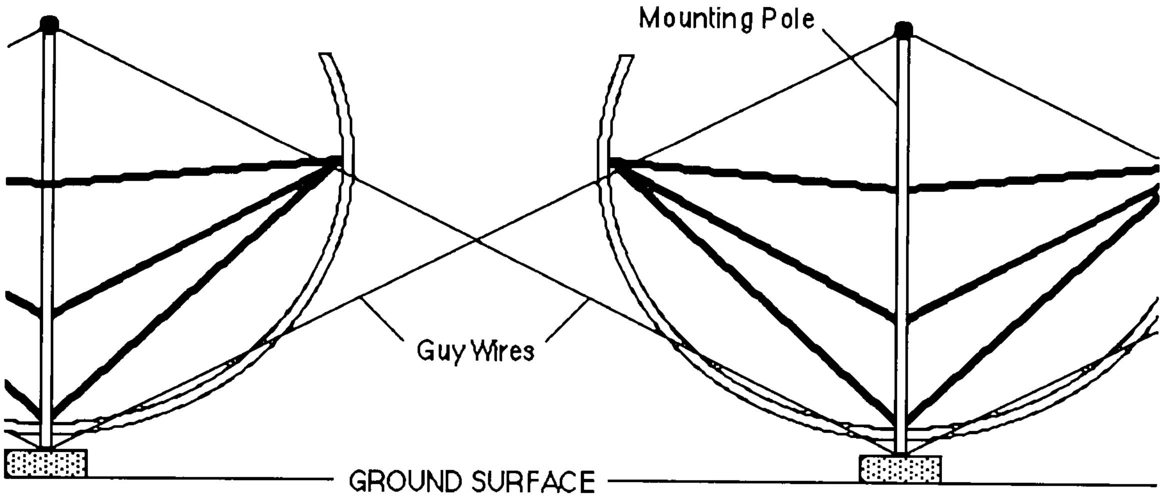


Figure 6-3
MOUNTING POLES AND GUY WIRES

Figure 6-1 shows a cradle drive track attached to points B1, B2, and C. Clearly, the track must be concentric to the polar axis. This does not mean that the polar and declination axes need to be coplanar. However, there is no reason that they shouldn't be coplanar. The drive motor can be mounted close to the ground on a pad or short pole, as shown in Figure 6-2. With a suitably designed dish bracing structure, a similar drive motor can be mounted in the cradle on member AC. This drives a track mounted on the dish structure concentrically to the declination axis. With this dish mount, a uniform wind would cause no torque on the drive system. However, wind is not uniform. It blows faster with increasing height above the ground. Also there is significant turbulence. Peterka and Derickson [1992] measured the torques around azimuth and elevation axes for a dish mounted on axes well behind the dish. If the dish is mounted on a monopod, the axes of rotation must lie behind the dish. A dish rotated around axes passing through the edge of the dish will have considerably less wind induced torque. From the data of Peterka and Derickson, it is not clear how much less the torque will be. To calculate the torques around axes of rotation lying in the plane of the edge of the dish, additional measurements would have to be made. In any case, the cradle mount, with its inherently lower wind induced torques plus the natural attachment points for long radius drive tracks, makes the drive system cheaper than that needed for a monopod mount.

Table 6-2 shows a design for a monopod that will hold a 10 meter dish with a 40 m/s wind directly into the face of the dish. If the dish is mounted to barely clear the ground, the weight of the steel in the monopod is comparable to the weight of the cradle and mount. In addition, the monopod requires a large block of concrete to hold it while the cradle needs very little, (except for the cradles at the edges of a concentrator field). Concrete is cheap. The big advantage of the cradle design is not the savings in material, but the savings achieved in the drive systems and in the fabrication of the dish.

Design Parameters

dish dia =	10	m	max force on dish =	106	kN
max wind velocity =	40	m/s	ID/OD =	0.95	
elevation =	0	m	max stress =	350	MPa
ground clearance =	0	m	E =	210	GPa
estimated dish weight =	7000	N	Sp Gr of steel =	7.30	
			Sp Gr of concrete =	2.40	

Size of Monopod

thickness of concrete=	1.75	m
diameter of concrete=	3.49	m
volume of concrete =	16.74	m^3
weight of concrete=	393674	N
monopod diameter=	436	mm
monopod wall=	10.9	mm
monopod weight=	7021	N
restoring moment=	712064	Nm
wind moment=	712064	Nm

Table 6-2
MONOPOD DESIGN FOR MOUNTING A 10 METER DISH

THE DISH AS PART OF THE CRADLE STRUCTURE

Consider a wind into the face of the dish. In this case, the cradle member B1-B2 will be in tension. If the dish structure is built as described in Chapter 5, most of the wind force on the dish is delivered to the apex of the bracing structure. The dish is mounted on two diagonal braces extending from the apex of the dish bracing structure to points B1 and B2 of the cradle. These mounting braces will be in tension. By selecting the proper height of the teepee frame apex, the horizontal component of the tension in the dish braces (shown in Table 5-1) will be about equal to the tension calculated for cradle member B1-B2 (shown in Table 6-1). This leaves cradle member B1-B2 unstressed, therefore not needed. The net stress across the face of the dish cannot be made exactly zero for all combinations of wind and dish directions. However, the residual forces across B1-B2 are small and can be transmitted through the dish itself.

7. RECEIVER

An optimum receiver has several characteristics. It intercepts a maximum of the light coming from the dish, it loses a minimum of heat, it is not damaged by the solar image in case of tracker failure, and it can operate at any position where a solar image could be delivered to it.

Receivers suitable for use with concentrator dishes fall into two general categories, internal and external. An external receiver is basically a heavy walled can painted black. Since light is striking most of the surface of the can, it cannot be insulated and thermal losses are higher than those for an internal receiver. (In effect, the concentration ratio cannot be made as high with an external receiver.) For this reason, the external receiver is rarely used. The internal receiver is basically a can with a cavity formed in one end. The cavity is painted black and all the light from the mirror passes into that cavity. The entire outside of the can is well insulated and most of the heat loss is through the aperture leading to the cavity. The effective concentration ratio (dish aperture area / cavity aperture area) is much higher with an internal receiver. An internal cavity receiver is shown in Figure 7-1.

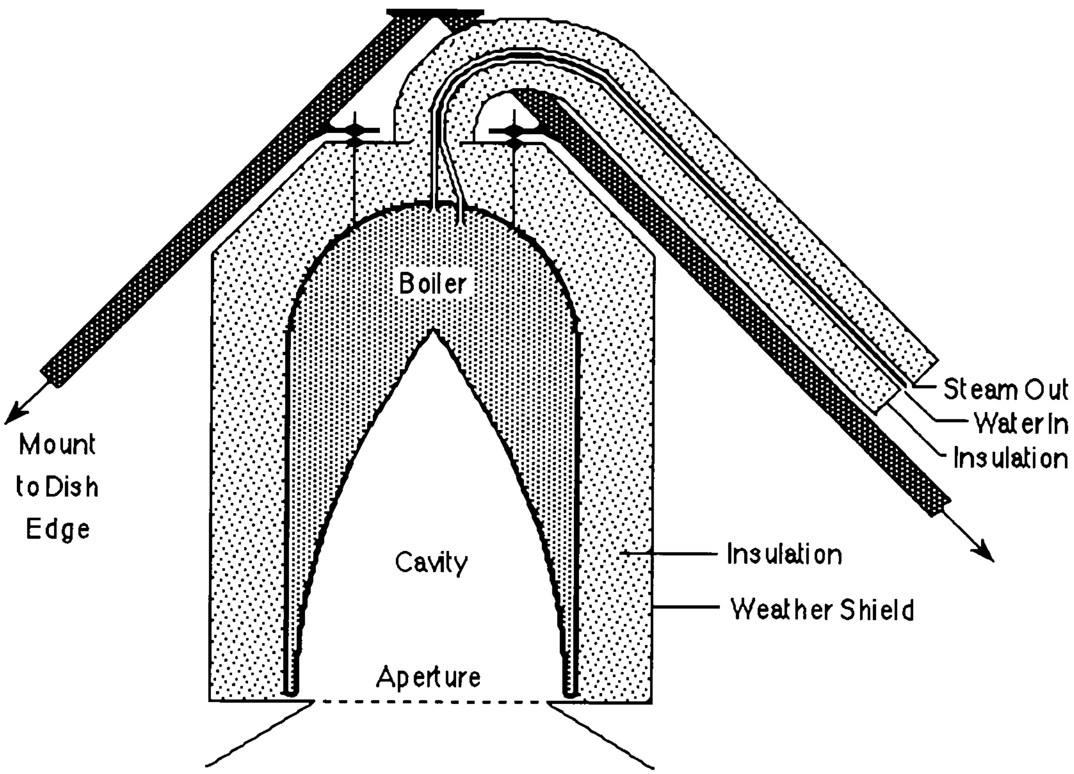


Figure 7-1
INTERNAL RECEIVER

CAVITY DESIGN

Cavity Radius

On a very clear day, solar power density striking the concentrator can be slightly over 1.0 kW/m^2. If the mirror happens to produce a good solar image, the power density at the center of the image could exceed 15 MW/m^2. Consider the boiling process on the other side of the absorber surface. At moderate power densities, microboiling occurs and the ΔT between the metal and water is low. At high power densities, the boiling becomes so violent that a steam layer is formed between the metal surface and the water and the thermal conductivity across the interface drops dramatically. In operation at high pressure, this could lead to a boiler explosion, which is undesirable.

Experiment shows [Borishanskii, 1959] that at 1 atmosphere pressure the maximum heat transfer that can occur in the microboiling regime is 1.25 MW/m^2. At higher pressures, this limit increases considerably, approaching 5 MW/m^2. But when a cloud passes, the system may have to start operation rather abruptly at full solar power and no system pressure. Also, there are likely to be hot spots in the imperfect solar image. In practice, designers limit the maximum power density striking the receiver surface to 500 or 600 kW/m^2.

The practical result of this power limit is that the light from the mirror must pass through some aperture (which reduces the heat loss) into a larger cavity behind. In effect. the absorbing surface lies behind the focal point of the dish and receives a defocused image of the sun. It is desirable that this cavity be as black as possible (to minimize loss of reflected light) and as small as possible (to minimize convection losses, especially near the ends of the day).

