AUROVILLE

SOLAR BOWL CONCENTRATOR FOR COMMUNITY SCALE STEAM COOKING

A practical application of solar thermal energy for institutional & industrial use.

Report - May 2008

A project of the Auroville Foundation:
Auroville Centre for Scientific Research Trust (CSR)
Auroshilpam,
605 101, Auroville Universal Township,
Tamil Nadu

Funded by the Government of India:
Ministry of Non-Conventional Energy Sources (MNES)
Block No. 14, C.G.O. Complex, Lodi road,
110 003 New Delhi

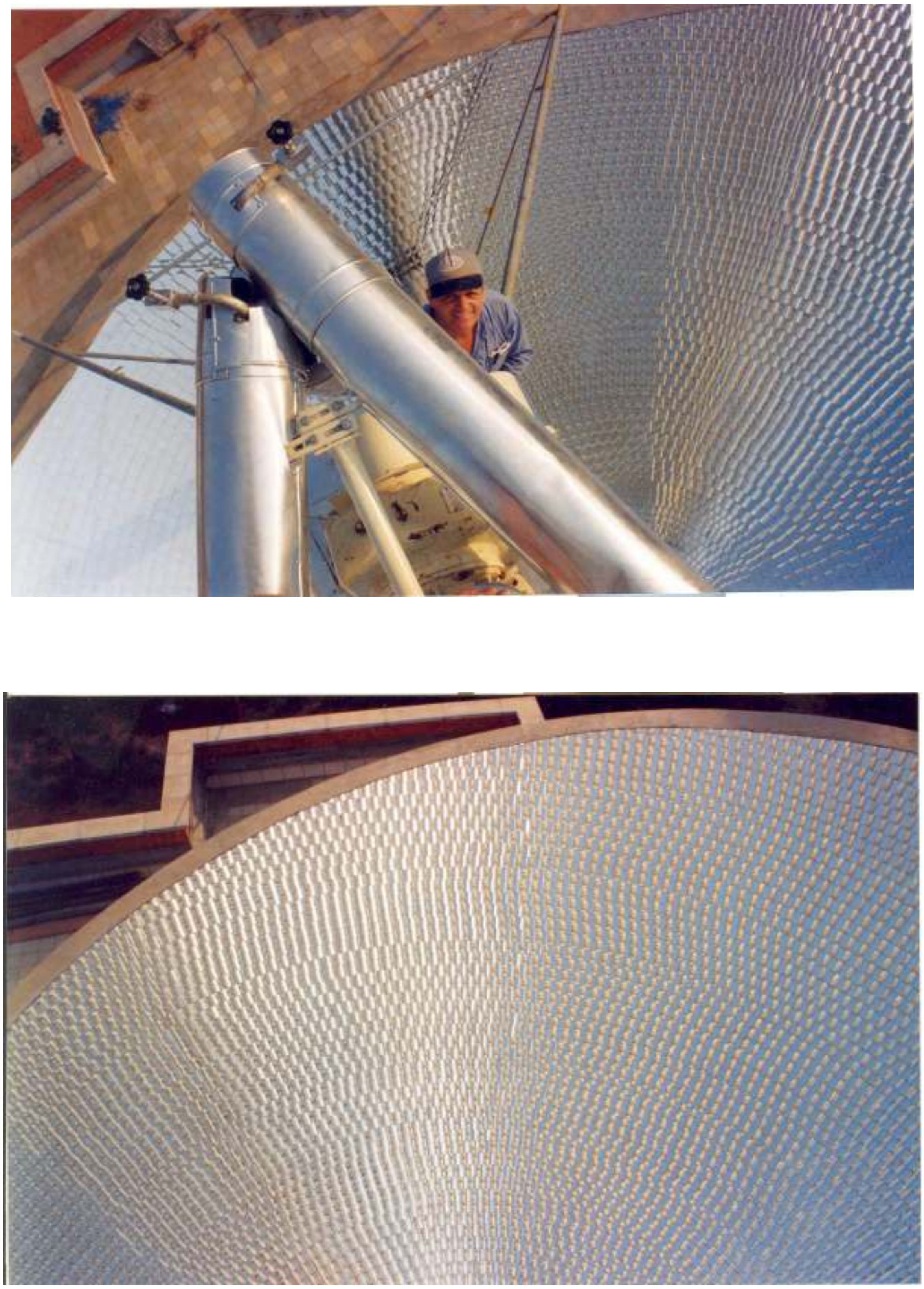

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Fig. 3 South façade of the Solar Kitchen

1. OVERVIEW

In September 1994, Auroville's Centre for Scientific Research (CSR) started building for the international community of Auroville a Community Kitchen named "Cuisine Solaire Pour Tous" (French for "Solar Cuisine For All"). The kitchen is commonly known as the "Solar Kitchen", which is how it is referred in this document. It was inaugurated at the end of October 1997 and since then lunch has been prepared and served there every weekday. The number of lunches prepared varies according to the seasons and years; it peaks at a little more than a thousand during the season. Dinners are also prepared but on a much smaller scale (100/evening).

The kitchen was designed to produce three meals a day for 1,000 of Auroville's residents and guests. About half of these meals were meant to be served on the spot in a dining room which is attached to this kitchen; the other half is sent to Auroville schools and communities.

Right from the beginning of the design process, it was decided that steam would be used as a heat transfer medium for cooking since it has many advantages over other systems. Moreover, the know-how could easily be obtained from a pioneer in this field: Auroville's (elder) sister organization, Sri Aurobindo Ashram in nearby Pondicherry. We decided to use a solar concentrator to produce this steam, and to install it in conjunction with a diesel-fired boiler in order to create a fully automatic hybrid system so that meals could be served in time irrespective of the weather conditions.

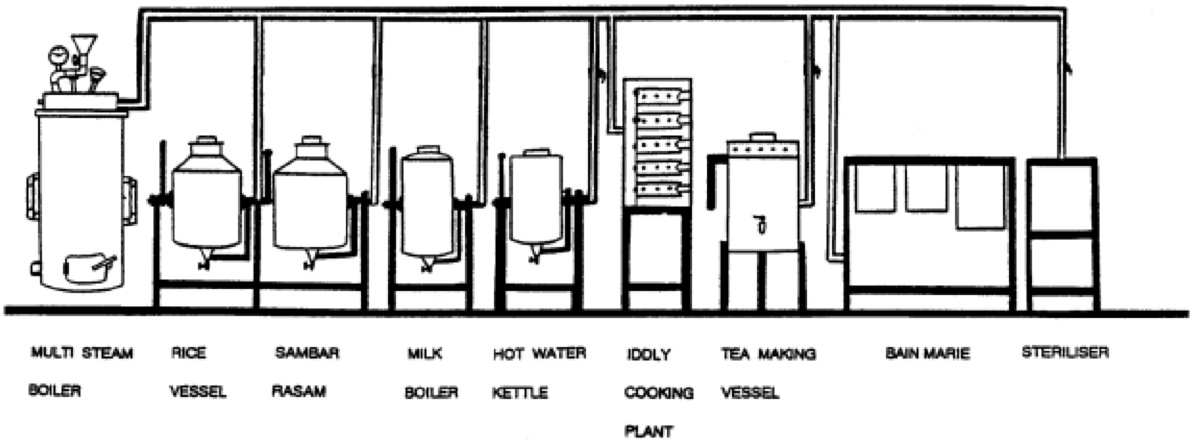
After studying the various types of concentrators, we opted in favor of a Fixed Spherical Concentrator (also known as a Solar Bowl). In the early eighties, four such concentrators had been built: a 20-meter diameter one in Texas (USA), a 10-meter diameter one in Marseilles (France), another 10-meter one in Haifa (Israel) and a smaller 3.5-meter diameter one in Auroville (India) by a member of our team. Information on Solar Bowls and other types of solar concentrators had been gathered since then; so we felt well informed to build a full scale Solar Bowl.

One of the conclusions of the American and French Solar Bowl projects was that Solar Bowls were well suited for developing countries. Solar Bowl technology is relatively simple and low cost and has the potential to use labor more intensively than capital. So, in the process of designing Auroville's Solar Bowl, replicability, cost-effectiveness and appropriateness to the developing country context were our main criteria in choosing among different technical options.

In December 1995, India's Ministry of Non-Conventional Energy Sources sanctioned Rs 15,00,000/- for the Auroville Solar Bowl project, and a first instalment was received in early 1996. This amount was later upgraded to Rs 20,00,000/- (twenty lakhs) and the project duration extended to 31st March 2000.

Sri N. Kannapan, Honorable Minister of State of Non-Conventional Energy Sources came to dedicate the Solar Bowl on 11th September 2001.

After operating the system for some time with the heat transfer fluid, it was decided for various reasons to scrap heat exchanger and hest storage tank and go for direct steam generation. This transformation has been successful and since then the system operates every day to our satisfaction.



F. 8 Typical steam cooking installation

F. 9 Steam cabinet for cooking rice and iddlys

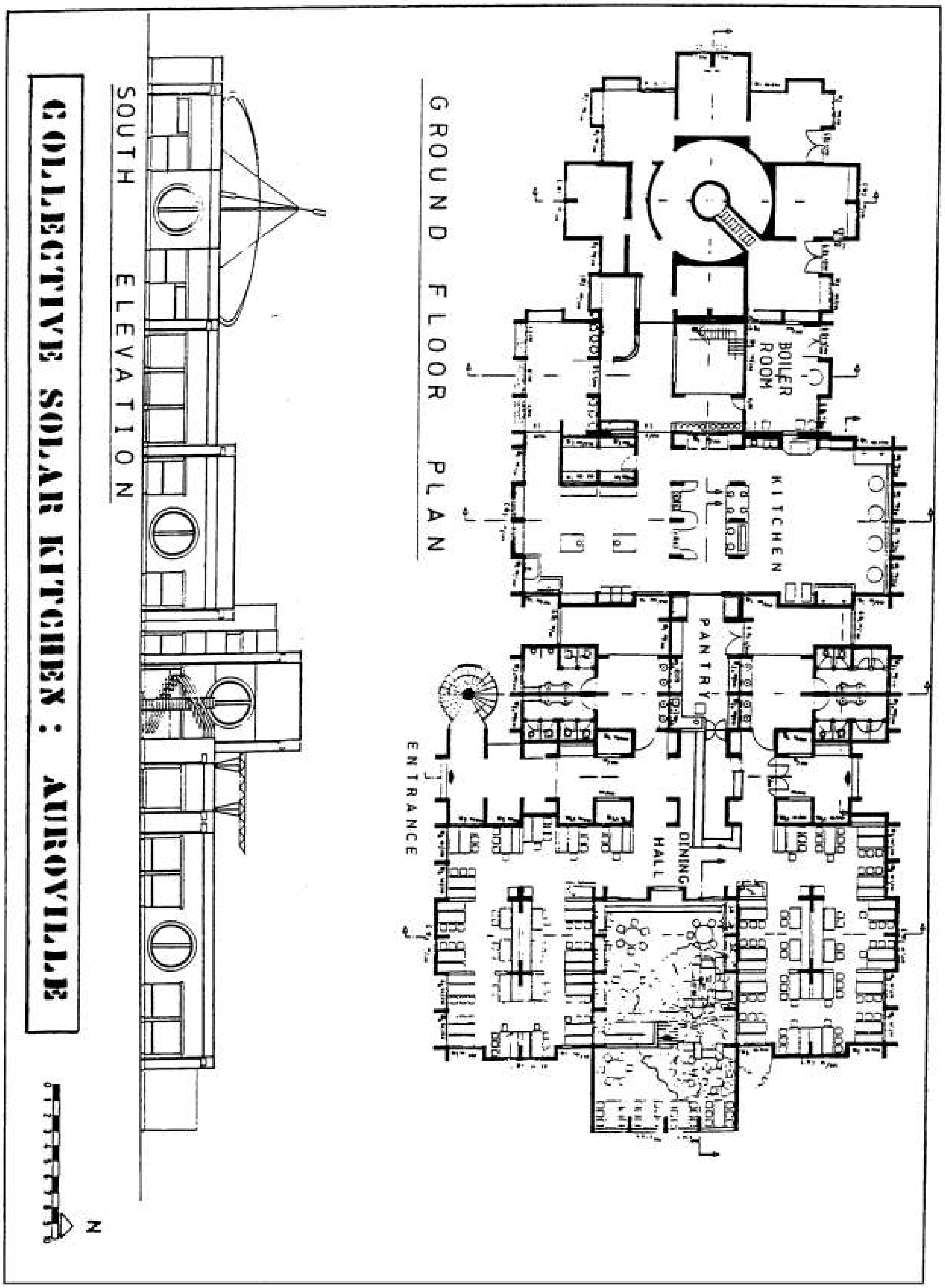


Fig. 4 Plan & South elevation of the Solar Kitchen

ACKNOWLEDGMENTS

To build in Auroville a Fixed Spherical Concentrator (Solar Bowl) and to put it to a practical use is an old idea. Implementing this idea was a collective endeavor.

Two resident-members of Sri Aurobindo Ashram planted the seeds of this project:

- **Shri Ved Prakash** started in 1969 to use steam to cook all the meals of the residents and guests of Sri Aurobindo Ashram. It was a first in India. Since then, Vedji and his team have continuously improved the system.
- **Dr. Chaman Lal Gupta,** a close associate of Auroville and Head of "Solagni" (the Solar Energy Research Unit of Sri Aurobindo Ashram), shared with his Aurovilian friends his belief in the potential of Solar Bowls.

Convinced by Dr Gupta's arguments:

- **Mr. John Harper**, an Aurovilian engineer, built in the early eighties at Auroville's "Centre Guest House" a small (3.5meter diameter) Solar Bowl for research purposes, with a grant from TERI (**Tata Energy Research Institute)**.
- **Mr. Jean Pougault,** another Aurovilian engineer went to the U.S. to study the 20 meter diameter Solar Bowl built by Texas Tech University, and then to France to discuss with Dr. Authier who had designed and built a 10 meter Bowl.
- **Mr. Joel Goodman**, an Aurovilian architect, spent many years investigating all the aspects of Solar Bowls. Thanks to a grant from the **National Endowment for the Arts** (U.S.A.), Joel published in 1993 a beautiful and inspiring monograph entitled: *"Solar* Concentrator Architectonics: Solar Bowl Architectonics and Interior Heliostats Architectonics*"*.