The mirror is less than 100% reflective and the cavity is less than 100% black. If each of these is assumed to be 90%, the maximum effective solar power is reduced to 810 W/m^2. Assume that the cavity is spherical, centered on the center of the aperture. To keep the absorbed power on the surface of the cavity down to 500 kW/m^2, the radius of the sphere would have to be

$$R_{sphere} = \text{sqrt}(810 / 500{,}000) * 1.12 * f = 0.044 * f$$

where f is the focal length of the dish and 1.12 * f is the distance from the edge of the dish to the focal point. If the inside of the cavity is a cylinder, the incident light from the edge of the dish strikes the surface at a 45° angle and the cavity radius can be reduced to

$$R_{cyl} = \text{sqrt}(810 / 500{,}000 / \text{sqrt}(2)) *1.12 * f = 0.038 * f$$

The radius of almost any realistic cavity shape will fall between these extremes. For comparison, using the same 15 mr acceptance angle that was used in Chapter 3, the aperture radius is

$$R_a = 0.015 * 1.12 * f * \text{sqrt}(2) = 0.024 * f$$

Using an aperture, and not just the entrance to the receiver cavity, cuts the area through which heat can escape by a factor of at least 2.5.

<u>Cavity Shape</u>

There are three somewhat conflicting goals in cavity design: minimum size, maximum blackness, and cheap to manufacture. The minimum size simple cavity is the spherical cavity described above. But it is not very black. Smaller, blacker cavities can be designed but they are prohibitively expensive to build. A more precise definition of the goal is needed. Design the minimum size simple cavity that is at least 99% black.

If a surface could be painted 99% black, there would be no problem. The spherical cavity would be fine. The best surfaces are only about 92% black. To do better requires a light trap of some sort. There is a method for generating a minimum size light trap for any desired blackness [Cordy, 1994].

Consider making the inside surface of the cavity a black mirror rather than a diffuse surface. This surface may be only 90% black, but it will reflect the remaining 10% of the light in a predictable direction. Now shape the inside surface of the cavity so any incoming beam will be reflected to strike the cavity surface at least one more time before being reflected out of the cavity. Figure 7-2 shows such a cavity. To make such a cavity a minimum size, it is necessary that the ray, after one reflection, just strike the backside of the aperture. The back of the aperture is reflective, so any light striking it will be reflected back into the cavity. It is obvious that the shape of the cross section of the surface is a circle centered on the opposite edge of the aperture.

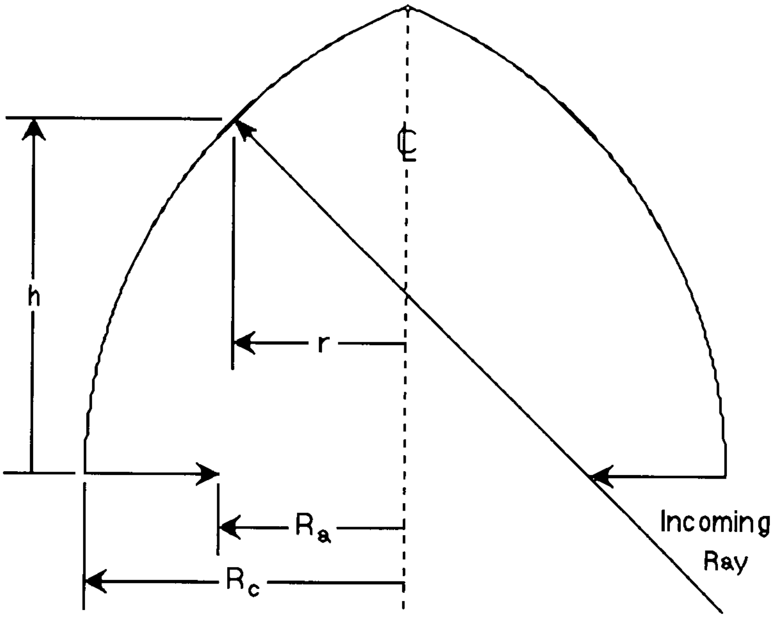


Figure 7-2
RAY TRACE INSIDE CAVITY WHERE RAY STRIKES CAVITY TWICE

The same argument can be extended to 3 (or more) reflections and 99.9% (or more) black. The more reflections that are required, the deeper the cavity will be, and the higher the convective heat losses will be. It makes no sense to try to go past 99.9% black. Figure 7-3 shows a ray trace for a cavity with a guarantee that any photon will strike the cavity three times before escaping. Any ray entering at the edge of the aperture and crossing the center line of the cavity, must be reflected on a horizontal path. Hence, the vertical cross section of the cavity wall must be a parabola with its axis lying in the plane of the aperture and its focal length being the sum of R_a and R_c. The formula for r as a function of h is:

$$r = R_c - h^2 / 4 / (R_a + R_c)$$

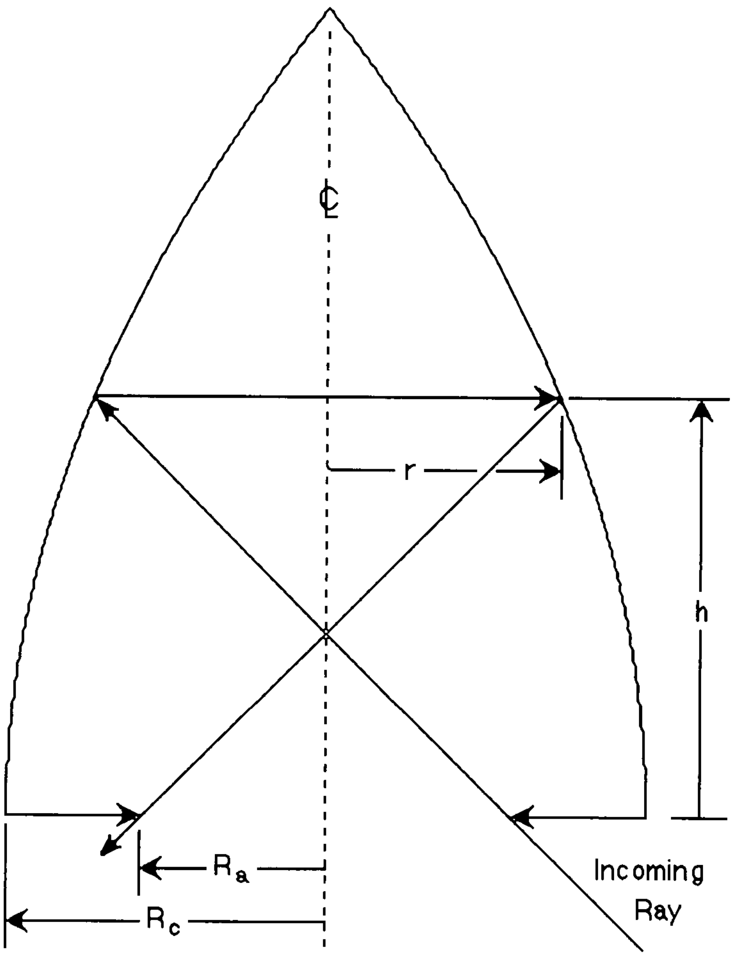


Figure 7-3
RAY TRACE INSIDE CAVITY WHERE RAY STRIKES CAVITY THRICE

The black mirror surface gives a second potential advantage. It can be coated with a wavelength selective material and be made a good mirror in the infrared as well as a good absorber in the visible. A smooth surface can be made to have a much lower emissivity than a rough surface. That will significantly reduce radiated heat loss from the cavity.

THERMAL SHIELD

Refer back to Figure 7-1. All internal receivers presently in use have a flat aperture plate but not the cone shaped piece of metal projecting below it. That added piece of metal serves several functions.

Most of the outside of the receiver housing is a sheet metal cover that is not in contact with any water. If the sun tracker or dish drive system fails, the solar image will pass slowly, first over the aperture, then over the rest of the surface of this cover. A paraboloid gives terrible aberrations when operated off axis. The solar image deteriorates to the point that it will not do much damage by the time it gets to the outside edge of the aperture plate. However, near the inner edge of the aperture, the power density can be 1.5 or conceivably even 2.0 MW/m^2. It doesn't matter whether the aperture plate is black, gray, or silver, if it is being struck by 1.5 MW/m^2, it will reach an equilibrium temperature of 1900K (assuming that heat is radiated from both sides of the plate). The sun moves across the sky at the rate of about one solar diameter in two minutes. That means if the dish drive stops, the sun image will cover any one point on the aperture plate for two minutes. The thermal time constant for any reasonable thickness of metal is several seconds. Equilibrium temperature will be reached. No inexpensive metal will tolerate 1900K in air. Unless something is done, the solar image will cut through the aperture plate and will melt the insulation behind it. This will lead to high maintenance costs.

There is a simple solution to the problem [Cordy, 1994]. Add the cone shaped metal below the aperture plate. Polish the surface facing the dish so it is highly reflective, say 80%. That alone won't help anything. Paint the other side very black, emissivity 90%. Now the equilibrium temperature from 1.5 MW/m^2 striking the polished surface is 1480K. This may not be pleasant, but it is survivable for short periods. The thermal shield is shown in Figure 7-1. A detail of the shield is shown in Figure 7-4.

The heat shield also presents an obstruction to airflow in the vicinity of the aperture. That will reduce convection losses from the receiver.

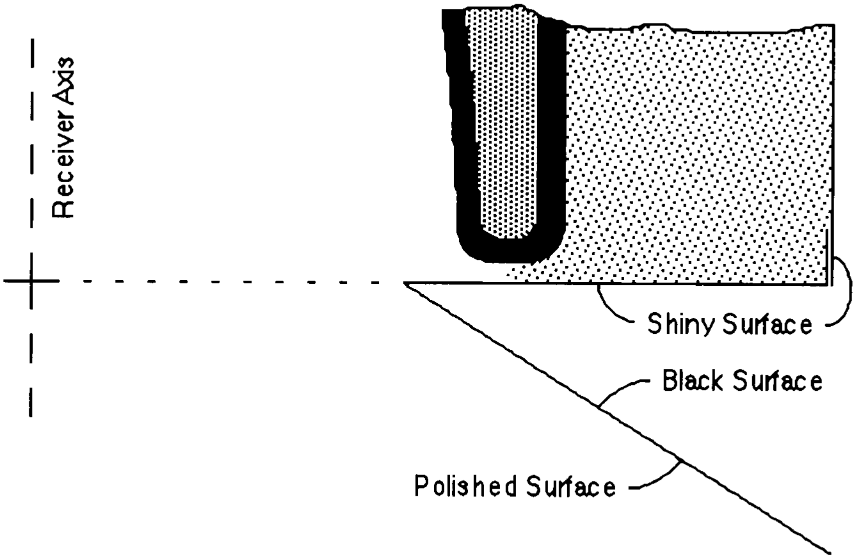


Figure 7-4
DETAIL OF THERMAL SHIELD

SECONDARY REFLECTOR

Note that the polished surface of the thermal shield appears to be an optical funnel guiding light toward the aperture. It is well known in the optics industry, but apparently not known in the solar industry, that by using a nonfocussing optical system, a higher power density can be achieved than is possible using only a focussing optical system. This is equivalent to increasing the concentration ratio and reducing the heat losses. If the polished cone has the right apex angle, it will also serve as a nonfocussing secondary reflector. The improvement is significant. As an example, consider a 10 meter diameter, f/0.6 dish. For a 15 mr acceptance angle, the aperture radius must be 148 mm without the secondary reflector, 102 mm with the reflector. The secondary reflector cuts the aperture area, and heat losses, in half.

The calculation of the angles involved is fairly straightforward. Figure 7-5 shows the important rays. Table 7-1 shows the results of the calculation for the smallest aperture with the secondary reflector in place using the dish size shown.

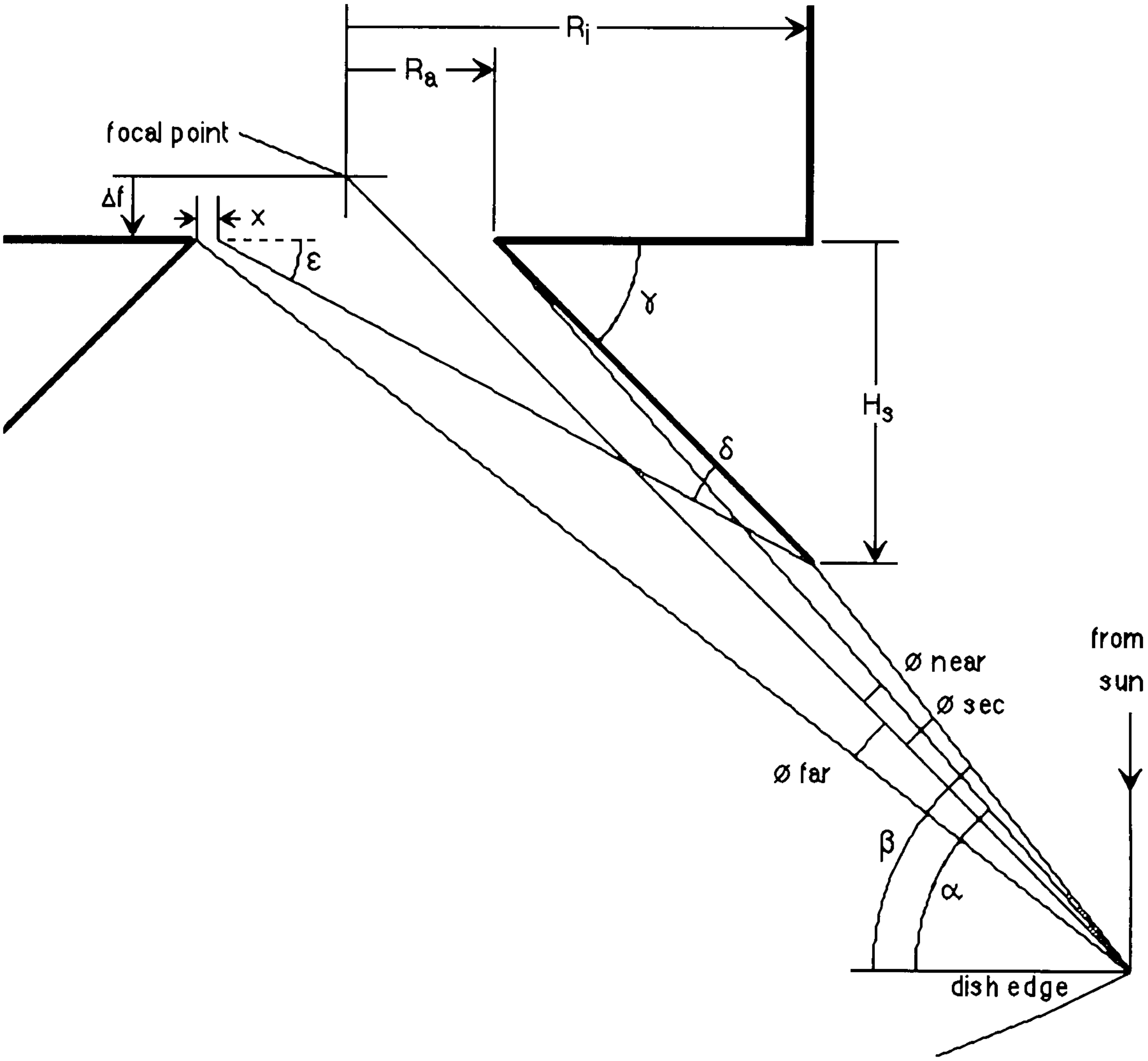


Figure 7-5
PARAMETERS IN SECONDARY REFLECTOR CALCULATION

Dish	Receiver	Angles	Clearance
$R = 5000$ mm	$R_i = 350$ mm	$\alpha = 0.781$ rad	$x = 0.013$ mm
$f = 6000$ mm	$\Delta f = 48.8$ mm	$\beta = 0.796$ rad	ø far = 15.04 mr
$H_d = 1042$ mm	$H_s = 157.5$ mm	$\gamma = 0.566$ rad	ø sec = 15.04 mr
	$R_a = 102$ mm	$\delta = 0.230$ rad	ø near = 5.36 mr
Concentration Ratio = 2403		$\varepsilon = 0.335$ rad	

Table 7-1
RESULTS OF SECONDARY REFLECTOR CALCULATION

STEAM PORTS

If the receiver of Figure 7-1 is operated on its side, as it is at sunrise or sunset, then the water will not contact the upper surface of the receiver chamber. It is entirely possible that high power densities could be delivered to a dry surface with a resulting boiler explosion. The situation is shown in more detail in Figure 7-6. The problem is not related to the exact shape of the cavity, and a conical cavity is shown for ease of illustration. The smallest elevation angle at which the entire optical surface of the receiver can be kept wet is

$$\Psi = \text{Atan}\,(R_c/L_r)$$

It is desirable to keep L_r small to minimize heat loss through the insulated outside surface of the receiver and typically $R_c/L_r = 0.3$. That means the receiver cannot operate within 16° of the horizon, over an hour lost at each end of the day.

The situation can be helped somewhat by putting the steam outlet at the periphery of the boiler. This is shown in Figure 7-7. Near sunset the steam outlet is above the center line of the boiler by a distance

$$H_{so} = R_{so} * \sin\,(\text{Lat})$$

where R_{so} = the radius from the boiler center line to the steam outlet and Lat is the latitude of the installation. If $R_{so} = R_c$, the minimum operating angle is approximately

$$\Psi = \text{Atan}\,(R_c/L_r * (1 - \sin\,(\text{Lat})))$$

At a latitude of 35°, Ψ is 7.3° and just under 0.5 hours are lost at each end of the day.