In 1990, while the Aurovilian architect **Ms. Suhasini Ayer** and I were building the Auroville Visitors' Centre, **Mr. Edward Giordano**, an Aurovilian, suggested we attach to this Centre's cafeteria a Solar Bowl to produce steam for cooking. Though we thought this particular kitchen was too small to be worthwhile, the idea of using a Solar Bowl for steam cooking remained in our minds. Using a Solar Bowl for steam cooking was really Ed's idea.

When in 1992, Suhasini and I decided to undertake the construction of a large community kitchen in Auroville, it had become the most natural thing to include a Solar Bowl in it. However, we would never have dared to take up such a project if the late **Dr. Ms. Sylvie Rousseau**, an Aurovilian with a Ph. D. in solar science, had not enthusiastically volunteered to take care of all scientific studies.

Dr. Bernard Authier and **Mr. Jean Debilly,** who had built a Solar Bowl in the early eighties in France, encouraged us to take up this project. They shared with our team their unique and invaluable experience, and as demonstrated by this report, their contribution proved to be crucial.

The construction of the Solar Bowl was linked inextricably with the Solar Kitchen it was meant to serve. Thus the design and construction of the Solar Kitchen was integral in providing momentum and purpose for the Solar Bowl project. Human and material resources had to be found to carry out both projects at the same time.

In terms of material resources, this Solar Bowl would not have been possible without a grant from India's **Ministry of Non-Conventional Energy Sources** (MNES) (Rs 20,00,000/-) and the matching funds generously contributed by several Aurovilians, Auroville business units and friends of Auroville.

In terms of human resources**, the core team was formed of Mr. John Harper,** the late **Dr. Sylvie Rousseau and myself** and also during the first phase of the project **Mr. Gilles Boulicot,** later replaced by **Mr. Andres Veski**. The contribution of many other Aurovilians – and friends – was crucial to the realization of specific parts of this project:

Building the Solar Kitchen, including the supporting structure of the Bowl:

- **Ms. Suhasini Ayer & Anita Gaur** (Indians) Architecture
- **Auroservice d'Auroville Trust** Structural design
- **Mr. S. Ramalingam** (Indian) Contractor

Solar engineering:

- **Dr. Sylvie Rousseau** (France) Solar design & calculations

Loop and controls of the loop

- **Mr. RangaRao** (Indian) Steam consultant based in Chennai
- **Mr. Patrick** (French) & **AV Water Service** Design and implementation

Ferrocement structure of the reflector

- **Mr. Steve Senesac** (American) Structural design
- **Mr. Gilles Boulicot** (French) Working drawings and implementation
- **Mr. Himal** (Indian) Rigid aluminum arm

Reflective surface

- **Mr. Jörg Zimmermann** (German) Study of the reflector
- **Mr. John Harper** (Canadian) Realization of the reflective surface

All steel & mechanical works (including tracking system)

- **Mr. Andres Veski** (Estonian) Design
- **Mr. Robi Trunz,** (Swiss) **& "Aureka"** Manufacturing

Tracking System (electronics and software)

- **Mr. Piero Cicionesi** (Italian) Computer software & system
- **Mr. Akash Heimlich** (American) Computer software
- **Mr. Nigel** (Indian) Electronic hardware

Control of the gear pump

- **Mr. Vladimir Ivanov** (Russian) Conception
- **and several other Aurovilians and students from India and abroad**

Mr. Jean-Claude, **Mr. Perumal, Mr.Valery, Mr. Boris, Mr. Elumalai and Mr. Segar,** the technicians operating the system at different point in time, helped assemble the whole system.

We all had the feeling of doing **the Mother**'s work and felt Her grace always present with us. To Her, and to all Her instruments in this collective endeavor, I express my deepest gratitude.

Auroville, April 2000

Gilles Guigan
Principal Project Investigator

Fig. 5 Inside the dining room of the Solar Kitchen

Fig. 6 The 3 Project investigators (right) with 3 friends

FOREWORD

This report documents the work done by our team since CSR received the grant from India's Ministry of Non-Conventional Energy Sources in February 1996 until today 2008.

When we started we knew almost nothing about steam and steam cooking; and we knew very little about Solar Systems in general and Solar Bowls in particular. We tried to include in this report all the information we had to learn as we progressed step by step with this project.

This report is written for the layperson. Are included in it considerations and tips one doesn't usually find in such documents and also justifications of our choices of technologies to assist those who could be interested to replicate it. Our aim being to ensure that potential users understand as much as possible the problems and options in such a project.

We would be very happy if this project and this report could inspire and help many other enterprising researchers to also try and solve their energy requirements using a Solar Bowl.

Auroville, May 2008

Gilles Guigan	John Harper
Principal Project Investigator	Engineer

2. STEAM COOKING

2.1. DESCRIPTION

In 1967, Sri Aurobindo Ashram at Pondicherry was the first in India to equip its Dining Room with steam cooking. It now provides three meals a day to 2,000 residents and guests; and on special occasions it provides three meals a day for up to 10,000 persons.

Using steam to cook in community-scale kitchens is now fairly common in India especially in areas where people's diet is rice-based (such as in the South). Most kitchens of large canteens, marriage halls, restaurants, hospitals and educational institutions are now cooking with steam. The equipment is now available off the shelf from a large number of manufacturers.

Steam cooking requires relatively low pressure and low temperature steam, which is normally produced by a conventional boiler. Depending on their type, these boilers are fired with wood, LPG, kerosene or diesel oil.

Four different types of containers can be used for steam cooking:

- Single jacketed vats (made of stainless steel) in which steam is directly injected into the vat holding rice, lentils, noodles or vegetables.
- Double-jacketed vats (made of stainless steel). Steam is made to condense between their two jackets. A steam-trap placed just after the vat prevents the steam from leaving the pot unless it has condensed into water. The hot water is then recycled after transiting in a "condensate tank”. Vegetables (soups, sambars, sabjis), lentils (dhal) and noodles are easy to cook in such vats. Milk and other beverages can also be heated up or boiled in such vats.
- Cabinets (made of stainless steel) are ideal for cooking either iddlys (a popular Tamil breakfast) or vegetables on trays, or rice in large cylindrical vessels that contain the rice and its cooking water. Steam is injected directly into the cabinet compartments.
- Large drums which are used to cook rice. Several cylindrical vessels containing rice and its cooking water are lowered into these drums, which are then closed with a heavy lid for heat containment.

Most of the food is cooked in single or double-jacketed vats. It is only the steam used in double-jacketed vats that is recycled; steam used in the three other types of containers literally evaporates.

Steam can also be used advantageously in kitchens to:

- Sterilize the dining room vessels.
- Keep food hot in a “bain-marie”.
- Produce hot water either by sending steam directly into a tank that is full of water, or by heating a coil that is immersed in a tank full of water.
- Provide steam or hot water to the kitchen’s laundry.

F. 10 Double-jacketed steam vat in cooking position

F. 11 Double-jacketed steam vat tilted to be emptied and cleaned

2.2. ADVANTAGES OVER CONVENTIONAL GAS COOKING

Steam cooking is healthy, easy to handle, fast, clean, economical, energy-efficient and environment friendly.

- Steam cooking is fast because it is a very efficient way to transfer heat: 250 liters of vegetables held in a large double jacketed stainless steel vat can be brought to boiling in less than 20 minutes. (Heat transfer is even more efficient in mild steel steam vats, but naturally these corrode).

- Food simply cannot burn while cooking with steam. Since the whole vessel is brought to a constant temperature of a little more than 100°C, no point reaches a higher temperature. With conventional systems, the part of the vessel that is above the flame can easily reach 300°C while other parts of the vessel remain comparatively cold. Steam cooking is healthy compared to conventional methods because the bottom of the pot does not reach high temperatures which usually diminish the nutritive value of the food cooked.

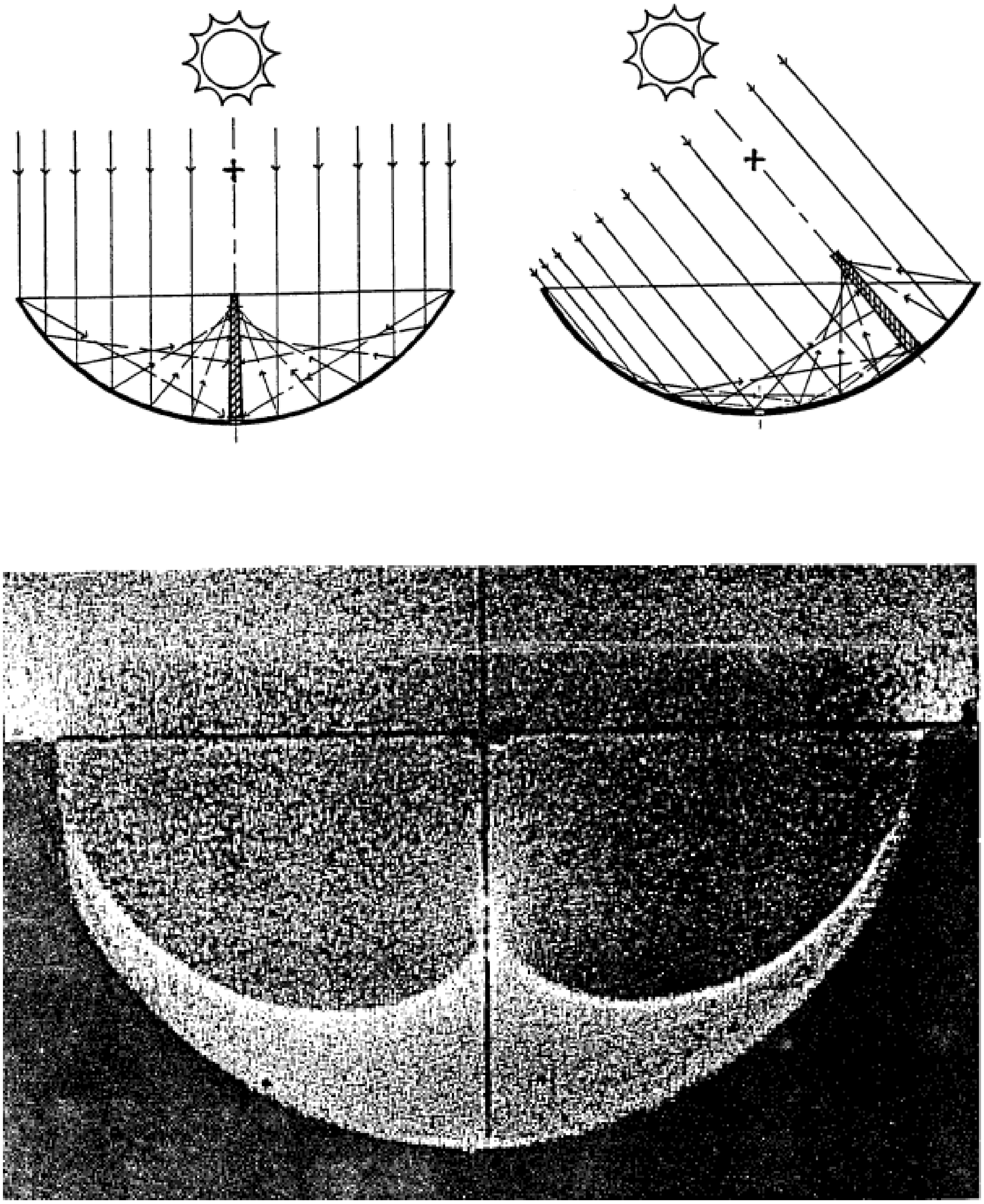
- As food cannot burn and thus stick to the bottom of the pots. The steam vats are never difficult to clean. Moreover, as the vats tilt along their axis, they can be cleaned easily using a hose.

- Steam cooking vats are very easy to empty since they tilt along the horizontal axis that serves as their support. Steam cooking vats are also very safe to empty. There is very little risk of burning oneself or spilling the soup on the floor since the load of the vessel always rests on its stand and tilting is very easy to control using a simple gear.

- Cooking with steam is clean and safe unlike cooking with conventional burners. Since there is no flame under the vessels, there is no risk of clothes catching fire, no fumes to pollute the air in the kitchen and no soot to soil the pots. Moreover, kitchens equipped for steam cooking are relatively cooler than conventional kitchens because the heat is not produced in the kitchen itself but in the boiler room.

- Steam cooking systems are more energy efficient than conventional burners, which heat only the bottom of the pot.

- Steam cooking can make use of free, environment friendly solar energy. A solar concentrator can produce steam relatively easily, especially since high pressure and high temperature are not required.



F. 12 Diagrams showing the reflection of the sunrays in a Solar Bowl

3. HOW TO PRODUCE STEAM WITH A SOLAR BOWL

Producing steam with a Solar Bowl requires a system with several components:

The **reflector** of a solar bowl is a fixed section of a sphere. Most bowls that have been built have an aperture angle of 120° and are tilted to compensate for the latitude at which they are located (at the equator, they would be horizontal).

A simple geometrical diagram shows that such concentrators have a linear focus that has the following characteristics:

- It remains always in line with the sun and the center of the sphere.
- Its bottom end touches the spherical surface.
- Its length is about half that of the radius of the sphere.

The **receiver** of such a concentrator is cylindrical and bolted at the end of a swinging arm with counterweight. The whole thing is suspended from a double-axes articulation placed at the center of the sphere. This central articulation is bolted in place on top of a tilted mast held in place by two steel guys. In most cases the base of this mast rests on a stand located within the bowl, but off its center in such a way that the swinging arm never comes within a meter from it.

A computerized tracking system keeps the receiver in the moving focus of the bowl. This means that the tracking system is designed to keep the swinging arm (and thus the receiver) in line with the sun during the hours (approximately eight a day) when the Solar Bowl can effectively harvest heat.

The system needs to be hybridized because Auroville's Solar Kitchen is designed to serve food in time every single day of the year. The solar system is thus coupled with a **conventional boiler** to ensure an adequate production of steam everyday, irrespectively of the meteorological conditions. It must be noted that very few industrialists would be interested to have a non-hybrid system that would not work at all on cloudy days and thus keep their suppliers, employees and customers waiting for clouds to clear. Almost all potential users are only interested in substituting as much conventional fuel as possible with solar energy.