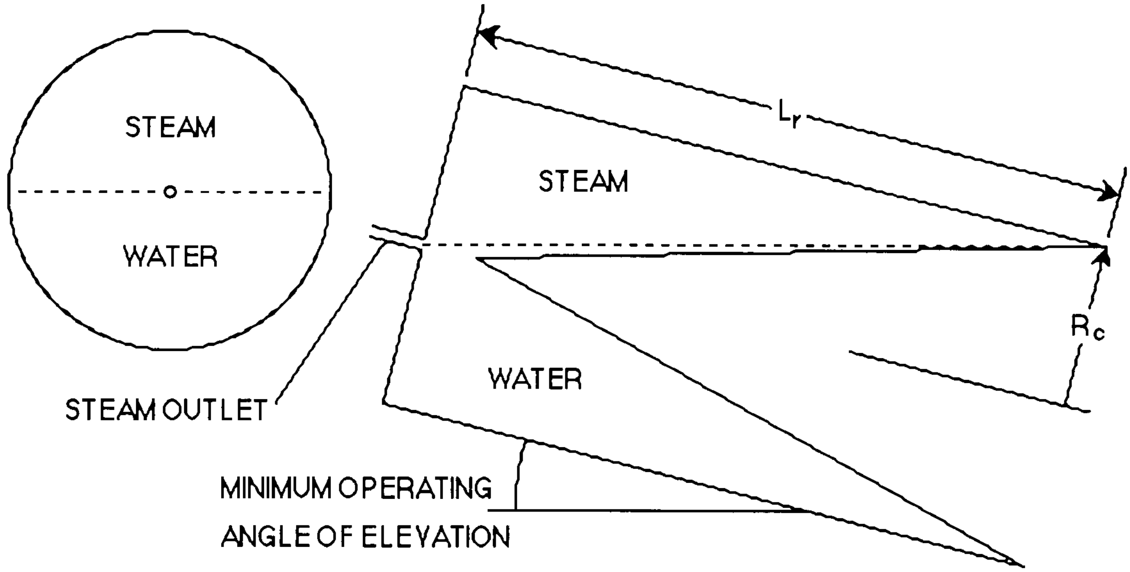


Figure 7-6
RECEIVER WITH CENTRAL STEAM OUTLET

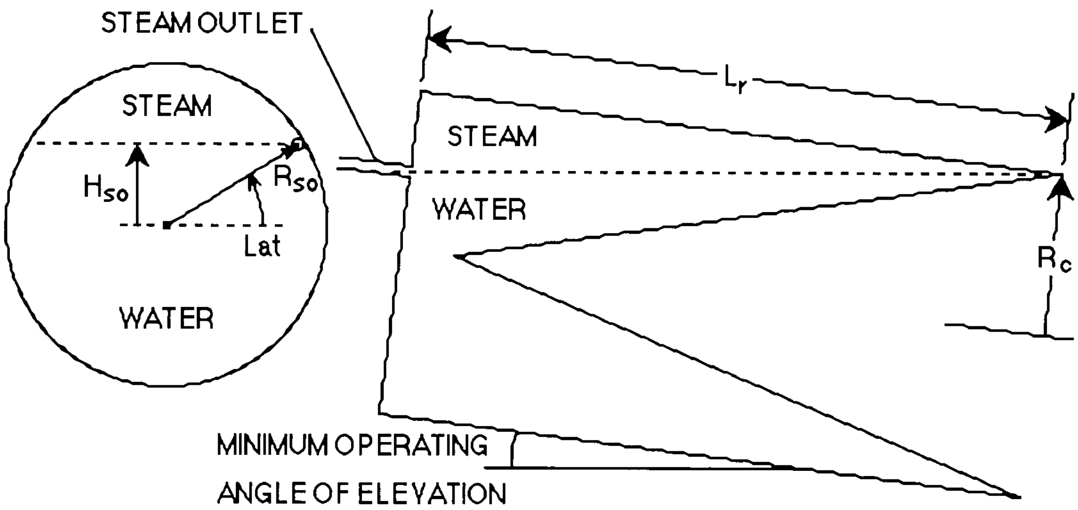


Figure 7-7
RECEIVER WITH STEAM OUTLET AT EDGE OF BOILER

An additional improvement can be made [Cordy, 1994]. The boiler is surrounded by insulation. The steam tube could occupy any space between the sun and the edge of the insulation without shading the dish. If two steam outlet ports are used, one can always be near the top of the boiler at either end of the day. From the end view in Figure 7-8 it can be seen that R_t is now much larger (typically 50% larger). Also, the water level is defined by the joint where the two outlet tubes are combined into a single tube. So L_r is larger. It is reasonable for L_r to be twice the length of the boiler or 6 times R_C. Now the minimum operating angle is approximately

$$\Psi = \mathrm{Atan}\left((R_c - R_{so} * \sin(\mathrm{Lat})) / L_{so} \right)$$

which, using the values above, gives $\Psi = 1.3°$ and a loss of time of 5.3 minutes at each end of the day. In practice, when the sun is that near the horizon, the lower part of the dish (which focuses light on the upper part of the receiver cavity) is in the shadow of other dishes, and the system can be operated to the horizontal at any latitude significantly away from the equator.

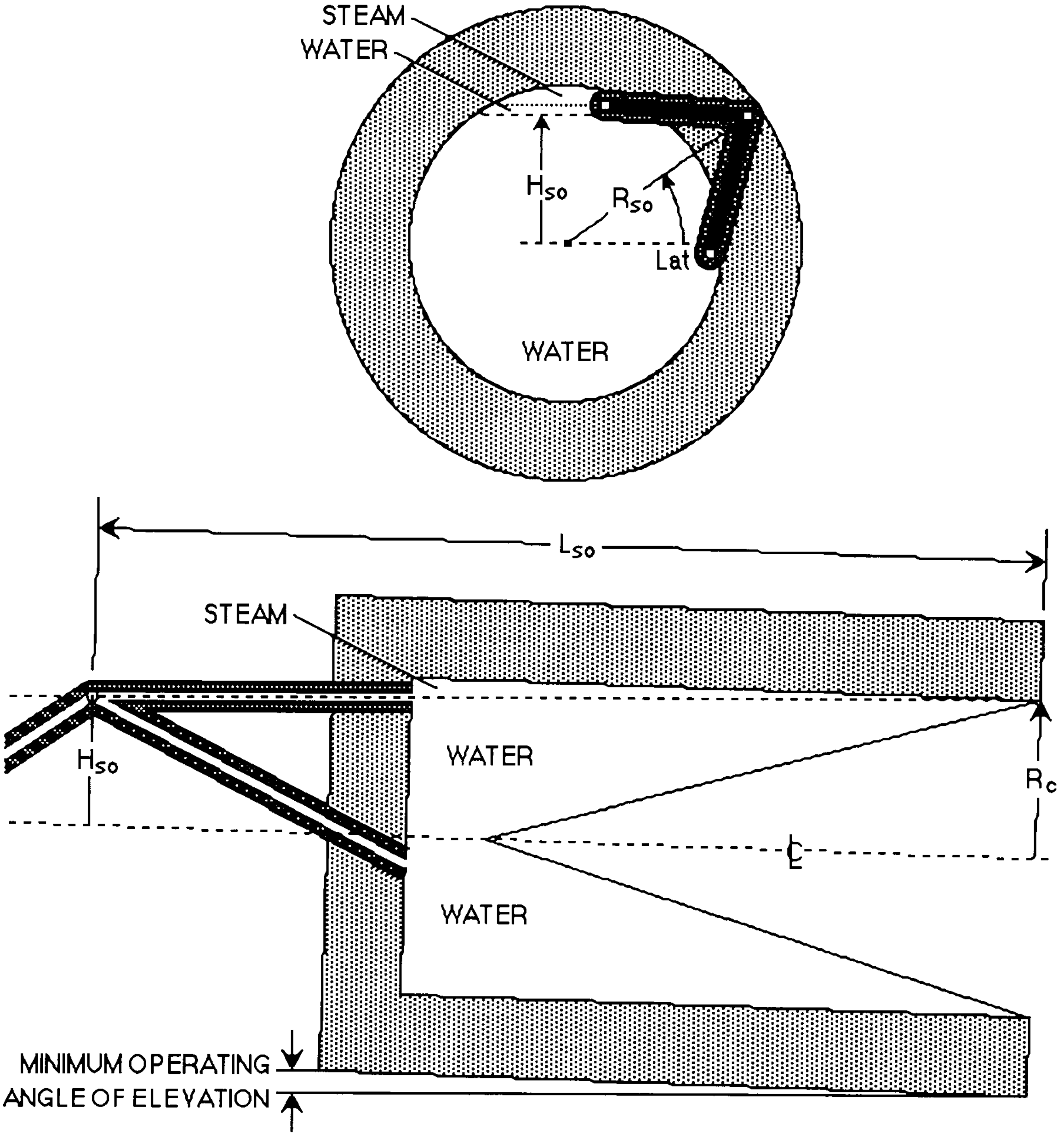


Figure 7-8
RECEIVER WITH TWO STEAM OUTLETS

8. PLUMBING

There are two, unrelated, problems associated with the plumbing in a field of solar energy collectors. First, the collectors move with respect to the surface of the earth. The high pressure, high temperature couplings that accommodate this motion are prone to failure. This is a widely recognized problem that has received a lot of attention. Second, the hot water going to the receiver is not as hot as the steam returning from the receiver. So the pipes have to be run separately and insulated separately. This is expensive. Nobody has recognized this to be a problem. It is possible to have either only one insulated pipe or two pipes at the same temperature within one unit of insulation going to each collector in the field. This saves insulation expense.

FLEXIBLE COUPLINGS

The best way to eliminate problems with flexible couplings and slip joints is to eliminate flexible couplings and slip joints. The small steel tubes going to the boiler could easily be bent by the dish drive system. After a few bends, the tube would work harden and fail. So that isn't a viable alternative either.

The tubes can, however, be flexed innumerable times without failure. As used here, bend implies a plastic deformation, flex implies an elastic deformation. If the routing of the tubes can be designed so the dish can move through its full range with no plastic deformation of the feeder tubes, then flexible couplings in the normal sense of the term can be eliminated entirely [Cordy, 1994].

The standard formula for the angle of deflection in a flexed tube or rod is:

$$\omega = \sigma L_t / E R_t$$

where σ is the stress in the tube, L_t is the length of the tube, E is young's modulus, and ρ is the radius of the tube. For elastic bending, σ cannot exceed the yield strength of the material. In steel, σ_{max} = 350 MPa and E=210 GPa. Solving for L and plugging in the values for σ_{max} and E yields:

$$L_{min} = 600 * \omega * R_t$$

Where L_{min} is the minimum length over which a tube can be elastically flexed through an angle ω. Around the declination axis, the tube will be flexed by ±23.5° (0.41 radians). To maintain elastic deformation of the feeder tubes, the flexure would have to be distributed over a length of 250 tube radii.

The standard formula relating angle of twist to stress in a tube or rod in torsion is:

$$\omega = 2 \sigma L_t * (1+\nu) / E R_t$$

where ν is the Poisson ratio. For steel, ν is about 0.3. From this and the values above, the minimum length over which a tube can be twisted elastically through an angle ω is:

$$L_{min} = 230 * \omega * R_t$$

At reasonable latitudes, the motion of the cradle around the polar axis will be no larger than ±110° (1.9 radians). To accommodated this motion by twisting the tube, a tube length of 440 times the tube radius is needed. Analysis shows that for reasonable head losses, the radius of the tube carrying steam should be about 0.001 times the dish radius. The tube carrying water can be much smaller. The declination axis motion can be accommodated by flexing a tube with a length of a quarter dish radius. The right ascension motion requires a tube length of 0.44 dish radius.

One suitable routing of the tubes is shown in Figure 8-1. The declination axis flexure is distributed over a tube length of more than one dish radius. The distance from the dish edge to the south cradle mount is about one dish radius, enough to accommodate the motion. A larger margin of safety can be achieved by routing the tube from some point on the polar axis of the cradle near the edge of the dish, past the equatorial end mount of the cradle, to a point on the ground directly over the polar axis of the cradle and and somewhat beyond the equatorial end of the cradle.

REDUCTION OF INSULATION ON PIPES

Water at high pressure is pumped from the power house through the collector field and a mixture of steam and water comes back. The steam is separated from the water. The steam is sent to the turbine and the water is pumped through the collector field again. At the back end of the turbine, residual steam is condensed at low pressure (typically 0.1 atmosphere) and pumped back into the high pressure system.

Normally, the cold water from the turbine and the hot water from the steam separator are mixed and distributed through the collector field. There is no energy loss in the mixing process. Typically, there will be about 4 parts water from the separator to 1 part water from the turbine. If the boiling takes place at 320C and the condensation takes place at 60C, then the water going to the collectors will be at a temperature of 268C. This pipe must be insulated to prevent serious heat loss. It cannot be bundled with the 320C steam line or energy will be drained from the steam line into the water line. (Again that does not lose total energy, but it does increase entropy and the turbine efficiency drops as a result.) So the two lines have to be insulated separately.

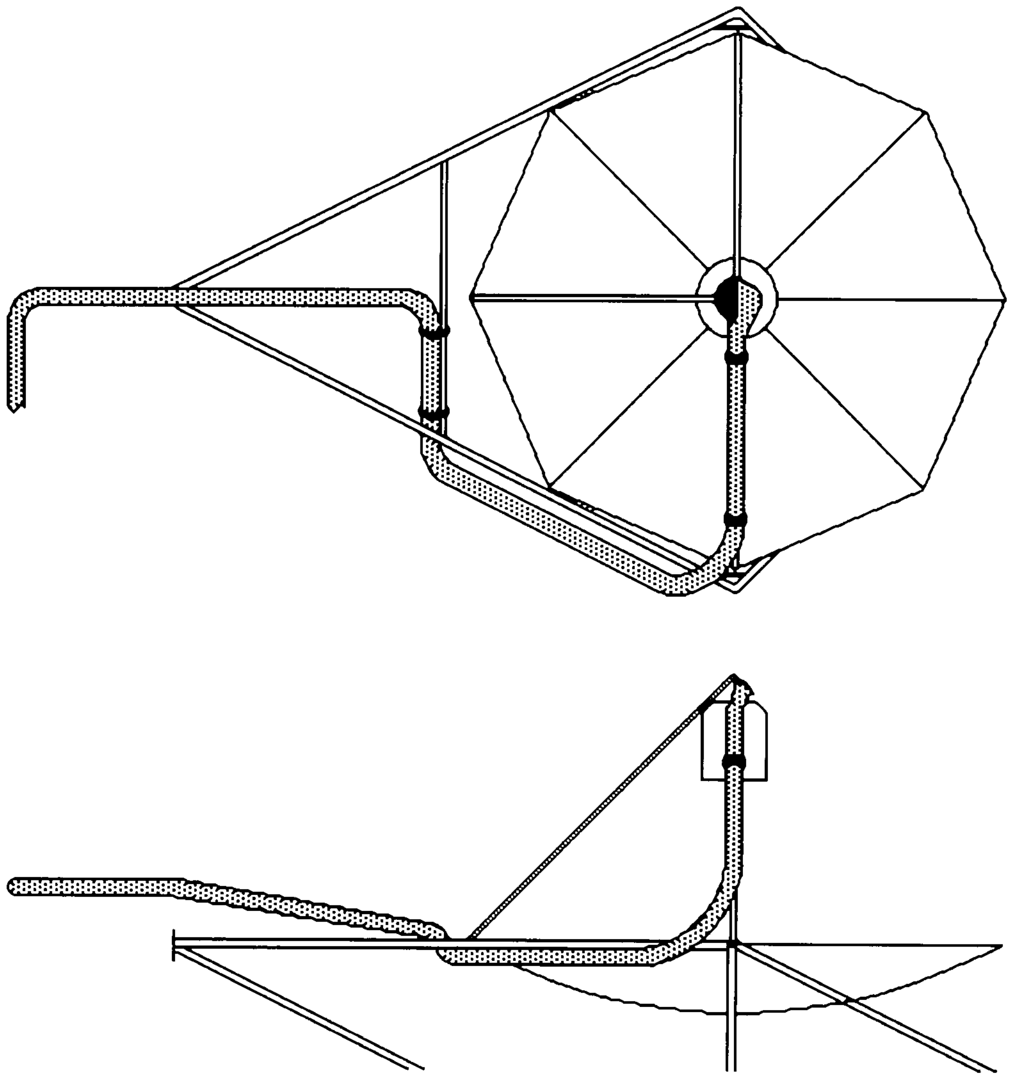


Figure 8-1
ROUTING OF PIPE FOR FLEXIBLE CONNECTION TO DISH

It is possible to have only one line of insulation going throughout the collector field [Cordy, 1994]. Consider the possibility of pumping the condensed turbine exhaust to one group of collectors and water from the steam separator to another group of collectors. The 60C turbine exhaust line can be uninsulated (or at most very minimally insulated). The water from the steam separator is the same temperature as the steam, so those two lines can be bundled together with no heat transfer. Only one line of insulation need be run to the dishes in either group. A schematic diagram of this flow sequence is shown in Figure 8-2.

It is desirable to have about 4 parts water and 1 part steam (by mass) in the flow leaving the receivers. That guarantees that no receiver will be run dry. If half the collectors in the array receive 60C water, they will heat the water to 320C and boil about 20% of that water. The other half of the collectors get a larger flow of water circulated from the steam separator so they also boil about 20% of the water they receive. There is no temperature change involved in that boiling process.

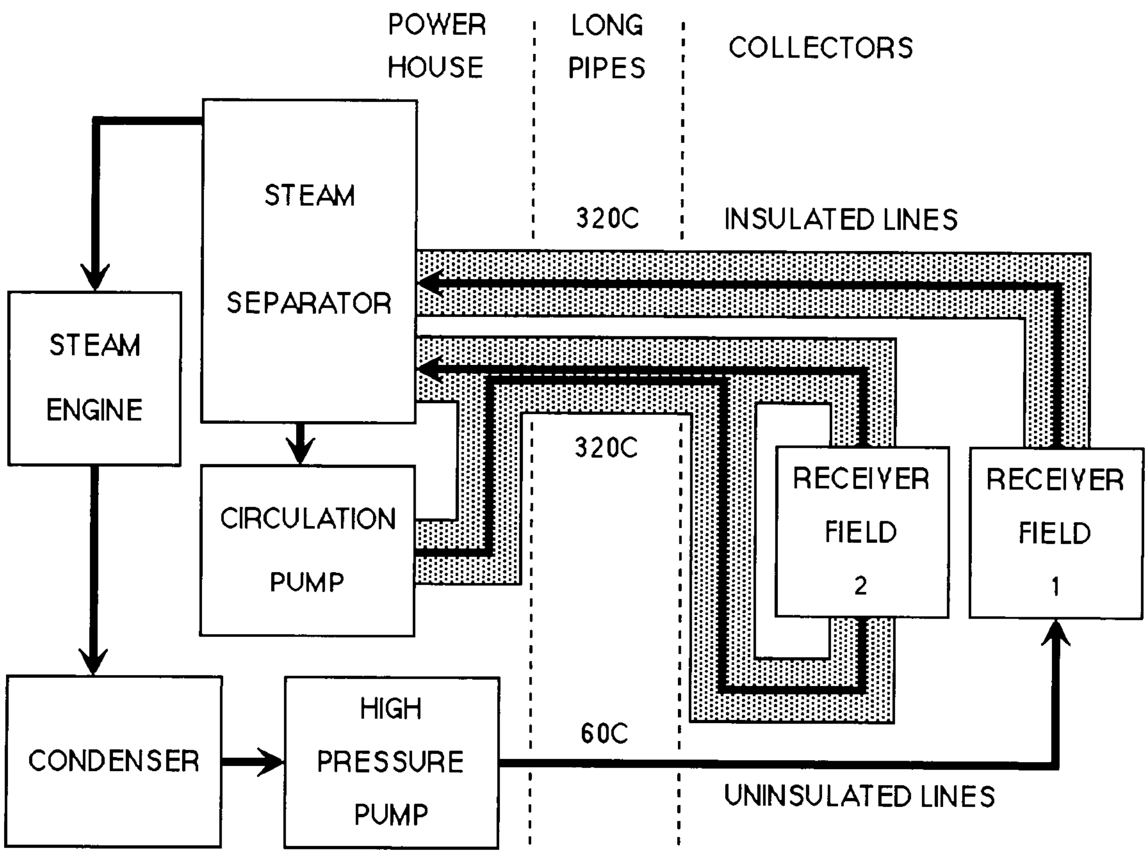


Figure 8-2
SCHEMATIC DIAGRAM OF FLUID FLOW

9. TRACKER AND DRIVE

Some solar collection facilities drive the mirrors to follow the sun with an open loop system. This contains a computer that is programmed to know the position of the sun throughout the year. This is not as simple as it might seem. The earth is in an elliptical orbit, the axis of the poles precess noticeably over a period of several years, and there is no convenient factor between the periods of a day and a year. All these factors conspire to shift the position of the sun such that it has no simple relationship to day and hour. The Astronomical Almanac [U. S. Government, annual publication] contains formulas for the position of the sun throughout the year which are accurate enough (but barely accurate enough) for purposes of solar energy collection. From these formulas, a computer can calculate the proper position of the mirror. Generally there is a position monitor on the mirror and the drive system nulls the difference between the computer output and the actual mirror position. To be successful, this system needs position readouts on both axes of rotation with accuracies of at least 12 bits. These are expensive. Accuracy is also dependent on a suitable placement of the reference position of the mirror. This is an expensive alignment process. Tracking also needs a clock in the computer that is accurate to within about 10 seconds. This is commonly done with an automatic radio link to WWV, which is not cheap.

To avoid all these expenses, most systems use active solar tracking. In these systems, the mirror is pointed in the right general direction. Then a solar image is detected and the mirror is driven in a way to keep the solar image in the proper position. The solar image at the entry to the receiver cavity contains an extremely high energy density and systems that try to track this image have been troublesome. Many other image trackers have been built. One simple method is to mount an opaque object over an array of photodetectors and track the edge of the shadow. In any of these trackers, it is essential that the tracker be aligned to the mirror with sufficient accuracy (within 5 mr maximum error). A simpler method [Cordy, 1994] is to mount the photodetectors near the center of the dish and track the shadow of the receiver. This not only removes the need for a separate shadow generator, but it removes many of the potential sources of error between the dish axis and the tracker axis.

The main problem with any tracker is that it fails to work when it cannot see the sun. Clearly this occurs whenever a cloud passes over. It also occurs near the ends of the day when shadows from adjacent dishes cover the tracker. To avoid this problem, hybrid trackers have been proposed (but, to my knowledge, none have been built). The hybrid tracker tracks the sun whenever a suitable solar image is available and drives the dish open loop when no image is available. Since open loop operation is needed for the period of one day, at most, and position correction will occur automatically whenever a decent solar image is available, no feedback from the dish position is needed. That eliminates the entire, expensive, dish position monitor and precision clock. The clock is needed only to start the drive at the proper time in the morning and (because the tracker will soon correct any errors) an accuracy of the clock of ±2 minutes is adequate. Any reasonable quartz clock can maintain that accuracy over a period of a year.