With regard to steam production, there were **three options** in front of us. In all cases a fluid is pumped through the receiver where it gets heated up to produce steam either directly in the receiver itself, or indirectly in a heat exchanger. The three options are:

- A system in which <u>water is turned into steam directly in the receiver</u>.
  This system has the advantage of simplicity – provided one can control it.
- A system in which <u>pressurized water</u> circulates in a primary loop and steam is produced in a heat exchanger.
- A system in which a <u>heat transfer fluid</u> circulates in a primary loop and steam is produced in a heat exchanger. This option has the advantage of offering the possibility to store heat in the form of hot heat transfer fluid.

Originally our intention was to opt for what seemed to be the simplest option: direct steam generation. However as we progressed with the project, we were convinced to go for the heat transfer fluid option – this for three reasons: 1) we liked the idea of storing heat at lunch time (when energy harvesting is the highest) when the staff is busy doing other things than cooking. 2) We were told that by having water/steam at two bars only in the receiver, there was a risk of film boiling which would result in a very poor heat transfer. 3) we were discouraged by solar scientists who had worked with such systems and told us that direct steam generation was difficult to control.

We did succeed in making the system work with the heat transfer fluid and collect data of the energy effectively harvested, but eventually we decided to revert to our original idea and go for direct steam production and it has been a success. The Auroville Solar Bowl has become a working tool saving a substantial amount of energy (diesel fuel) every month.

4. CRITICAL NON-TECHNICAL CONSIDERATIONS

4.1. COOKING SCHEDULE

Two constraints oblige the users of solar thermal energy to use this energy as soon as it is produced; or at least very soon after:

- Solar thermal energy systems require a significant investment; therefore, the energy they produce should not be wasted. If the energy produced by such systems is not fully used, their economical viability is in jeopardy. Therefore such systems are normally not over-dimensioned to produce a surplus of energy in order to be sure to always supply energy as and when required.
- Energy storage, and in particular storing heat, is always a costly and inefficient affair, it should thus be limited to a minimum. Our heat storage tank was dimensioned to store approximately one hour of peak production.

Let us note that Solar-PV and Wind systems face the same constraints as Solar Thermal systems; they produce energy whenever the meteorological conditions are favorable, and not necessarily when the users want it. Some conventional systems (nuclear energy, hydropower on rivers) also face similar constraints as the quantity of energy they produce simply cannot be adjusted to the need – at least not quickly.

If these energy-producing systems are generating electricity; wastage due to storage can be avoided by feeding the power directly to a grid in which more flexible power plants (such as thermal power plants) are also included. However, in the case of stand alone systems (and systems producing heat for process are always stand alone), one has to find ways to use most of this energy as soon as it is produced**. In solar thermal systems, heat has to be used as soon as produced, or at least very soon after. If this is not possible, the economic viability of the system will be jeopardized.**

In our system, the quantity of solar steam utilized will increase if it can be utilized just as and when produced. The heat storage tank does give a certain time lag (it was dimensioned for 1 hour of peak production), but once the tank is full all the solar steam produced is wasted if not used. As sunshine is spread unevenly over some 12 hours, cooking has to be spread over at least 6 hours. This means that **the cooking team has to be requested to follow a specially adapted cooking schedule** in order to cook as much as possible when solar steam is available. For example, actual cooking should take place from 9.30 AM to 12.30 AM for lunch and from 1.30 PM to 4 PM for dinner.

The cooking team may be reluctant to observe such a cooking schedule as cooks naturally prefer to cook as and when convenient to them. This would however mean that the conventional boiler would always be preferred to the solar boiler, even on sunny days, and that the solar steam would go waste. If such were the case, our solar bowl wouldn't prove itself viable; it would become a nice and unused luxury ornament on the roof! Of course, this would be against our final aim, which is to prove with exploitation data that a solar bowl can be technically and economically viable for such an application.

It is absolutely essential to insist that this specially adapted cooking schedule be followed. Otherwise, there would be very little fuel saving and the system wouldn't be economically viable. As is often the case, the problem is neither technical nor financial; it is a question of

human/social behavior. The users have to become more energy conscious and adapt to nature. Unfortunately, this is much easier said than done.
In order to help the cooking team to be energy conscious, the following instruments may be installed inside the kitchen, near the steam cooking containers:

- A thermometer indicator informing the cooks of the temperature inside the heat storage tank so that they know whether they should try to use more steam, or –if possible – postpone cooking some items.
- A witness lamp indicating that the conventional boiler is "on", which means: "If possible postpone your cooking till the sun produces more steam".

4.2. SAFETY MEASURES

Solar bowls using a heat transfer fluid can be dangerous because of the heat they generate, and because there will be no obvious visual warning of this danger:

- By stepping inside the bowl at daytime one can get roasted if one comes within two meters of the focus – where the receiver should be. As a safety measure, this bowl has been purposely built on top of a terrace, which is only accessible by staircases whose access are controlled by lockable doors. In addition to this, written warnings may be placed well in view both in the local language and in English.
- The receiver, the pipe lines and the heat storage tank are very hot (250°C and possibly more), however these components are suitably heat insulated.
- There is always a risk of leakage of very hot heat transfer fluid that could burn people or even catch fire (this, however, is unlikely. See further in the chapter pertaining to heat transfer fluids). All safety measures need to be taken to prevent such leakage.

There is however no risk of explosion as there is only little pressure in both parts of the loop (primary 1 bar and secondary 2-3 bars). Even the conventional boiler is safe, as we have purposely opted for a "non-IBR boiler" – meaning that its specifications are such that it is not subject to the stringent provisions of the "Indian Boilers Regulation Act".

There is however a risk that the coil of the heat exchanger would leak/break and steam be released within the very hot heat transfer fluid. This would create a major problem.

There is also always the possibility of a rupture in the pipe line filled with hot heat transfer fluid – especially in the receiver. We haven't found as yet a good solution to prevent the loss of heat transfer fluid and the danger attached to it.

In addition to the danger posed to people, there is a risk of damage to the equipment due to excess heat in the receiver or due to excess wind. Measures taken against both risks are explained in the chapter pertaining to the tracking system.

F. 13 Standing in the Bowl within reasonable distance from the focus
(Photo taken with a 'fish-eye' lens)

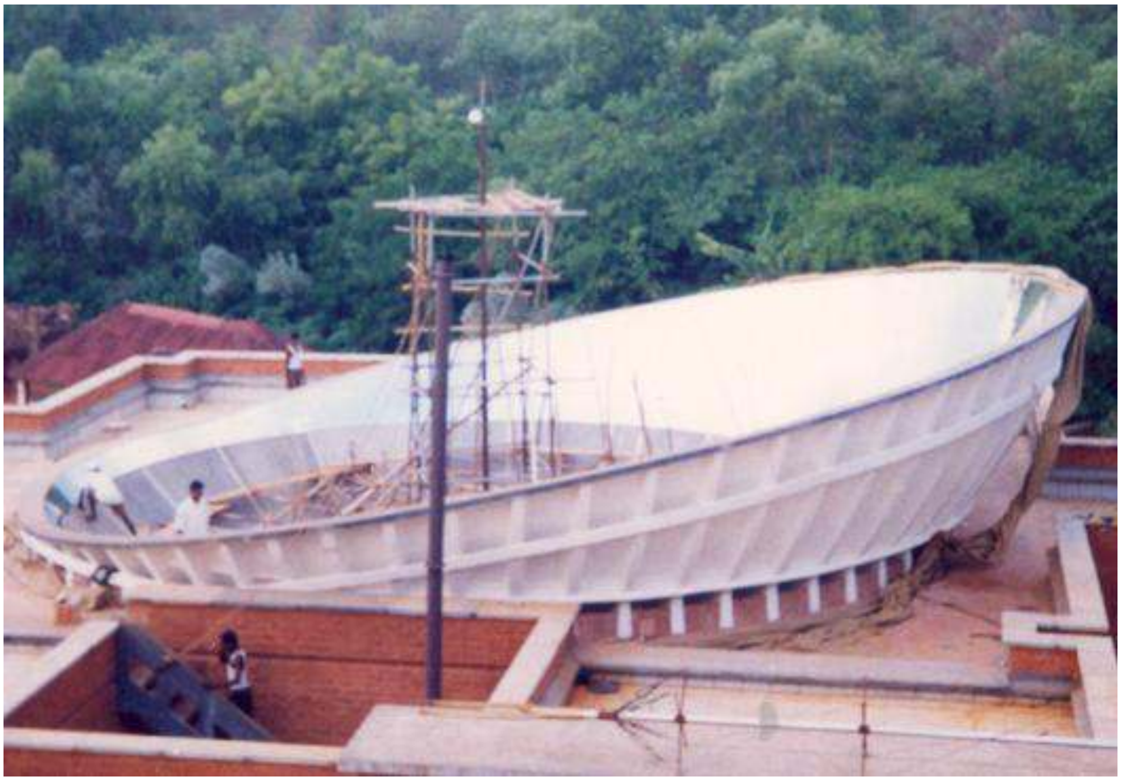


Fig. 14 Solar bowl seen from the East
(tilted by 12° towards the South)

5. REFLECTOR (Fixed spherical)

5.1. TILT TOWARDS THE SOUTH, APERTURE ANGLE & TYPE OF FACETS

We had several reasons to integrate this solar bowl in the roof of the Solar Kitchen:

- Rainwater falling on the bowl can be drained by gravity.
- The space below the bowl can be made usable.
- The access to the space surrounding the bowl can be effectively restricted, which is essential for the safety of people and to protect the mirrors from damage.

The solar bowl is tilted towards the South by 12° to compensate for its latitude - even though other experiments have shown that this tilt is not absolutely necessary in tropical areas.
Actually, the main facade of the Solar Kitchen is almost oriented East-West but not exactly (by 12.35° approximately), it was decided for esthetical reasons to take as axis for this tilt the longitudinal axis of the building and not the exact geographical East-West axis.

We opted for an aperture angle of 120°. Almost all other existing bowls used the same angle since a smaller angle would reduce the sun ray collection area while a larger one creates too much shadow in the early morning and late afternoon.

We decided not to use any "vizor" (additional mobile element of the spherical mirror the PERICLES had experimented with to try and improve the efficiency in the early morning and late in the day).

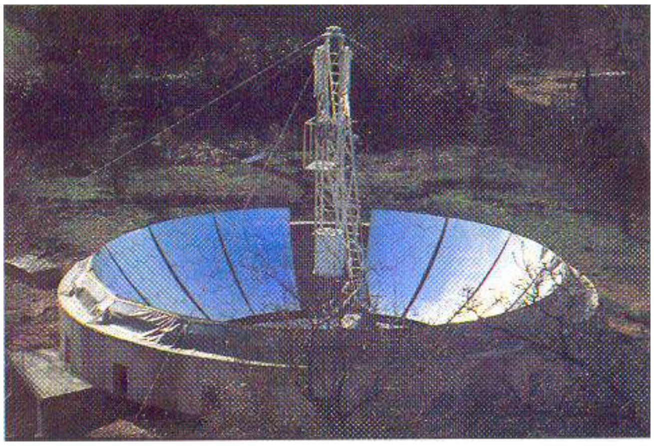
To create a spherical mirror, we decided not to use facets of spherical mirrors, but smaller facets of flat mirrors. This much cheaper option was already the solution adopted for Auroville's Mini Solar Bowl built in the early eighties.

The American, Israeli and French bowls, also constructed in the early eighties, used specially manufactured curved mirrors mounted on steel frames. In the case of the French bowl, this steel structure was resting on a RCC structure.

Curved mirrors are obviously the ideal solution from an optical point of view; and it should be possible to find a way to fix them on a masonry or rammed earth structural shell. Unfortunately spherical mirrors are presently too expensive, as glass companies have to charge a lot to produce them in such a small quantity.

Though we did not choose the solution of spherical facets, this option should not be forgotten for future bowls if ever the cost of spherical mirrors drops, or if ever one could start producing solar bowls on a small scale. "Hindusthan Safety Glass Ltd." from Calcutta made for us a sample of a hexagonal mirrors (side 35cm); but its quality was not good enough for it to be put to use.

MINI SOLAR BOWL
Auroville, India
Operational in 1982
Diameter: 3.5 meters
Aperture angle: 120°
Inclination: 12° South[1]
Built by: John Harper, Auroville Alternative Technology Group



MINI PERICLES
First built in Marseilles France then rebuilt in Recife, Brazil
Operational in 1980
Diameter: 10 meters
Aperture angle: 120°
No inclination[2], but "vizors"
Built by Prof. Bernard Authier, CNRS (Centre National de la Recherche Scientifique)

Stationary spherical solar concentrator with tracking absorber

Haifa, Israel[3]

Operational in 1979

Diameter: 10 meters

Built by Faculty of Mechanical Engineering, Technion

Israel Institute of Technology,

ADVS (Analog Design Verification System)
Crosbyton, Texas, USA
Operational in 1980
Diameter: 20 meters
Aperture angle: 120°
Inclination: 15° South[4]
Built by: Texas Technical University, Sponsored by US DOE

[1] Auroville's latitude is 12º North.
[2] Recife's latitude is 9º South.
[3] Haifa's latitude is 32º North.
[4] Crosbyton's latitude must be 32º North .

5.2. SIZING OF THE REFLECTOR

The size of the reflector depends on the estimated energy requirement and on the estimated overall thermal efficiency of the system.

5.2.a. Estimated energy requirement of Auroville's Solar Kitchen

As per the data given to us by the management of the Dining Room of Sri Aurobindo Ashram, a regular South Indian meal consists of 3 dishes (rice, lentils and vegetables) that are all cooked separately. The experience of other steam kitchens is that:

To cook 1 dish for 10 people:	1 kg of steam is required.
To cook 1 meal (3 dishes) for 10 people:	3 kg of steam are required.
To cook 1 meal for 1,000 people:	300 kg of steam are required.
To cook 2 meals a day for 1,000 people:	600 kg of steam are required.

We had two reasons not to include the energy needed to prepare the breakfast:

1) We expect that very few breakfasts will be prepared/served at the Solar Kitchen,
2) At the time breakfast needs to be prepared, the sun will still be too low on the horizon to be useful.

To heat up 600kg of water from 25°C to 100°C, and then turn it into steam, the energy required is: 600 (75 + 539) = 368,400kcal; or 368,400 x 0.001161 = 427kWh

Energy requirement: 600kg of steam/day, or 430kWh/day

5.2.b. Estimated overall thermal efficiency of the system

The thermal efficiency of the solar bowls that have already been built and studied made it possible to evaluate the efficiency of the Auroville bowl. As these other bowls are of different size and were built in very different latitude and climatic zones, we had to make a correlation to compare their efficiency:

We considered a reference solar bowl of 15 meter diameter (aperture area $=(\pi \times 15^2)/4 = 176.62m^2$) exposed to the amount of solar radiation that prevails in the Auroville area (roughly $1kW/m^2$ and a mean average daily global radiation of $5.5kWh/day/m^2$).

In such conditions, the average daily output produced by the various bowls would be:

• Crosbyton Bowl	(1980, USA)	470kWh/day (thermal)
• PERICLES Bowl	(1980. France)	477kWh/day
• Auroville Mini Bowl	(1982, India)	419kWh/day

We do not have any data for the Israeli bowl.

The total global radiation received per day by this reference bowl is ($176.62m^2$ x $5.5kWh/m^2$) = 971.4kWh; therefore, the thermal efficiency of the above mentioned Solar Bowls varies between 43 and 49%. Taking 47% as a medium value, implies that a reference bowl of 15meter diameter located in the Auroville area would have a thermal output of (47% x 971.4kWh/day) = 456.6kWh/day.

Supporting structure of the reflector

Hole below the bowl to retrieve the receiver for maintenance operations

(Note the staircase cum ramp)

5.2.c. Diameter, and other geometrical characteristics of the reflector

As the energy requirement of Auroville's Solar Kitchen is of 600kg of steam/day (that is 430kWh/day), **our solar bowl needs to have an aperture diameter of 15 meters.**

Having made the following design choices:

- Aperture angle : 120°
- Tilt towards the South : 12°
- Aperture diameter of the bowl : 15.00m

The following can then be calculated:

- Radius of the sphere : 8.66m = (7.5/sin60° = 7.5/0.866)
- Surface of the sphere (to be lined with mirrors): 235.50m² = (π x 8.66²)
- Aperture area of the collector : 176.62m² = (π x 15²/4)

5.3. BUILDING THE STRUCTURE OF THE REFLECTOR

5.3.a. Supporting structure of the reflector

The ferrocement section of a sphere rests entirely on three circular Reinforced Cement Concrete (RCC) beams whose three centres are all on a vertical line that passes through the centre of the sphere. The first and second (starting from the center) of these RCC beams are supported by two cylindrical masonry walls. The third one was cast together with the RCC slab of the terrace - that itself rests on a (5meter x 5meter) grid of masonry walls that are all perpendicular to each other.

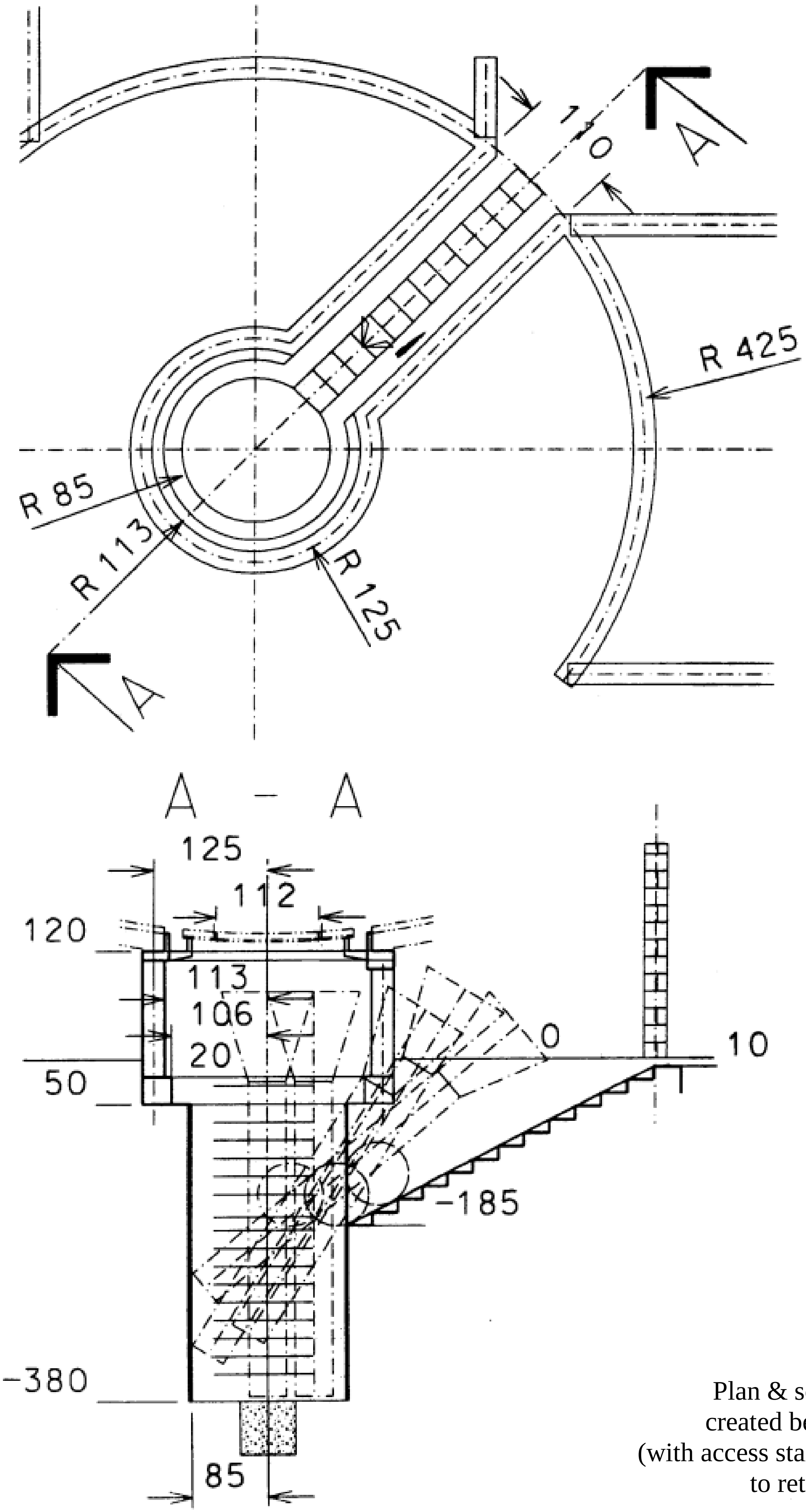
"Masonry walls" here are made of cement stabilized Compressed Earth Blocks. The building was built entirely with such blocks that were produced on site using earth extracted on the spot, mixed with 5% cement and then compressed in a manual press (a technique CSR has specialized in). These walls could however have been built with some other building material, such as fired bricks.

5.3.b. Hole to retrieve the receiver for maintenance operations

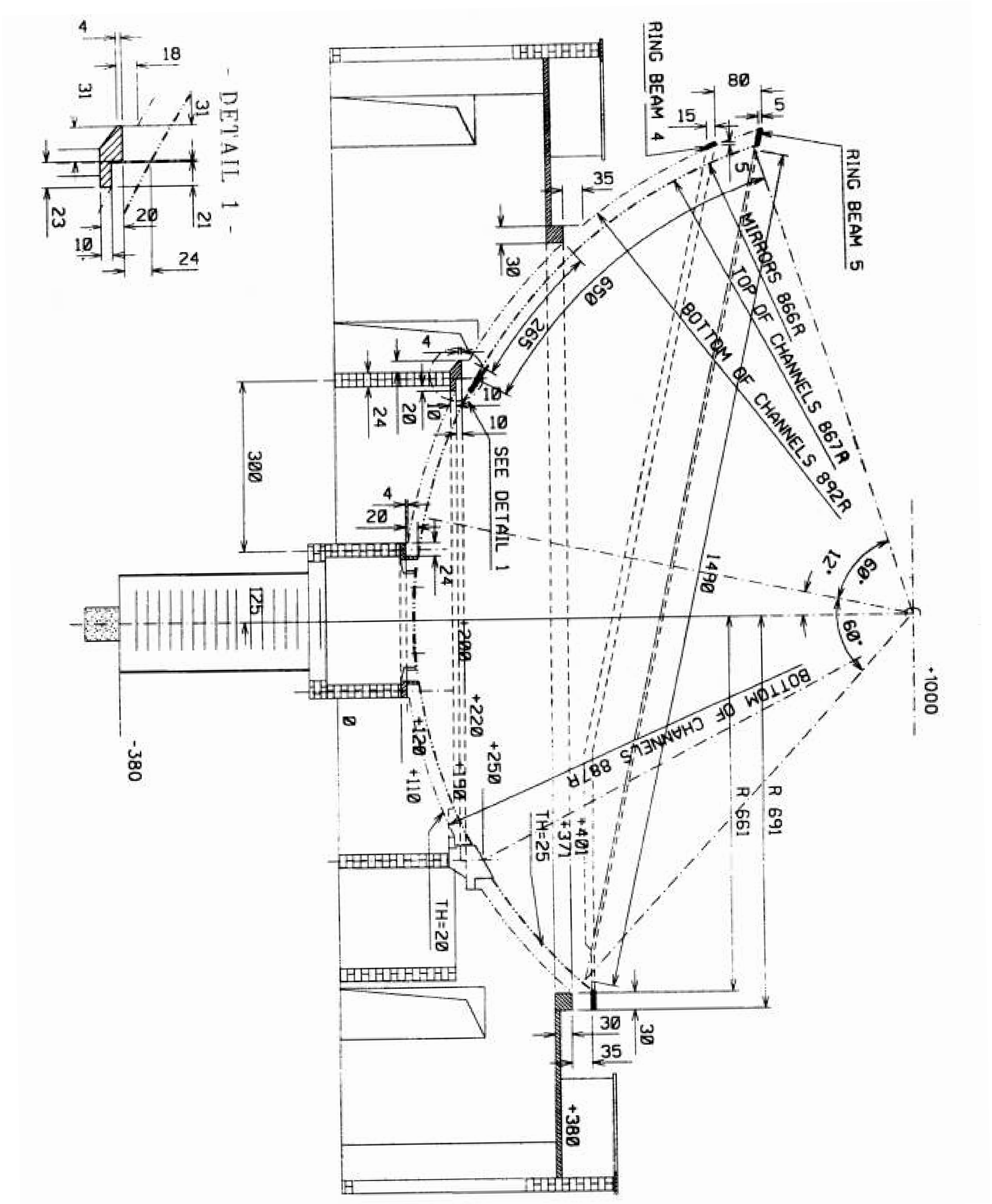
The receiver will need to be regularly maintained, and on occasion modified, repaired, and possibly sent to a workshop.

Performing these operations (at night) in the middle of the bowl would be difficult for the workers and would risk damaging the mirrors. It was therefore decided to:

1) Design the swinging arm such that the receiver can be easily lowered vertically.
2) Provide a circular trap door in the lowest part of the reflector.
3) Dig a 4.5m-deep hole below the trap door; that is within the first cylindrical wall.
4) Provide an easy access to this hole in the basement from the technical room on the ground floor.



Plan & section of the hole
created below the reflector
(with access staircase cum ramp)
to retrieve the receiver



North-South section of the Reflector
(Note below the bowl the hole to retrieve the receiver)

5.3.c. Structure of the reflector

Since we planned to create a spherical mirror out of small facets of flat mirrors (see paragraph 5.1.), we needed to create a structural spherical surface on which they could be glued. We considered masonry to be the simplest solution to create such a surface.

To make a bowl out of masonry, there are mainly five solutions:

- Build a cylindrical masonry wall; fill it with rammed earth - or broken bricks mixed with lime - to give it a spherical shape; and then, plaster it into a perfect spherical shape. This is probably the cheapest method and it was used for the first Auroville bowl which was small (3.5m diameter). But for this new bowl (15m diameter), we considered more suitable to integrate it in the terrace of a building. Of course the simplest method is to dig a hole in the earth in the shape of a sphere, and plaster it. But evacuating the rainwater becomes a problem.

- Build a spherical cap in RCC. However this is a cost-prohibitive proposal because it is very costly to make a spherical shuttering.

- Build in situ a ferrocement shell of even thickness. This does not seem complicated to do in theory, however, considering the large size of this structure we thought that it could be rather difficult to make a shell that would be cheap enough (less than 5 cm thick). It would also be difficult to first create a reasonably accurate sphere using several layers of mesh and then plaster this structure without deforming the sphere.

- Build in situ a ferrocement shell with ribs (steel trusses) made of “Tor” steel. We thought this could be cheap and feasible to make, but it would not be easily replicable by non-specialists in ferrocement.

- Build a shell made of prefabricated ferrocement elements. The Auroville Building Centre (AV-BC, one of the units of CSR) being one of India’s leading experts in this cost effective and easily transferable technology, we opted for this solution.

Auroville’s 15meter-diameter bowl is thus made of 96 prefabricated ferrocement elements which were made just like the very popular and cost effective ferrocement roof channels, except that they are curved and tapered.

Moulds of two different sizes were made in masonry:

- A small mould to make 32 small elements that are all the same and which once in place radiate around a large hole (2m diameter) that is at the lowest part of the sphere.
- Two larger moulds to make 64 elements that are both wider and longer than the first ones. Once in place, these radiate around the circle formed by the outer edge of the first set of channels. Each one of these larger elements has a different length in order to create the 12° tilt towards the South.

To obtain the desired thickness of standard ferrocement roof channels one uses a rigid template. It was not possible to use in this particular case as the section varies. Therefore, to first make the moulds and then to maintain the desired thickness, the 3 moulds were made next to the base of one of the towers of the building. We used as template a non-extensible rod that hung from a steel hook cantilevered off the tower on a temporary steel structure. In order to take into consideration the thickness of the plaster, the length of this rod was a few centimeters longer than the radius of the hemisphere.