When the dish is mounted on a polar axis gimbal, as it is in the system described here, the right ascension drive normally runs at a constant speed and the declination drive is stopped. By using a small, synchronous motor on the right ascension drive that runs at the proper speed, the dish will nominally follow the position of the sun with no further correction. When errors occur, they are corrected either by turning off the motor or running it at double frequency. If the solar image is lost, the error signal generator is turned off, and the dish will be very close to the right position when the solar image returns. There is essentially no added expense for this hybrid tracker over the basic solar tracker, a claim that no other hybrid tracker can make.

Given the tracker, it is still necessary to have a mechanism that will actually move the dish. Most existing systems use gears (huge gears that would look appropriate on cog wheel locomotives) or screw systems (similar to, but bigger than, those found on automatic satellite tracking antennas). With the long radius drive tracks mounted on the dish and cradle described here, much cheaper drive mechanisms become applicable. One obvious possibility is to mount a motorcycle chain in the drive track and drive it with a sprocket mounted on a motor and reduction gear. An even cheaper method is to use a bidirectional rope drive (the term rope is used here to include steel cable). These have been proposed for solar applications, but never used. Earlier proposed mechanisms have never had a satisfactory method of maintaining tension in the rope. Without that, they will slip, which means they won't work.

It is possible to design a bidirectional rope drive with a tension adjustment that is cheap and applicable to driving a solar collector [Cordy, 1994]. There are several possible embodiments of this mechanism, the most elegant being shown in Figure 9-1. The drive rope must not slip under conditions of maximum wind induced torque. This could be done by maintaining a high tension in the rope at all times. That causes rapid rope wear. It is desirable to have a low tension in the rope and still guarantee against slipping. This can be done by taking the rope several turns around the drive pulley. In a bidirectional system several pulleys must be used, not just a simple shaft, to keep the rope from stacking up against the end of the drive shaft. A low tension on one side of the drive pulley will sustain a high tension on the other side of the drive pulley, without slipping. As the wind changes, the high tension side may be on either side of the drive pulley. Having tensioners on both sides of the drive pulley is not a viable option for several reasons. The most obvious is that turbulence in the wind could slam the dish rapidly back and forth against the stops backing up the tensioning mechanisms. The drive shown in Figure 9-1 eliminates this problem. In effect it has two sets of drive pulleys mounted on one shaft, one set on each side of the tensioning mechanism. Since the rope is being taken out of a track, passed through the drive system, and returned to the same track, it is desirable that the input and output ropes be colinear, or nearly so. The mechanism shown in Figure 9-1 does this too.

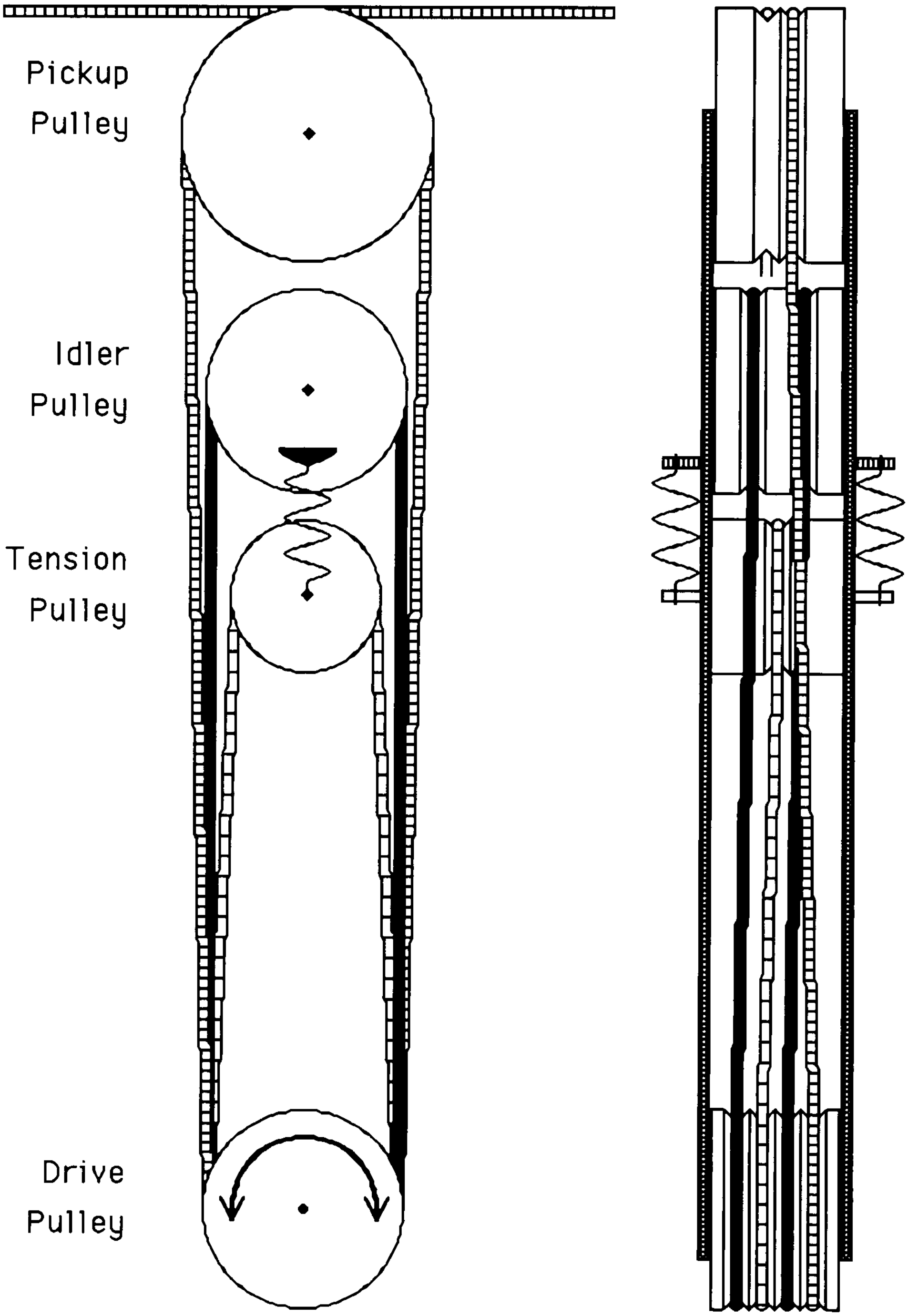


Figure 9-1
BIDIRECTIONAL ROPE DRIVE

For drawing clarity, the rope is shown passing over the drive pulleys only four times. This can be increased to any even number of times.

10. OPTIMUM SPACING

In an array of solar collectors, there is inevitable shading among the collectors. This reduces the average daily output. To maximize the return on investment from the collectors, they should be widely spaced. To maximize the return on investment in land and plumbing, the collectors should be tightly packed. Obviously, there must be an optimum spacing between these extremes.

The average daily sunlight intercepted by a member of an infinite array of collectors will be a function of east-west spacing, EW; north-south spacing, NS; atmospheric transmission, τ; and latitude, Lat. The cost of the system can be divided into the cost of items related to packing density, (Land, part of the plumbing, P_{ew} and P_{ns}, and part or the cradle, Cr, and guy wires, Guy) and the cost of everything else, C_{fix} (independent of packing density). The factor related to the cradle enters the calculation because it is desirable to mount the equatorial end of one cradle and the polar end of the adjacent cradle on the same concrete pad. If NS is increased, the cradle has to be made longer, hence heavier and more expensive. The average daily sunlight intercepted must be calculated over an array of different dish spacings. The cost of the various parts of the solar system for each of those spacings must also be calculated. The two can be divided to give average daily sun hours per dollar for each of the spacings. This is equivalent to return on investment. The goal is to find the set of spacings that maximize this value.

To calculate the cost of the system, it is necessary to use a consistent set of units. Land is the cost of land, including development cost, in $/m^2 of land. P_{ew} and P_{ns} are the plumbing costs of the main trunks and dish row distribution lines respectively, in dollars for insulated pipe per meter of length of pipe. Normally P_{ew} and P_{ns} are small enough that it doesn't affect the answer significantly to use a value of zero. M is the number of dishes in a north-south row of dishes. Cr is the cost of the additional material needed to extend the length of the cradle from A to the declination axis by one meter. This cost is significant. This number can be calculated only by doing a complete cradle design for two lengths near the value suitable for the final north-south spacing. Guy is the cost to the guy wires and mounting pole to increase the east-west spacing by one meter. C_{fix} is the cost of everything else in the system, including the power house and the land it is on, in \$/m^2 of mirror. Now the cost per unit area of dish for each value of EW and NS can be calculated using the formula:

$$Cost = C_{fix} + 4/\pi * (L * EW * NS + (P_{ew} / M + Guy) * EW / D + (P_{ns} + Cr / \cos(Lat)) * NS / D)$$

where EW and NS are expressed in dish diameters and D is the diameter of the dish.

To calculate the average sunlight intercepted, it is necessary to calculate the sunlight intercepted for many different times during each of many days during the year. In order to get sufficient accuracy, it was necessary to calculate the intercepted sunlight for every 2° of earth rotation and for 90 different days between the solstices. The solar position can be expressed easily in terms of a global polar coordinate system. Atmospheric absorption can be expressed easily in terms of a local polar coordinate system. Possible shadowing from several neighboring dishes must be considered. The actual calculation of the average sunlight intercepted by an isolated dish requires a tedious set of coordinate system rotations that are already well understood. To calculate the effects of dish shading requires some approximation. Otherwise, there are an infinite number of dishes that might produce some shading. I chose to consider dishes in the 6 rows nearest the dish under consideration. To approximate all the rest, I erected a hypothetical wall 10 rows away. It is also necessary to consider shading from the next dish toward the equator.