Masons at work on two of the three moulds

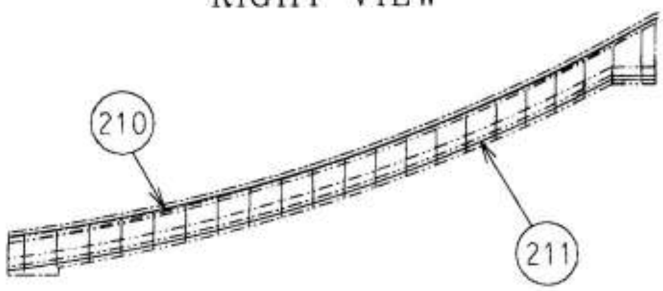
(Note the steel structure which cantilevers from the side of the tower to hold the steel rods used to obtain the required thickness of the prefabricated element)

Preparation of the steel reinforcement for the prefabricated elements

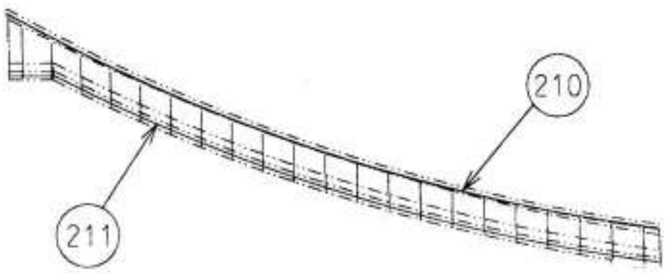
(Note the longitudinal steel rods, the stirrups made of steel wire and the chicken mesh)

2 of the three moulds on which the prefabricated elements were made

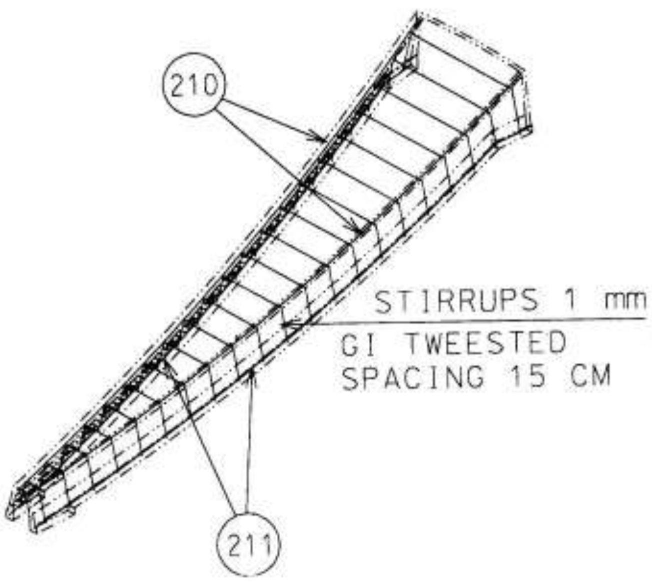
RIGHT VIEW



LEFT VIEW



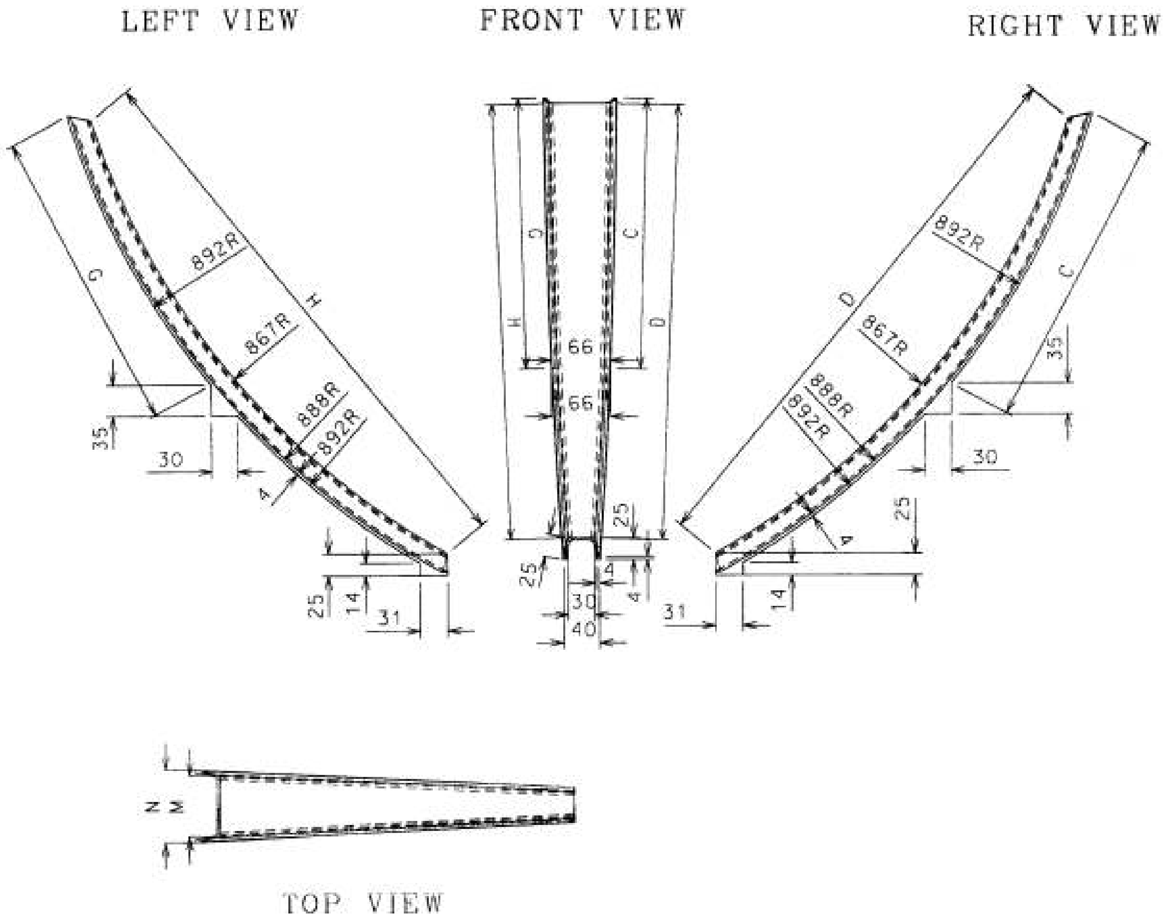
PERSPECTIVE



Plans of the (32) small prefabricated ferrocement elements

Small prefab. ferrocement elements being cured using coir dust

Large prefabricated ferrocement elements being cured

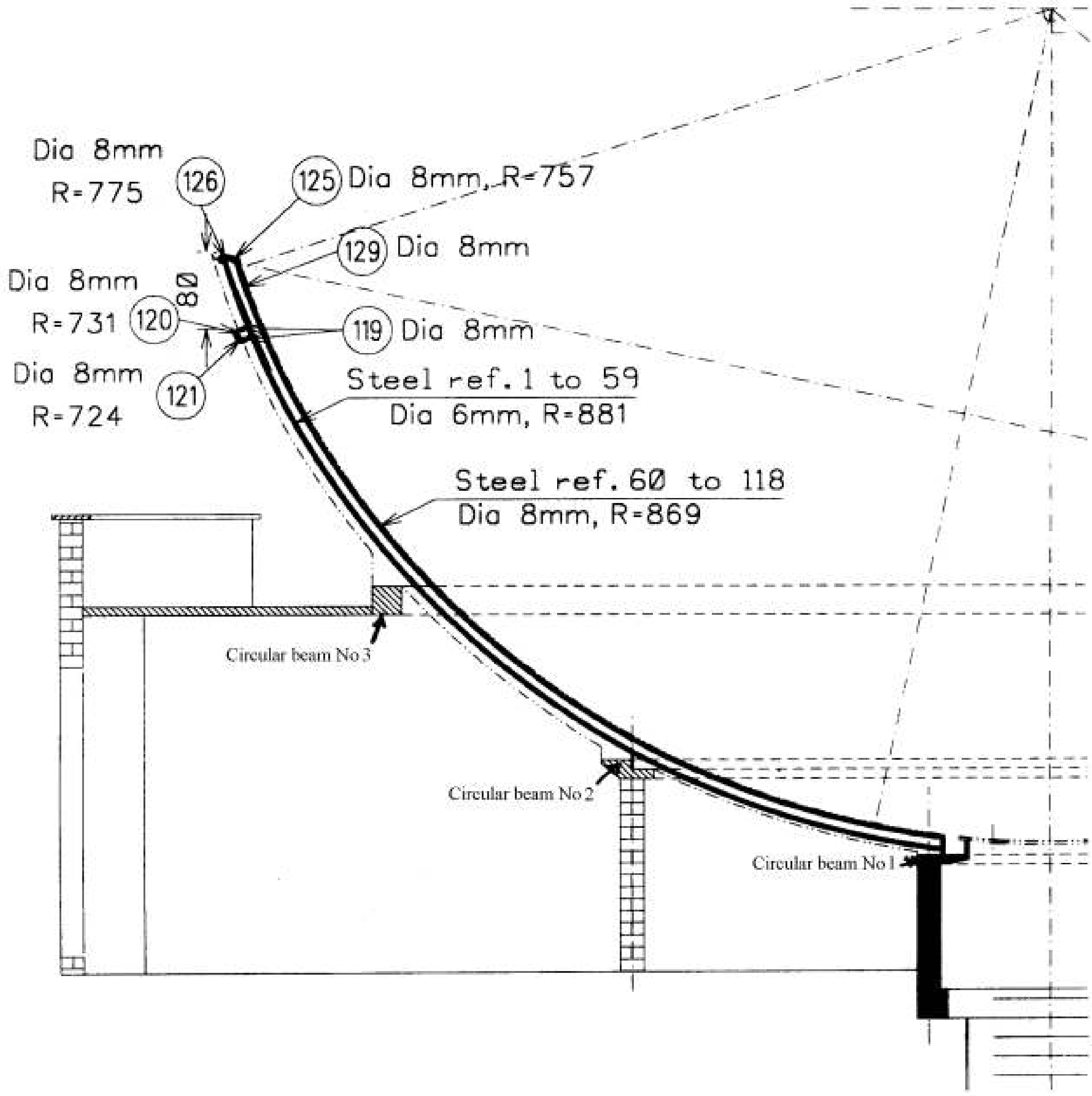


Typical plans of one of the 64 large prefab. ferrocement elements

Many of the large channels are in place while only one of the small ones can be seen resting on the first and second beams

One end of the 32 prefabricated elements of the first row of elements rests on the first and their other end rests on the second circular RCC beams.

The second row of 64 prefabricated elements rests on the second and third circular RCC beams. All 64 elements extend beyond the third RCC beam; some by less than one meter; and others by as much as three meters.

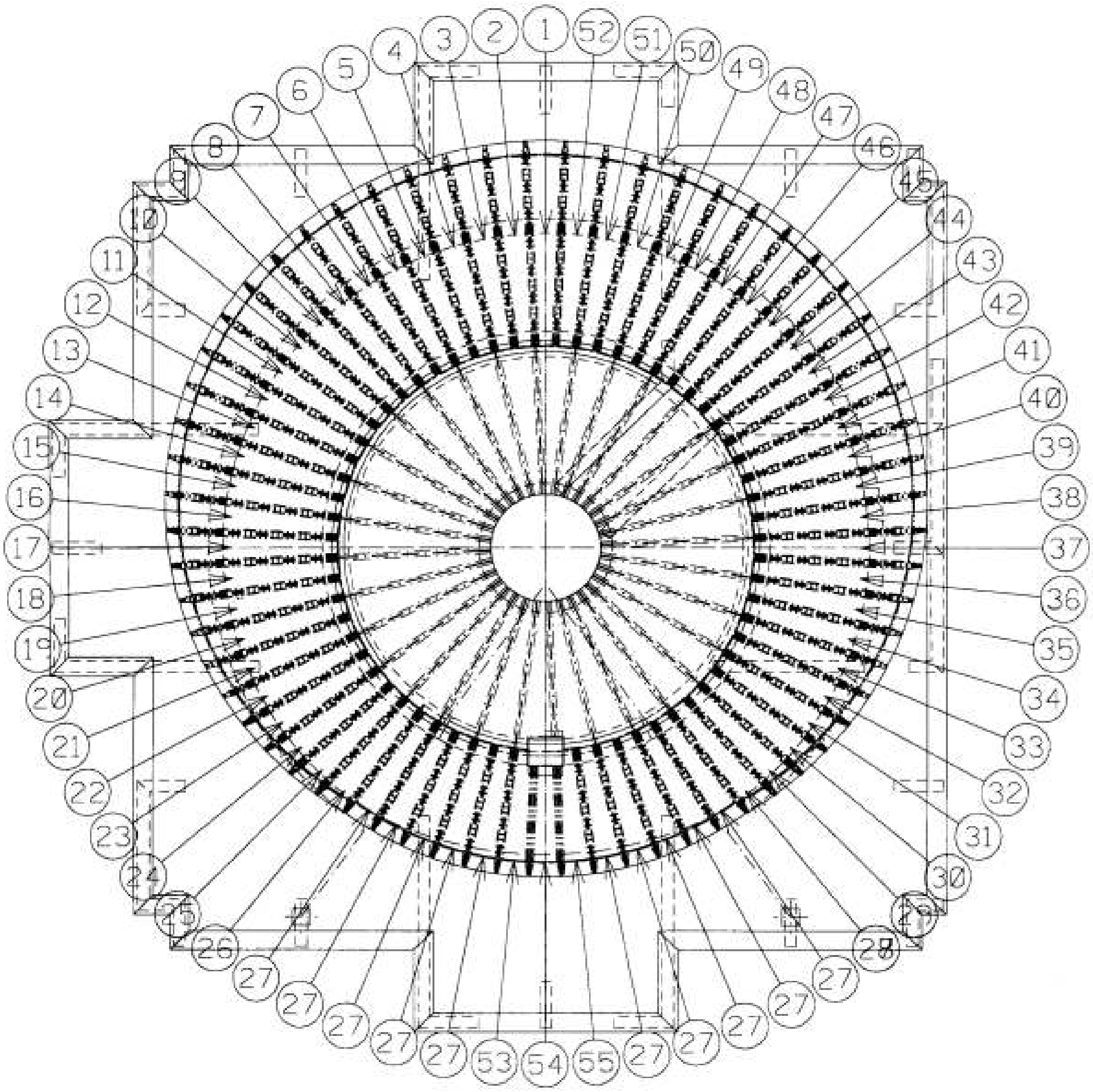


Section of the reflector
(consisting of prefabricated elements)

To place correctly these 96 elements, a temporary mast was erected at the center of the Bowl. This mast is held in place by two sets of three guy-wires each. A pivot was fitted on top of the mast (actually a little below the point where the top set of three guy-wires are attached). From this pivot (that is exactly at the center of the hemisphere), a non-extensible cable was stretched in order to check that the 96 elements were all placed at the correct distance from this center. Placing exactly each element proved to be a more tedious task than expected.

The 96 prefabricated ferrocement elements before they were joined

Base-plate of the mast



Plan of the spherical reflector

indicating the reference number of the 64 large prefabricated elements
only 10 of them (ref. 27) are identical; all others are different from each other

In order to keep the elements solidly together, two strong ferrocement beams were cast in situ at the extremity of these 64 elements, and also approximately halfway between the third circular RCC beam and their extremity.

Two ferrocement beams tie the 64 prefab elements together

Bowl seen from below

Concrete (cement:sand:pebbles = 1:2:3) was poured in the gap left between the prefabricated elements once all the 96 (32 + 64) prefabricated elements were put into place and braced together with the two circular ferrocement beams.

To cover the 2m diameter hole at the bottom of the bowl, one more element has been prefabricated in ferrocement. It still leaves a hole of 80cm diameter that is sufficient to let the receiver pass through it. A last element made also of ferrocement covers this smaller hole. It will be moved each time the receiver is lowered into the hole.

Hole at the bottom of the reflector (note the gutter)

Ferrocement element to reduce the size of the hole

5.4. MAKING 3 TEST SURFACES AND A VERY RIGID ALUMINUM ARM

We devised successively three different test surfaces in masonry to find answers to three problems:

- How accurately spherical can the surface be made?
- What type of adhesive for the mirrors is the most suitable?
- What shape and size of mirrors would give an acceptable approximation of the sphere? How accurately can we focus the mirrors, and how can we protect them from corrosion?

The following three test surfaces were made. On top of the parapet of the building, we erected a custom-made structure, ending with a pivot placed at the virtual center of the spherical test surfaces.

The first test surface was a prefabricated circular element made of ferrocement, and cast on a mold that was accurately spherical as it was made using a circular template. This element was adjusted in place with the help of a cable tied at one end on the pivot. We soon realized that this was not accurate enough.

Test surface No.1, the aluminum arm and its fixed pivot

To obtain more accurate second & third test surfaces, we first made a very rigid swinging arm (a radius of the sphere) out of aluminum profiles rigidified with cables and attached it to the pivot. At its lower end, we attached a kind of trowel that had been ground on the spot to give it a perfectly circular shape (with the same radius as the sphere we wanted).

For the second test surface we built four masonry walls and filled this enclosure with earth and rubble. We then made a fine plaster on top of this rubble using the aluminum arm to obtain a surface as accurately spherical as possible.

For the third test surface, we used elements we had manufactured for the structure of the reflector, which we had to discard as they were damaged while de-molding. These elements rested on two masonry walls. We joined these prefabricated elements and treated their surface in the same manner as we later did for the reflector.

A view of test surfaces 2 & 3 is shown on page 54.

5.5. PLASTERING THE STRUCTURE TO OBTAIN A PERFECT SPHERICAL SHAPE

5.5.a. Making a special pointing device.

We designed and manufactured a special pointing device to serve two different purposes:

1. To measure the accuracy of the curvature of the spherical masonry surface.
2. To orient properly each of the flat mirror facets.

This special pointing device holds a laser pointer and a target. It was designed in such a way that, if placed at the center of an ideal spherical mirror, the laser beam would always hit the center of the target after reflecting on the spherical surface:

- The entire pointing device pivots around two perpendicular axes intersecting at the center of the sphere.
- The center of the laser pointer and the center of the target are exactly symmetrical to each other in relation to the center of the sphere; and their distance to this center is approximately 25cm.
- The laser pointer is of a cheap type used in conferences and slide-shows.
- The target is made of a white translucent plastic disc (25cm diameter) on which concentric circles are drawn. The radiuses of these concentric circles are such that each circle represents a deviation of one arc-minute from the ideal spherical surface. In this way, it was very easy to read the deviation of the mirror facet.

Special pointing device

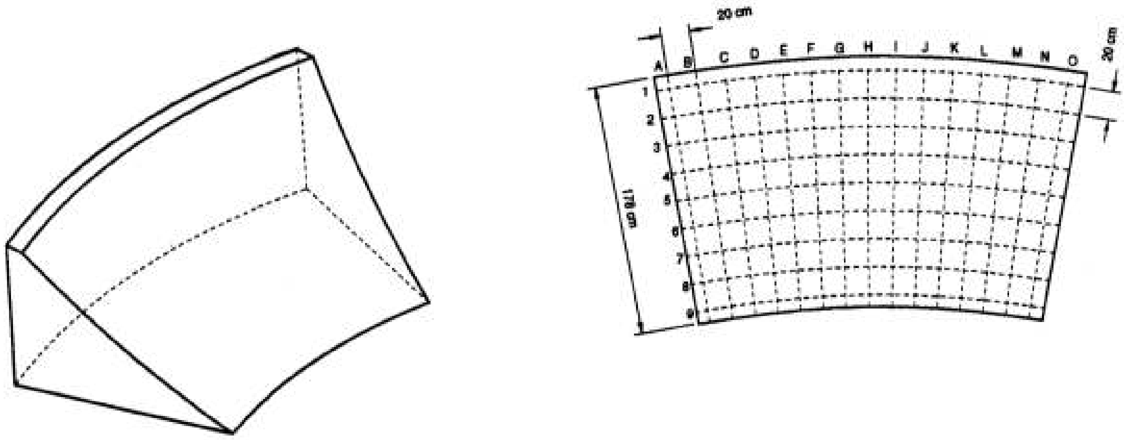
5.5.b. Surface accuracy of the second test surface

After curing the second test surface, we set about to determine the accuracy of its curvature using our pointing device:

- We marked the spherical masonry test surface with a grid having fifteen vertical columns and nine horizontal rows.
- We successively placed at each grid point a small triangular mirror.
- We pointed the laser beam of our special pointing device to the center of the triangular mirror.
- We measured how much off-center the reflected laser beam was on the target, simply by reading where the reflected laser beam hit the target. In this case, the deviation of the mirror facet is equal to the deviation of the plastered surface from an ideal spherical one.

Each grid point was actually tested using triangular mirrors of four different sizes (15cm, 10cm, 5cm and 2cm edges) to try to determine how the orientation accuracy is influenced by the size of the mirrors (which might give a first information on the appropriate size of the mirrors to be used for the bowl).

Second test surface with a triangular mirrors



Partitioning the second test surface

From the centre of the test surfaces, the operator aims at the centre of the triangle with a laser pointer.

As one would intuitively expect, the measurements made with the larger mirrors showed a more accurate surface orientation than those made using smaller mirrors. The larger mirrors integrate the small defects of the masonry surface. For the 15cm mirrors, 95% of the locations had an orientation error of less than 14 minutes, while for the 2cm mirrors, 95% of the locations had an error of less than 35 minutes.

Sample of the results (for triangles of 2cm and 10cm) are given on the following pages while the remaining results are given in Annexure A.

Triangles 2cm

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	18	13	13	4	12	6	6	9	12	33	16	21	10	11	7
2	11	5	13	17	18	16	3	5	23	35	10	24	9	36	25
3	21	13	21	32	6	5	25	40	13	40	26	8	6	30	30
4	5	30	3	35	25	5	19	17	12	18	13	15	3	10	19
5	3	15	14	37	3	11	17	22	21	8	15	14	14	8	16
6	17	13	7	35	3	15	2	19	28	8	25	17	9	15	12
7	17	19	21	23	7	35	9	16	10	9	26	15	4	35	35
8	9	3	22	3	12	16	18	9	5	5	12	18	11	24	26
9	13	10	9	26	2	8	9	28	12	9	11	37	18	19	1

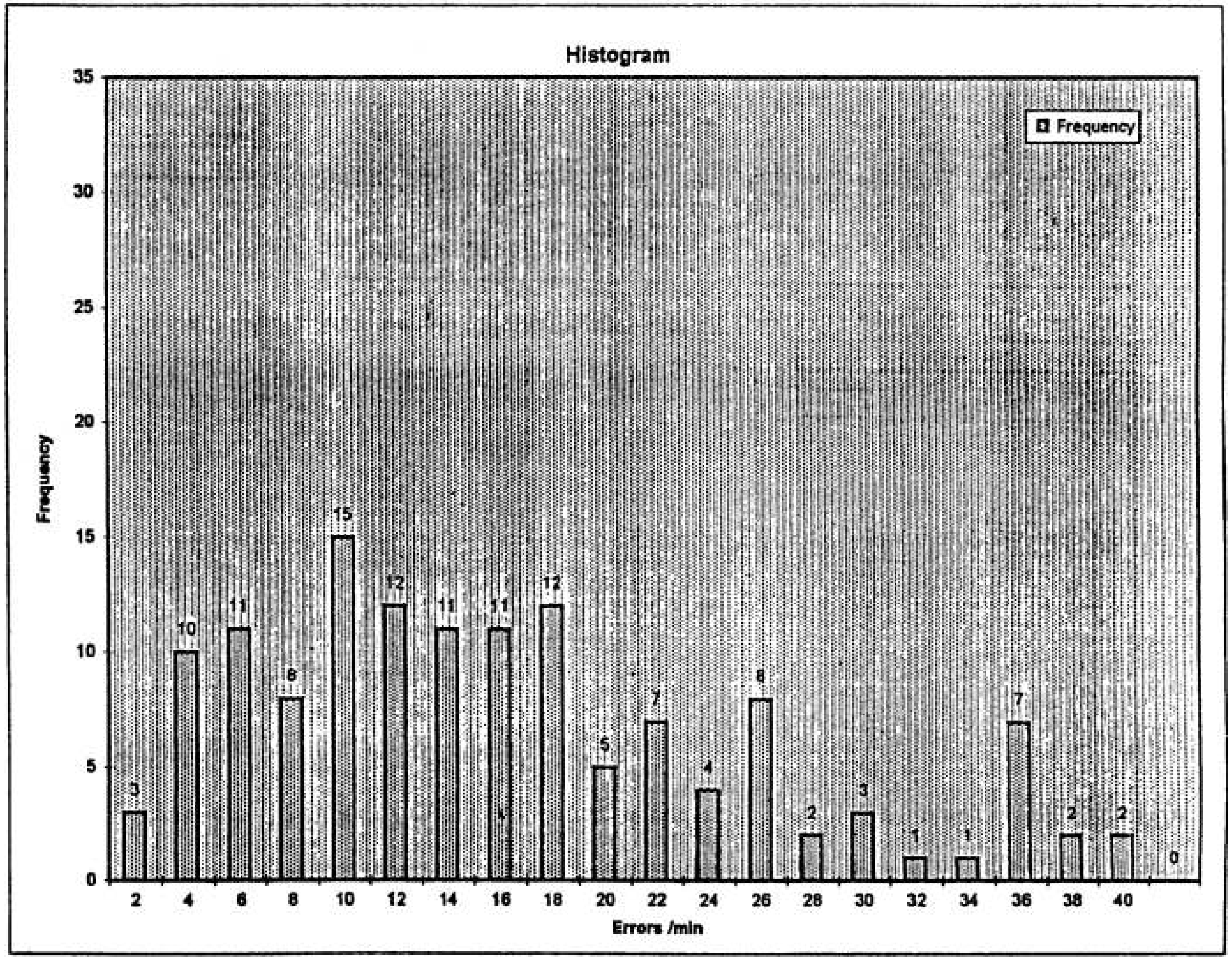
average	15.66667
aveage deviation	7.683951
max	40
min	1

Bin	*Frequency*	%
2	3	2.22
4	10	7.41
6	11	8.15
8	8	5.93
10	15	11.11
12	12	8.89
14	11	8.15
16	11	8.15
18	12	8.89
20	5	3.70
22	7	5.19
24	4	2.96
26	8	5.93
28	2	1.48
30	3	2.22
32	1	0.74
34	1	0.74
36	7	5.19
38	2	1.48
40	2	1.48
More	0	0.00

95% under 35

Histogram for triangles of 2cm

Bin	Frequency
2	3
4	10
6	11
8	8
10	15
12	12
14	11
16	11
18	12
20	5
22	7
24	4
26	8
28	2
30	3
32	1
34	1
36	7
38	2
40	2
More	0