To get the average daily sun hours requires that the atmospheric absorption be calculated for each of the dish positions. The sun is dimmed by atmospheric absorption as it approaches the horizon. A formula for atmospheric transmission [Hottel, 1976] is:

$$\tau = a_0 - a_1 * \exp(-k/\cos\phi)$$

where a_0, a_1, and k are constants that depend on local conditions and ϕ is the solar angle away from the vertical in the local polar coordinate system. This can be normalized to:

$$J = S + (1-S) * \exp(k*(1-1/\cos\phi))$$

where J is the solar intensity at any given ϕ relative to the intensity at the vertical and S is the ratio of solar intensity at sunrise or sunset to its intensity when coming from the vertical. This formula uses just three variables (S, k, and ϕ) instead of four (a_0, a_1, k, and ϕ). The range of values for a_0 and a_1 given by Hottel yield values of S between 0.1 and 0.4. In clear air, k is near 0.3. Hottel gives values for nominally average climatic conditions. Thus they are pessimistic for the desert conditions where solar collectors are usually located. I did the calculations for average sun hours for six different values of S, from 0.1 to 0.6 in steps of 0.1 and three values of k, from 0.2 to 0.4 in steps of 0.1. Calculations show that the sunlight collected depends on k, but the optimum spacing does not vary with k. The sunlight collected and optimum spacing are dependent on latitude, and there is the possibility of building a solar power generator at any latitude. I did all the calculations for all latitudes from 0° to 60° in increments of 5°.

There is one additional complication. The array of dishes might be laid out in a triangular pattern or a rectangular pattern. I calculated both. The rectangular pattern is better at all latitudes, but the advantage is under 2%.

To generate the desired values of average sun hours at appropriate spacings requires the calculation of sunlight intercepted at nearly 500 million combinations of NS, EW, S, k, Lat, time of day, day of the year, and collector array geometry. Each of these calculations involve several coordinate system rotations, determination of atmospheric absorption, and various possible dish shadings. To get the results required running four HP 110 computers continuously for two years (over 70,000 cpu hours). Table 10-1 gives the results for a rectangular array of dishes at latitudes of 25° and 35° (where the best deserts lie), k = 0.3, and S = 0.4 (good values for a high desert).

Latitude = 25°

EW-> NS	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	3.0	3.1	3.2	3.3
1.5	9.279	9.310	9.336	9.357	9.374	9.388	9.400	9.410	9.420	9.430	9.439	9.449	9.459
1.6	9.329	9.359	9.384	9.404	9.419	9.431	9.441	9.449	9.457	9.463	9.469	9.476	9.483
1.7	9.370	9.400	9.425	9.444	9.458	9.470	9.478	9.485	9.491	9.496	9.500	9.504	9.508
1.8	9.403	9.434	9.459	9.479	9.494	9.504	9.513	9.519	9.524	9.528	9.531	9.533	9.536
1.9	9.429	9.461	9.488	9.508	9.524	9.535	9.543	9.550	9.554	9.558	9.560	9.561	9.563
2.0	9.447	9.482	9.510	9.531	9.548	9.560	9.570	9.576	9.581	9.584	9.587	9.588	9.589
2.1	9.459	9.495	9.525	9.549	9.567	9.581	9.591	9.599	9.604	9.608	9.611	9.612	9.613
2.2	9.465	9.503	9.535	9.561	9.581	9.596	9.608	9.616	9.623	9.628	9.632	9.633	9.635
2.3	9.467	9.507	9.540	9.567	9.589	9.606	9.619	9.630	9.638	9.644	9.648	9.651	9.653
2.4	9.467	9.507	9.542	9.570	9.593	9.612	9.627	9.639	9.648	9.656	9.661	9.665	9.668
2.5	9.467	9.507	9.542	9.570	9.593	9.614	9.631	9.644	9.655	9.664	9.671	9.676	9.680
2.6	9.467	9.507	9.542	9.570	9.593	9.614	9.631	9.646	9.658	9.668	9.676	9.683	9.688
2.7	9.467	9.507	9.542	9.570	9.593	9.614	9.631	9.646	9.659	9.670	9.679	9.687	9.694
2.8	9.467	9.507	9.542	9.570	9.593	9.614	9.631	9.646	9.659	9.670	9.680	9.688	9.696

Latitude = 35°

EW-> NS	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	3.0	3.1	3.2	3.3
1.8	9.016	9.048	9.075	9.096	9.114	9.127	9.138	9.148	9.156	9.164	9.171	9.177	9.185
1.9	9.075	9.107	9.133	9.155	9.171	9.184	9.194	9.202	9.210	9.216	9.221	9.226	9.231
2.0	9.105	9.138	9.164	9.185	9.202	9.214	9.224	9.231	9.238	9.243	9.247	9.251	9.254
2.1	9.129	9.163	9.190	9.211	9.228	9.240	9.250	9.257	9.263	9.268	9.271	9.274	9.276
2.2	9.149	9.183	9.211	9.233	9.250	9.263	9.273	9.280	9.286	9.291	9.294	9.297	9.298
2.3	9.164	9.199	9.228	9.251	9.269	9.283	9.293	9.301	9.307	9.312	9.315	9.317	9.319
2.4	9.174	9.211	9.241	9.266	9.285	9.299	9.310	9.319	9.326	9.330	9.334	9.336	9.337
2.5	9.181	9.219	9.251	9.276	9.297	9.312	9.324	9.334	9.341	9.346	9.351	9.353	9.355
2.6	9.184	9.224	9.257	9.284	9.305	9.322	9.335	9.346	9.354	9.360	9.365	9.368	9.370
2.7	9.185	9.226	9.260	9.288	9.311	9.329	9.343	9.355	9.364	9.371	9.377	9.381	9.384
2.8	9.185	9.226	9.261	9.290	9.314	9.333	9.348	9.361	9.371	9.379	9.386	9.391	9.395
2.9	9.185	9.226	9.261	9.290	9.315	9.335	9.351	9.365	9.376	9.385	9.393	9.398	9.403
3.0	9.185	9.226	9.261	9.290	9.315	9.335	9.352	9.366	9.379	9.389	9.397	9.404	9.410
3.1	9.185	9.226	9.261	9.290	9.315	9.335	9.352	9.367	9.380	9.391	9.400	9.407	9.414

k=0.3 S = 0.4

Table 10-1
AVERAGE DAILY SUN HOURS IN A RECTANGULAR ARRAY

From these numbers, the optimum dish spacing can be calculated. The optimum spacing is not strongly dependent on the assumptions made about any of the costs involved. Certainly it is less than a linear relationship. Errors in assumptions about costs result in smaller errors in predicted optimum spacing. Table 10-2 gives the optimum spacing using S = 0.5, L = 1.5, $P_{ew} / N_{ns} = 0$, $P_{ns} = 15$, Cr = 80, Guy = 0, several values of C_{fix}, and both latitudes. Guy = 0 is a valid value. As the guy wire is lengthened, there is less tension in the guy wire and less compression in the mounting pole. It happens that the typical EW spacing is right where the sum of guy wire cost and mounting pole cost is a minimum. The most likely value of C_{fix} in this design is near $200/m².

In Table 10-2, the column A-Dec is the distance from node A of the cradle to the declination axis, in dish radii (as expressed in the cradle discussion, chapter 6). Conveniently, the optimum NS spacing for the installation gives a dimension for the cradle that is near optimum for the cradle design.

At 35° latitude, the optimum density of dishes is about 17%. It would be only 13% in a conventional installation, where there is not the cost of lengthening the cradle. Optimum density would be further reduced using the higher costs of existing solar collectors. The designers at STEP were very proud of the fact that they had achieved a packing density of 41% without the dishes hitting each other. This is clearly the wrong goal.

An analysis of optimum spacing of dish concentrators in a rectangular grid using weather data from Barstow, CA (latitude = 35°) has been published [Pons and Dugan, 1986]. Their conclusion was that the optimum density of dishes is in the range of 30%. One of the main sources of difference is that they assumed their dishes would not go within 10° of the horizontal. That may be a receiver limitation in their design. Because of this, they lose 11% of the total daylight hours. Their conclusion should have been that if the dishes never aim close to the horizon, then the dishes can be tightly packed. This explains some, but not all, of the difference in results. Using values appropriate to the Pons and Dugan analysis yields an optimum dish density of 12% if the dishes can be operated to the horizontal.

	Lat = 25°				Lat = 35°			
C_{fix} $/m²	EW_o Dia	NS_o Dia	Dish density	A-Dec Rad	EW_o Dia	NS_o Dia	Dish density	A-Dec Rad
150	2.5	1.5	21%	1.7	2.4	1.8	19%	1.9
200	2.6	1.5	20%	1.7	2.5	1.8	17%	2.0
250	2.7	1.5	19%	1.9	2.5	1.9	17%	2.1
300	2.6	1.7	18%	2.2	2.6	1.9	16%	2.2

Table 10-2
OPTIMUM COLLECTOR SPACING IN A RECTANGULAR ARRAY

11. OPTIMUM SIZE

Return on investment is maximized if the dish size is optimized. In general, mechanical problems and expense go up with the cube of dish diameter. Energy collected goes up with the square of dish diameter. That implies that the collector field should consist of millions of little tiny dishes. Other parts of the system increase in cost more slowly. Notably, construction labor costs increase more slowly than dish area, the drive system and plumbing costs increase much more slowly than dish area, and the tracker electronics are essentially independent of dish area. All that implies that the system should consist of a single dish about the size of Arizona. Somewhere between the two extremes is an optimum dish size. Table 11-1 shows an analysis of the relation between dish diameter and cost.

The cost analysis is broken into the five major categories: cradle, dish, drives, receiver, and plumbing. Each category is broken into various material and labor costs. Where appropriate, unit costs are shown. Material costs for the cradle and dish are derived from the design spreadsheets discussed earlier. A few items, like the receiver, are given item costs, not unit costs. Labor hours are estimated and multiplied by the labor rate shown at the top. The effect of changing dish sizes on the cost of items is assumed to fit the formula:

$$cost_D = cost_{10} * (D/10)^{Exp}$$

Where $cost_D$ is the cost of an item for a given dish diameter, D, $cost_{10}$ is the cost of that item for a 10 meter dish, and Exp is an exponential scaling factor.

Material costs are based on large scale production. For instance, dish ribs are based on a quote of 45¢/lb based on buying steel sheet by the roll and running it through a slitting and blanking operation a roll at a time. A roll of steel weighs many tons. (Quotes in the US are still made in English units.) Clearly this would not be a small operation.