TRIANGLES 10 CM

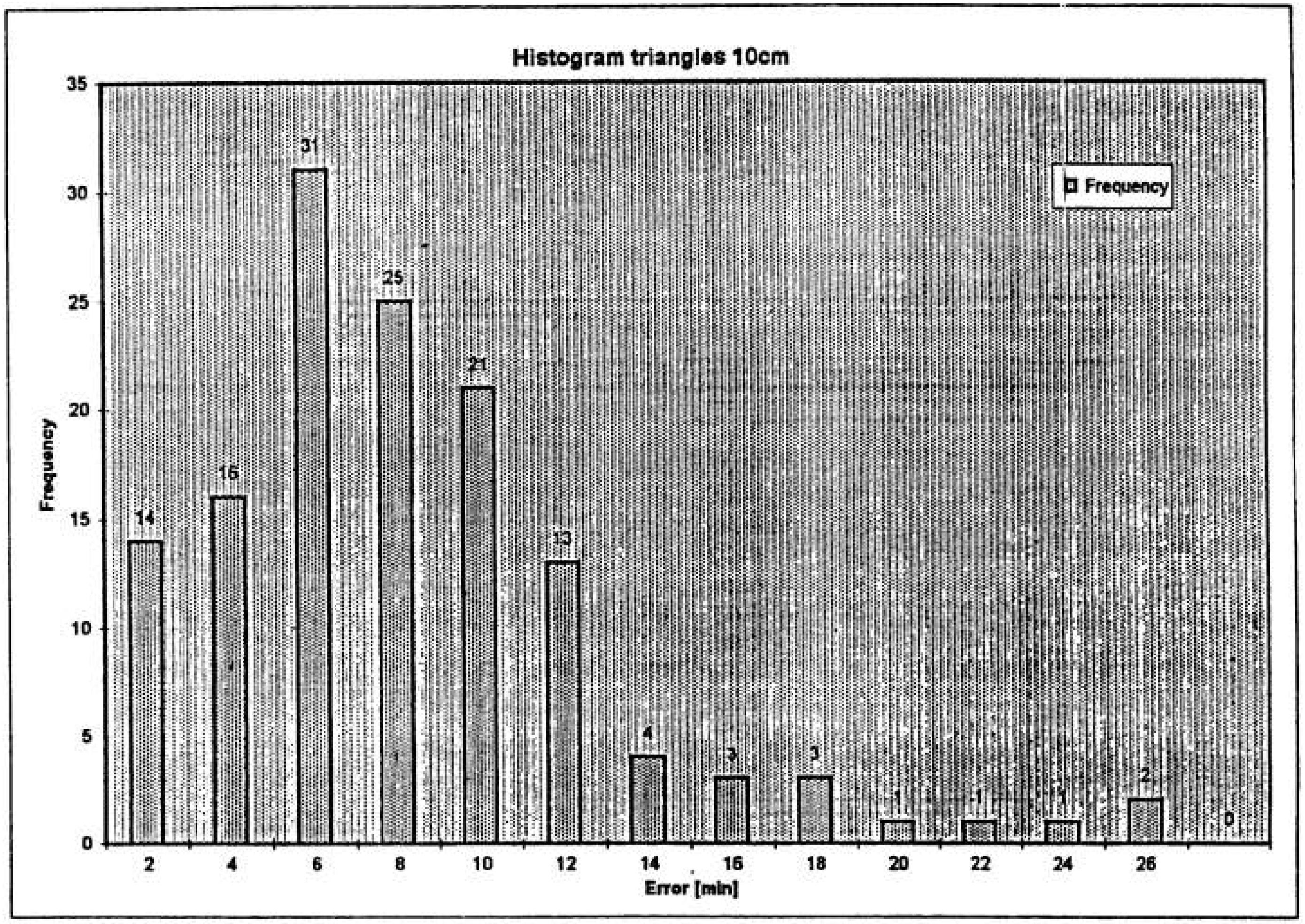
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	11	11	1	8	21	2	14	4	12	11	6	3	6	7	6
2	8	8	9	7	5	3	5	10	10	18	5	9	4	18	6
3	11	11	9	9	9	3	5	18	4	14	11	8	5	8	23
4	4	8	9	19	5	4	8	8	8	8	5	4	8	6	7
5	7	10	6	25	2	6	5	25	7	0	12	4	5	7	2
6	11	7	1	9	5	8	6	6	4	11	10	6	11	6	0
7	9	15	1	9	3	6	4	8	11	5	13	5	6	14	10
8	9	4	9	6	5	4	2	7	6	8	10	2	6	3	10
9	5	7	9	8	7	2	9	16	5	1	1	9	16	12	2

average	7.777778
average deviation	3.455144
max	25
min	0

Bin	*Frequency*	%	
2	14	10.37	
4	16	11.85	
6	31	22.96	
8	25	18.52	
10	21	15.56	
12	13	9.63	
14	4	2.96	
16	3	2.22	95% under 16
18	3	2.22	
20	1	0.74	
22	1	0.74	
24	1	0.74	
26	2	1.48	
More	0	0.00	

Histogram for triangles of 10cm

Bin	Frequency
2	14
4	16
6	31
8	25
10	21
12	13
14	4
16	3
18	3
20	1
22	1
24	1
26	2
More	0



Masons using the aluminum arm to make the spherical plaster

5.5.c. Surface treatment of the entire spherical shell

For the surface treatment of the third test surface and also for the entire surface of the bowl, we used the technique that proved satisfactory for second test surface. Specifically: to make the final plaster, we used the very rigid swinging arm made out of aluminum profiles straightened with cables. The top end of this aluminum arm was made to pivot at the center of the sphere on top of the temporary mast.
The inside surface of the shell was then painted with 30kg of a liquid silicone sealant ("Nishiwa SH" from Sri Ganesh Chemicals, Chennai).

5.6. REFLECTIVE SURFACE (facets of mirrors)

As mentioned in paragraph 5.1 we opted for a reflective surface made of thousands of small flat mirrors of a type that is easily available on the market.

5.6.a. Selection of the mirror type

The main criteria for selecting the type of mirror were:

- Excellent reflectivity
- Resistance to heat
- UV resistance
- Resistance to corrosion (from the cement, the adhesive, the water and the air)
- Strength (as maintenance people will be stepping on them)
- Hard to scratch (both by sand storms and maintenance people stepping on them)
- Cost effectiveness

After testing various types of mirrors, 3mm thick "Modiguard" float glass mirrors were found to be the best for this particular use.

5.6.b. Selection of the adhesive

The main criteria for selecting the type of adhesive were:

- Ease and accuracy of focusing
- Should not corrode the silver coating of the mirrors
- Resistance to heat
- Cost-effectiveness

We carried out the following tests:

1. Square mirrors of two sizes (10cm x 10cm & 15cm x 15cm) were fixed with contact glue (rubber cement) to the cement surface and their orientation was measured using the laser pointing device. Rubber cement was applied very thinly to the surface, so that the mirrors are really touching the surface. As one would expect, their orientation errors were similar to the errors in the underlying cement surface, with deviations of up to 30minutes being measured.

2. In an attempt to reduce the errors in mirror orientation and the number of mirrors to be glued, we tried gluing long strips (10cm x 122cm) of mirrors with contact glue. There was indeed an improvement, but it was found that the end portions of the strips tended to remain flat (thus introducing errors in orientation of again up to 30 arc-minutes at the mirror ends). In addition the strips tended to "pop off" the cement surface because of the tension in the mirrors caused by bending. Only mirror strips stuck with "3M" two-face tape resisted this popping off; but the cost of this tape is prohibitive.

3. As our design condition specifies that errors in mirror accuracy should be less than 5 arc-minutes, we studied the possibility of orienting each mirror individually. This had already been done in 1981 for Auroville's Mini Solar Bowl. One man had his eye at the Center of the sphere (behind cross hairs) and guided another man who was laying the mirrors one by one. Each (5cm x 5cm) mirror was oriented in such a way that the first man would see his own eye (behind the cross hairs) reflected in the mirror that was being positioned.

   To be able to adjust the orientation of a mirror, one needs to use an adhesive which has a certain thickness, like silicon, as it allows movement for approximately one minute after it has been stuck. After that, the silicone hardens and the mirror won't move anymore. However the silicon adhesive needs 24 hours to fully harden.

It was found that by using our laser pointing device, one could quite easily adjust the orientation of any square to less than 2 arc-minutes. Tests showed that 9 silicon dots at the back of the mirrors were sufficient for sticking and that once the silicone was cured the mirrors kept well their orientation - even if they were walked on.

5.6.c. Selection of the anti-corrosion treatment

For both the French and American bowls, their spherical mirror facets were held in place by a steel structure. For both Auroville's Mini Solar Bowl and the Solar Kitchen Bowl, their flat mirror facets are stuck on a masonry shell**. Our experience in Auroville's Mini Solar Bowl has shown that the silver coating of the mirrors may get corroded.** According to Professor B. Authier (head of the French Bowl Project) it is caused mainly by the migration of ions from the cement to the silver coating. Therefore we needed to develop an original technique that would allow us to orient each facet accurately, and also prevent corrosion of the silver coating.

The quality, cost and longevity of the reflector definitely play a crucial role in the economical viability of the solar bowl. The structure of the reflector will keep its shape and will be long lasting. But what about the reflective surface? If the quality of the reflectivity goes down as time passes, the receiver will receive less heat and the thermal efficiency of the whole system will be reduced - maybe even drastically. Though it is technically possible to change the reflective surface, it would be very tedious and quite costly; it is therefore essential for us to use a technique for laying the mirrors that will keep them in good shape for at least 10 years – and if possible 20 years.

What follows summarizes two sets of mirror corrosion tests that led to the choice of a final solution to avoid corrosion of the back of the mirrors.

Tests we had done in the past had shown that one has to use a silicon with neutral curing as ordinary silicon adhesive release during its curing acetic acid that damages the silver coating.

Corrosion tests on the second and third test surfaces

(Note the strips on the second test surface)

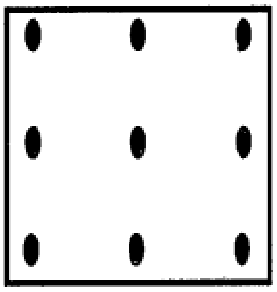
Test set A

1. On 2.11.97, a set of square mirrors (15cm x 15cm) were glued out of doors on a masonry surface.
   - The plaster on the masonry surface was approximately 75 days old.
   - We used "Modiguard" float glass mirrors. (Later we used them also for the bowl).
   - All mirrors were glued on with the same Silicone adhesive (Elastosil 300).

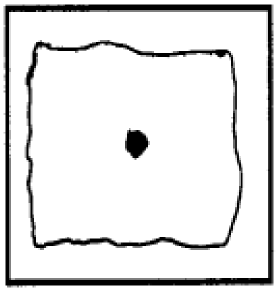
2. The cement surface was divided into 5 separate areas and each area was coated in a different way, using either:
   - Epoxy primer (red) shalimar.
   - White cement milk.
   - Epoxy paint (white).
   - Liquid silicone sealant ("Nishiwa SH" from Jai Ganesh Chemicals).
   - Untreated control surface.

3. On each of these painted areas, 3 sets of mirrors (4 in each set) were glued (see drawing next page). The 3 sets of mirrors had been treated differently.
   I Unpainted mirrors.
   II Backs painted with epoxy primer (red, shalimar).
   III Backs painted with Dr. Beck's gelcoat (red).

   Each set of mirrors (of I, II, or III) was again divided in two, with two different gluing methods being used:
   a. Using 9 dots of 1cm² in the corners, edge centers and center of the mirror (two mirrors on left of the set of 4) (see below).



   b. Using a continuous silicone strip around the mirror edge, plus a dot in the center (the two mirrors on the right of each set of 4).

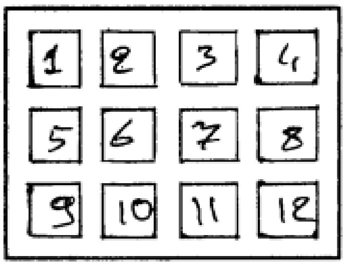


A. Epoxy primer on cement

I : mirrors unpainted

II : mirrors painted epoxy primer

III : mirrors painted Dr. Beck’s gelcoat

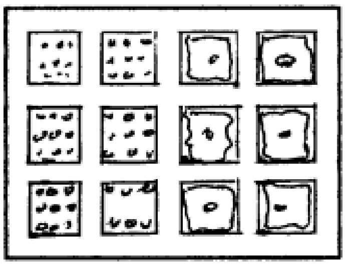


B. Cement milk on cement

I : mirrors unpainted

II : mirrors painted epoxy primer

III : mirrors painted Dr. Beck’s gelcoat

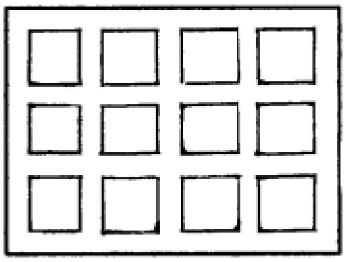


C. Epoxy paint or cement

I : mirrors unpainted

II : mirrors painted epoxy primer

III : mirrors painted Dr. Beck’s gelcoat

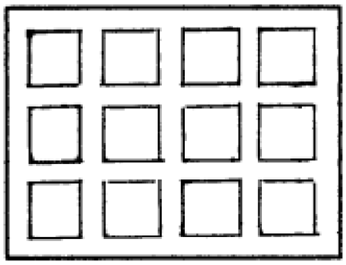


D. Silicone sealant
(Nishiwa) on cement

I : mirrors unpainted

II : mirrors painted epoxy primer

III : mirrors painted Dr. Beck’s gelcoat

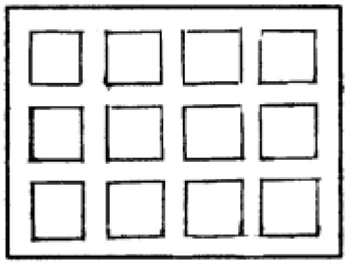


E. Uncoated cement

I : mirrors unpainted

II : mirrors painted epoxy primer

III : mirrors painted Dr. Beck’s gelcoat



Mirror test setup

4. On 16.2.98, i.e. after 108 days - during which the monsoon came and went - the mirrors were evaluated for corrosion effects.
   Three types of defects were visible:
   1. Small pinpricks - like black points - up to 1mm ∅.
   2. Black or yellow spots - above 1mm ∅.
   3. Light shadings, or 'halos' seen over the full extent of the underlying silicone glue.

   All the defects were counted and are noted in the raw data sheet (see next page).

5. For the purpose of evaluation the defects are given numerical weights as follows:
   a. Pinpricks are given a value of 1.
   b. Dots up to 2mm ∅ are given a value of 5. (the few dots above 2mm ∅ were subdivided into clusters of 2mm dots).
   c. Halos of light shaded areas are given a value of 50 as these are thought to indicate areas that will eventually show extensive corrosion. Very light halo effects are counted as 30.

6. Using the above described numerical weighting system, we condensed the raw data table of mirror defects in the following table:
   (lower values indicate lower corrosion of the mirrors).