Labor costs are based on having a dedicated production facility where tubes are put into jigs and cut to length and angle without having to make individual measurements. The cut pieces are put securely into other jigs and welded. The fiberglass is blown through a chopper gun in very little time. The bulk of the fiberglass time is spent on care and preparation of the molds, care and cleaning of the chopper gun, and rolling the air out of the glass mush produced by the chopper gun.

Labor costs generally go up slowly with dish size. In some cases, they don't go up at all until something gets so big that it needs three men to handle it instead of two. It is not a continuously variable situation as the equations imply. The discrete effect also shows up in material costs, but generally not to a large degree. The exception is the mirror material. It comes in 60 inch width. To efficiently use the material (one of the largest single cost items in the list), permitted dish sizes are not continuously variable. Dish diameters can increase in steps of about 2 meters. The system cost as a function of dish diameter goes through a broad minimum, so going to the nearest "permitted" size does not affect the result very much.

Labor	Rate $40	/hr	10 meter cost	Exponent	8 meter cost	12 meter cost
Cradle and Mount						
Steel	$0.10	/N	773	3.00	396	1336
Concrete	$1.50	/kN	34	1.63	24	46
Cut	$40	/hr	73	0.50	66	80
Weld	$40	/hr	220	1.00	176	264
Install	$40	/hr	240	0.50	215	263
Dish						
Steel	$0.10	/N	577	3.55	261	1102
Cut	$40	/hr	133	0.50	119	146
Weld	$40	/hr	600	1.00	480	720
Install dish	$40	/hr	120	0.50	107	131
Glass	$0.50	/N	1143	3.98	470	2361
Reflector	$13.00	/m2	1040	2.00	666	1498
Make glass	$40	/hr	1600	2.00	1024	2304
Install glass	$40	/hr	40	1.00	32	48
Install reflector	$40	/hr	80	0.50	72	88
Drives						
Tracker			100	0.00	100	100
Motors & gears			100	0.50	89	110
Install	$40		40	0.00	40	40
Receiver						
Material			200	0.50	179	219
Install	$40	/hr	20	0.00	20	20
Receiver support						
Steel	$0.10	/N	30	3.00	15	52
Cut	$40	/hr	20	0.50	18	22
Weld	$40	/hr	60	1.00	48	72
Plumbing (field)						
Steel	$8.00	/m	304	1.00	243	365
Insulation	$6.00	/m	114	1.00	91	137
Cut	$40	/hr	13	0.00	13	13
Weld	$40	/hr	60	0.50	54	66
Insulate	$40	/hr	7	0.00	7	7
Plumbing (dish)						
Steel	$6.00	/m	270	1.00	216	324
Insulation	$6.00	/m	270	1.00	216	324
Cut	$40	/hr	13	0.00	13	13
Weld	$40	/hr	40	0.50	36	44
Insulate	$40	/hr	13	0.50	12	15
	TOTAL	$	8349		5518	12329
		$/m^2	106.30		109.77	109.02

Table 11-1
SYSTEM COST FOR SEVERAL DISH DIAMETERS

The cost calculated here represents a factor of five reduction in cost from the cheapest existing systems. A lot of this improvement is due to the fact that no existing system has been built using the principles of mass production. The dish ribs will be cut to width and length, with the ends at the right angles in an automatic machine turning out ribs by the ton. The tubes for the dish and cradle will be cut to the right length with the ends at the right angles while they are held in fixtures that require practically no set up time. With enough volume (especially with the numerous identical dish braces), this could be done at the tubing factory, at practically no cost as the nearly infinite lengths of tube come out of the tube making machine. (There is already a saw that cuts the tube to some manageable length.) The pieces for cradles and dishes can be completely assembled in jigs before any welding is done. Nothing is measured or adjusted. Assembly of the dish into the cradle and the cradle onto its mount is almost as automatic. The cradle mount must have some fine adjustment capability at the polar end to align its axis to the earth's axis. This is done at night by mounting a small telescope into the cradle and sighting on Polaris. By using something as basic as shims and turnbuckles, the cradle axis can be adjusted in a few minutes. The end pivots of the cradle need to be located with respect to each other to within ±5 cm. (±2 cm would be nice but better would be undetectable in operation). That is not a precision adjustment.

With the optimum dish size being about 10 meters, a few more words should be written about the possibility of a distributed engine system. A 12 meter dish can be made with little cost penalty. That should generate about 18 kW_e. The plumbing cost for the distributed receiver, central engine system is about 10% of the collector system cost. The distributed engine system has extra costs of its own. It is much heavier than a simple receiver, so the tripod holding it over the dish must be much stronger. To support the extra weight, the cradle must be somewhat stronger. (The cradle strength is defined largely by wind load in any case.) The receiver and engine must be able to operate over a wide range of orientations, an unusual requirement for an engine. The biggest factor is the cost per watt is always higher in a smaller engine and generator. The collector system is about the same cost as the engine and generator. If many small, dish mounted engines represent an increased engine cost of more than about 10% over a larger, stationary engine, then it is cheaper to use a distributed receiver with a central engine. This is true even if the problems caused by having the heavy engine mounted on the dish could be solved for free. It is almost certain that the distributed engine system cannot compete economically with the central engine system.

12. OPEN ISSUES

The biggest unresolved issues have to do with the dish material. The finite element analysis done by Blythe was for a 4 meter dish. It is unknown how to scale that to larger dishes. The main question is related to transverse deflection in moderate wind. I have derived a formula for this deflection but it doesn't fit Blythe's results very well. The dish is a major cost item. If I put in a scale factor to make my calculation agree with Blythe, then the cost of the 10 meter dish drops to $\$90/m^2$ and the optimum diameter goes to over 12 meters. These are significant changes. The finite element analysis needs to be done again for a bigger dish.

The transverse deflection of the dish is strongly related to the stiffness of the dish material. Chopper gun glass is very poor in this respect. Metal dishes could be much thinner. Carbon fiber could be even thinner than steel. Something as simple as using unidirectional filament glass cloth in the dish would allow a 16 meter dish to be 1 mm thick. It is likely that significant improvements can be made to the system cost with different dish materials.

The biggest single cost item is the labor involved in making the fiberglass dish. The material cost of the fiberglass is the second biggest item. Injection molding of plastic has improved dramatically in recent years. Many car body parts are now plastic and it appears that they don't distort much after coming out of the mold. It may be possible that whole dish sections could be injection molded with a suitably fiber reinforced plastic. This would eliminate fabrication costs for the dish sections (at least from the point of view of the dish assembler). It might also be thinner, lighter, and less expensive than the material used in a fiberglass dish. Clearly, injection molded plastic would require a much bigger initial investment in molds.

There is a possibility that even modest winds could cause vibrations in the dish. No dynamic analysis of the interaction between the wind and the dish has been done. This would be a very difficult problem.

As mentioned in chapter 4, the possibility of superheating the steam by using a receiver with liquid salt or metal needs further investigation. It is unlikely to be attractive either thermally or economically, but this has not yet been proven.

A recent suggestion [Hopkins, 1994] is to burn garbage to superheat the solar generated steam during the day. This would get rid of the garbage and improve efficiency of the whole installation. Then the whole electric generator could be operated by burning garbage at night. This would greatly improve the operating duty cycle of the engine and generator. This all opens a whole lot of new questions and to date I haven't even figured out how to do the economic analysis.

13. SUMMARY

This thesis presents a design for a solar power system that is much cheaper to build and is more efficient than existing systems. Innovations include a concentrator dish that is both cheaper and stronger than existing dishes; a strong, inexpensive cradle in which to mount the dish; a receiver that delivers more of the solar energy to the steam with less heat loss; a thermal shield / secondary reflector; several improvements to the system plumbing; and tracker and drive systems that are cheap and reliable. In addition, analyses were done to determine the optimum dish spacing in the collector field and the optimum diameter of the dishes within the field. Results of these analyses are presented.

A strong, low cost concentrator dish is designed. It is based on a steel structure in the form of a teepee frame with a center pole and radial steel ribs giving support to the fiberglass dish. It has the great advantage that it is strong enough that it does not need to be driven to a stow position in high wind. This makes the drive system easier. In large sizes, this dish is considerably cheaper to make than existing dishes. It also provides convenient mounting points for a long radius declination drive. The long radius drive minimizes the drive forces needed. This dish has the potential disadvantage that it cannot be mounted on any existing mount. The weight of a ten meter diameter dish would be close to 7000 N.

A cradle is designed specifically to hold the new dish. The cradle is strong enough that it can hold the dish at any orientation in high winds without failure. A cradle to hold a ten meter dish would weigh about 6000 N, about the same as the steel tube in a monopod mount. The primary advantage of the cradle is that it will accommodate the strong, cheap dish. A significant secondary advantage is that it is a polar mount that provides convenient mounting points for a long radius right ascension drive. The polar mount minimizes the required speed from the drive system, and is almost a required feature for installations in the tropics. The long radius drive minimizes the required drive forces.

A new receiver is designed that delivers a larger fraction of the solar energy to the steam. Improvements include a blacker cavity, a convection baffle, a secondary reflector to trap more of the rays at the edge of the blurred solar image, a thermal shield that protects the receiver in case of tracker or drive failure, and a dual steam exhaust so the receiver can be operated from sunup until sundown.

The system plumbing is also analyzed. It is shown that if the water and steam pipes are properly connected from the earth to the cradle and from the cradle to the dish, the movements of the cradle and the dish can be accommodated by elastic flexure of the tubes themselves. No other fittings are needed. This makes the plumbing cheaper and much more reliable. It is also shown that the system efficiency can be made higher, and the cost lower, if the water from the condenser is not mixed with the water from the steam separator until after the two have passed through separate receivers.

An economic analysis is made of the optimum dish spacing. At the latitude of most U. S. deserts, it is found that the dish aperture area should be about 17% of the land area. This is a much lower density of collector than is found in existing installations. Part of the reason is that this design can operate to the horizontal, thus collecting energy for the entire day.

Lastly, an analysis of collector system cost is made to determine the optimum dish size for the new system. The optimum size is in the range of ten meters diameter. Similar analyses of old style dishes mounted on monopods repeatedly yielded optimum sizes in the range of four meters. The new design meets the "compete with coal" cost requirement. At its optimum size, this solar collector system can be built for little more than $\$100/m^2$, half the cost per unit area of the DOE long term goal.

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