   A. Mirrors on cement plaster treated with epoxy primer:

47	10	56	195	I. (unpainted)
68	50	58	88	II. (epoxy primer)
3	0	0	0	III. (Dr. Beck's gelcoat)

   B. Mirrors on cement plaster treated with white cement milk:

0	1	15	11	I. (unpainted)
61	94	54	59	II. (epoxy primer)
45	1	0	0	III. (Dr. Beck's gelcoat)

   C. Mirrors on cement plaster treated with Epoxy paint (white):

59	30	31	36	I. (unpainted)
75	55	241	82	II. (epoxy primer)
0	1	3	0	III. (Dr. Beck's gelcoat)

   D. Mirrors on cement plaster treated with silicone sealant:

2	51	2	8	I. (unpainted)
78	61	50	61	II. (epoxy primer)
9	0	2	0	III. (Dr. Beck's gelcoat)

   E. Mirrors on untreated cement plaster:

14	10	10	4	I. (unpainted)
68	4	30	90	II. (epoxy primer)
8	0	3	4	III. (Dr. Beck's gelcoat)

Raw data sheet for mirror corrosion as measured on 18.02.98

Set A.

1.	27 points + 4 2 mm dots	7.	8 points + halo
2.	5 points + 1 2 mm dot	8.	33 points + halo 9. 0
3.	11 points + 9 2 mm dots	9.	0
4.	15 points + 36 2 mm dots	10.	0
5.	18 points + halo	11.	0
6.	0 points + halo	12.	3 points

Set B.

1.	0	7.	4 points + halo
2.	1	8.	9 points + halo
3.	10 points + 1 2mm dot	9.	20 points + 5 2 mm dots
4.	11 points	10.	1 point
5.	11 points + halo	11.	0
6.	44 points + halo	12.	0

Set C.

1.	9 points + halo	7.	16 points +halo 35 2mm dots
2.	0 points + light halo	8.	12 points + halo 4 2mm dots
3.	1 points + light halo	9.	0
4.	6 points + light halo	10.	1 point
5.	25 points + halo	11.	3 points
6.	5 points + halo	12.	0

Set D.

1.	2 points	7.	0 points + halo
2.	1 points + halo	8.	11 points + halo
3.	2 points	9.	4 points + halo
4.	8 points	10.	0
5.	28 points + halo	11.	2 points
6.	16 points + halo	12.	0

Set E.

1.	14 points	7.	0 points + light halo
2.	10 points	8.	90 points
3.	10 points	9.	3 points + 1 2mm dot
4.	4 points	10.	0
5.	18 points + halo	11.	3 points
6.	4 points	12.	4 points

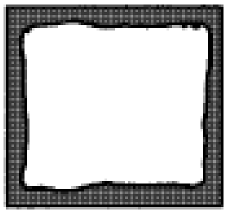
Test set B

A second set of mirror trials started on 13.09.97 and ran also through the monsoon period till evaluation on 18.02.98. The mirrors had thus been exposed to weather for 5 months.

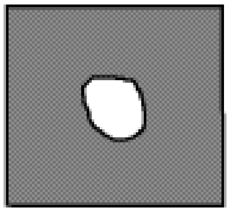
In this test the same “Modiguard” mirror was laminated to a back sheet of 2mm clear glass. The laminated mirrors were then glued with silicone (Elastosil 300) onto a cement plaster surface out of doors.

The lamination was done in 2 different ways:

a. Using a ring of silicone (Elastosil 300) between the mirrors & plain glass to join them - sealing the edges completely (3 sets were fixed for testing).



b. Using Araldite epoxy glue, spread over the entire surface of the mirror back, to fix the plain glass (4 sets were fixed for testing).



Record of defects observed on 18.02.98 showed the following:

Set a: Mirror 1 had one black point and one clouded area 5 mm x 8 mm
Mirror 2 had one black point
Mirror 3 had one clouded area 5 mm x 1 cm

Set b. <u>No defect in any mirror</u>

Conclusion:

1. Mirrors in trial “A” protected by Dr. Beck’s gelcoat have lasted much better than the other two cases on every type of painted cement surface. This is the most striking and significant trend in test surface No 2.

2. The large corrosion effects in test set “A” shown by these tests appear when the silicone glue is applied in a ring around the mirror edge. Thus we should use the “9 dots” gluing method if painted mirrors were to be used. It is assumed that the method of gluing with a ring of silicone causes more corrosive liquid from the cement to be trapped behind the mirror.

3. The choice of treatment indicated by test set “A” for the cement surface is less clear-cut. If one takes the total of the weighted values of each of the 5 options, the untreated cement surface (option “E”) actually has the lowest total (i.e. best result!). The best actual result was obtained using the epoxy primer on the cement and Dr. Beck’s gelcoat on the mirrors.

Considering the perfect results shown by trial B-b (lamination of 2mm glass using Araldite), we were moved to choose this method for our application.

The indication of a much longer lifetime is a decisive factor; but this option of course increases the time needed to realize the reflective surface as twice as many glass pieces need to be cut and then glass and mirror need to be stuck together.

Economically however, this option of lamination is not more expensive than the best trial obtained using paints in the test set of 2.11.97. Test set “A” of 2.11 indicates that a near perfect result (of unknown durability however) could be obtained by coating the mirrors with Dr. Beck’s gelcoat. This material, according to the literature, has a coverage of ½Kg/sqm for a double coat on a surface, which costs Rs 207/sqm according to the market rate for gelcoat, hardener and thinner. The cost of the epoxy primer on the cement adds a cost of about Rs 35/sqm giving a total of Rs 242/sqm for this option. For the laminated glass solution, we have a 2mm glass cost which is Rs 115/sqm, and then the cost of the Araldite. 5 grams of Araldite, costing Rs 2.8/- are sufficient to glue one mirror backing. This gives a cost of just Rs 100/sqm of mirror for the glue and a total cost of Rs 215/sqm for 2mm glass backing plus glue.

The extra labor for glass cutting in this option is offset by the lack of extra labor cost needed to apply paints to the cement or mirror surfaces.

One of the laminated mirrors piece has then been tested for strength of glass-to-glass bonding by being immersed in an ultrasonic cleaning bath at 80°C overnight. The ultrasonic vibration failed to cause separation of the laminated piece; thus indicating an excellent bonding.

After conducting all these tests, we are confident that the laminated mirror option – which we are implementing – is the best and most durable choice for use in this solar bowl. We will however carry out further tests – for future applications – using other materials for lamination such as metal foils.

The outcome of these tests is that we decided to use “Araldite” to laminate each one of the mirrors with a 2mm-thick plain glass (of the “Modi Glass” brand) of exactly the same size. It also confirmed that it is appropriate to use a “neutral cure” silicone (“Elastosil 300 white”) to stick these laminates on the cement surface.

It is this laminate (mirror-glass) that will be stuck to the plastered masonry surface using 9 dots of silicone (as explained in paragraph 5.6.b.).

5.6.d. Sizing the facets (focus' size; focusing accuracy)

In order to decide upon the size of the facets, it is essential to know what is the incidence of the size of the mirror facets and of their orientation accuracy on the spreading of the reflected rays and therefore on the diameter of the receiver.

If the sun were a point, if the facets of the mirrors were both spherical and all perfectly oriented, the focus of a Solar Bowl would be a line without any thickness. But 1) the sun is seen with an aperture angle of 30minutes, 2) the mirrors in our case are flat facets of a certain size (to be chosen) and 3) all of these facets will certainly not be oriented perfectly accurately.

We have to evaluate the combined influence of these 3 elements.

If we simply add the three worst scenario for each of these elements: 1) sun-ray coming from the outer periphery of the sun, 2) hitting a corner of 3) the worst focused trapezoidal mirror; we get absurd results. Absurd because such an occurrence is very rare and therefore probably irrelevant. To know it for sure, a statistical calculation is absolutely necessary.

This calculation will lead to the sizing of the receiver. Since it has to intercept a maximum of reflected rays, it should have the same size as the dispersion zone around the ideal reflection line. But this dispersion zone should be as small as possible in order to have a receiver with a small diameter. The smaller the focusing zone will be:

- The least energy losses there will be.
- The lighter - and cheaper - the receiver will be; and together with it: the swinging arm, the counterweight and the monopode.
- The simpler - and cheaper - the tracking system will be, as the whole swinging arm with receiver & counterweight whose movement it has to control will be lighter.

By using a computer program called "PERFAC", we were able to define an acceptable compromise for the size of the mirrors and the size of the receiver.

PERFAC is one of the software written in France by the CNRS (Centre National de la Recherche Scientifique) that realized a 10-meter diameter bowl in Marseilles in 1980-84. Dr. Authier who was the head of this project called PERICLES has now retired, but was kind enough to give us copies of three programs (PERFAC, CHAUDIER & THERMIQU) his team wrote for the design and evaluation of his project.

PERFAC makes statistical calculations using the "Monte Carlo" method. The sun is divided into 63 "elements" and many "points" characterize the bowl interception area (called "pupil"). We considered 100 "points" on one diameter of the "pupil". Each sun "element" sends one ray on each "point". The program then calculates where each reflected ray hits the receiver and counts all the reflected rays hitting the different parts of the receiver.

Each flat mirror on the spherical surface of the bowl is divided in 10 different zones; each zone being characterized by a percentage of the total area of the mirror and the average deviation between an ideal ray reflected by a spherical surface and the actual ray reflected by the flat mirror.

PERFAC calculates the following parameters pertaining to the receiver in a spherical concentrator:

- Geometrical and energetic interception on each “slice” of the receiver.
- Geometrical and energetic concentration ratio on each “slice” of the receiver.
- Incident angle of sunrays on each “slice”.
- Total interception factor.

The input variables are the following:

- Angle of the sun.
- Size of the mirrors.
- Accuracy of the tracking system.
- Accuracy of the alignment of the mirrors.
- Diameter of the low concentration part of the receiver.
- Aperture of the cone (high concentration part).

Considering the reflection pattern of a solar bowl and the studies made previously by the PERICLES team, we know that the receiver will consist of a cylindrical element (low concentration part) and just on top of it, of an inverted truncated conical element (high concentration part). We also know that its total length will be about half the radius of the sphere.

We used the PERFAC program to make a parameter study of all input variables. First we calculated the influence of the variation of one of the input variables on the total interception factor for different angles of the sun. After defining the laws of influence of each factor separately, we could calculate and understand their combined influence. We could thus draw some conclusions about the size of the mirrors to be used and the acceptable values for the precision to be achieved by the tracking system and the mirror alignment and finally the optimal size and shape of the outer surface of the receiver.

This parameter study is described in detail in Annexure B.

Here are the main conclusions of the parameter study we did with PERFAC:

Using 15cm x 15cm square mirrors as reflective surface, we opted for a receiver of 23cm diameter for the cylinder and 72cm aperture diameter for the truncated cone. If we use such a receiver, then:

- The precision in the orientation of the mirrors starts having a significant impact when it is over 5' and it remains acceptable up to 10'.
- The precision in the positioning of the receiver by the tracking system has an equivalent influence. So, a tracking error of 5' is good and it is acceptable up to 10'.

We chose 15cm x 15cm mirrors because it is the biggest size of mirrors giving still acceptable angular deviations between the sunrays reflected by the flat facet and the rays that would be reflected by a spherical facet. Using 10cm x 10cm square mirrors would reduce the average deviation, but multiply the number of mirrors, therefore increasing drastically the work and the time needed to prepare and fix them accurately. The total surface to be covered with mirrors being 235.5m^2, we need either some 23,550 facets of 10cm x 10cm or some 10,466 facets of 15cm x 15cm.

We checked the time necessary to lay accurately one mirror on the surface and found out that it can be done in 2 minutes. On an average however our team lays 100 mirrors every evening between 5pm and 10pm; that is to say that they need an average of 3 minutes to lay one mirror. This is due to the fact that it is difficult to remain concentrated for 5 hours every evening for months in a row. Which means that our team will need 105 working days to lay 10,500 mirrors. To these, we have to add: Sundays, holidays, rainy days, days for re-arranging the scaffolding, etc. So, it is a total of 4 to 5 months that will be needed. We found this to be acceptable. Of course, one could half this time by having a second team working from 10pm to 2am; but it would be more costly.

5.6.e. Final design of the receiver

The parametrical study was done for the following input data:

- Aperture diameter of the bowl: 15meters,
- Radius of the sphere: 8.66meters
- Receiver Ø BC 22cm
Ø HC 89cm

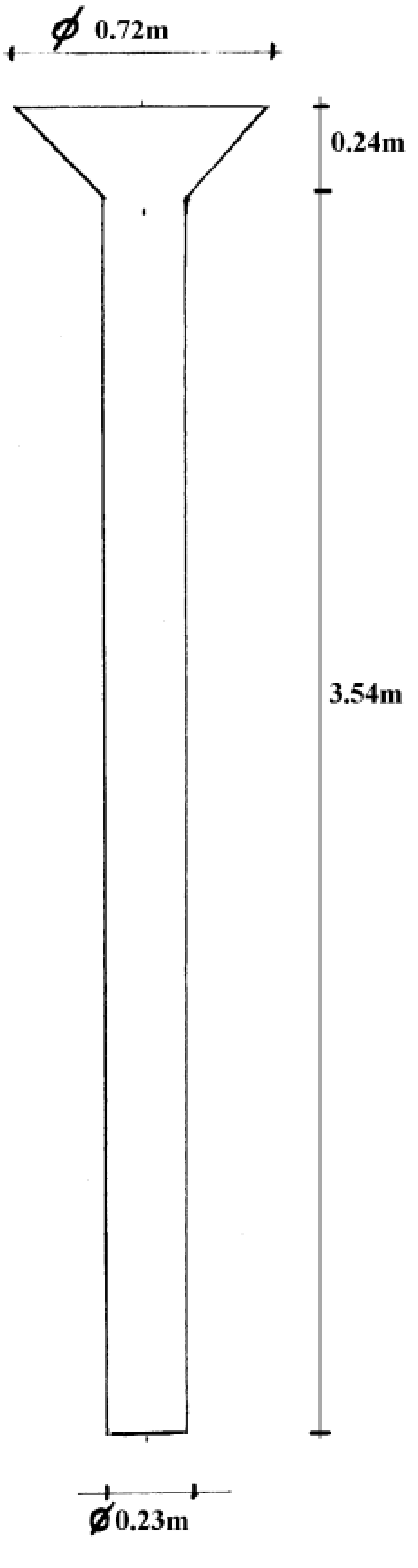
But now that the reflective surface is partly realized, we measured the actual dimensions. They are:

- Aperture diameter of the bowl: 14.9meters,
- Radius of the sphere: 8.60meters

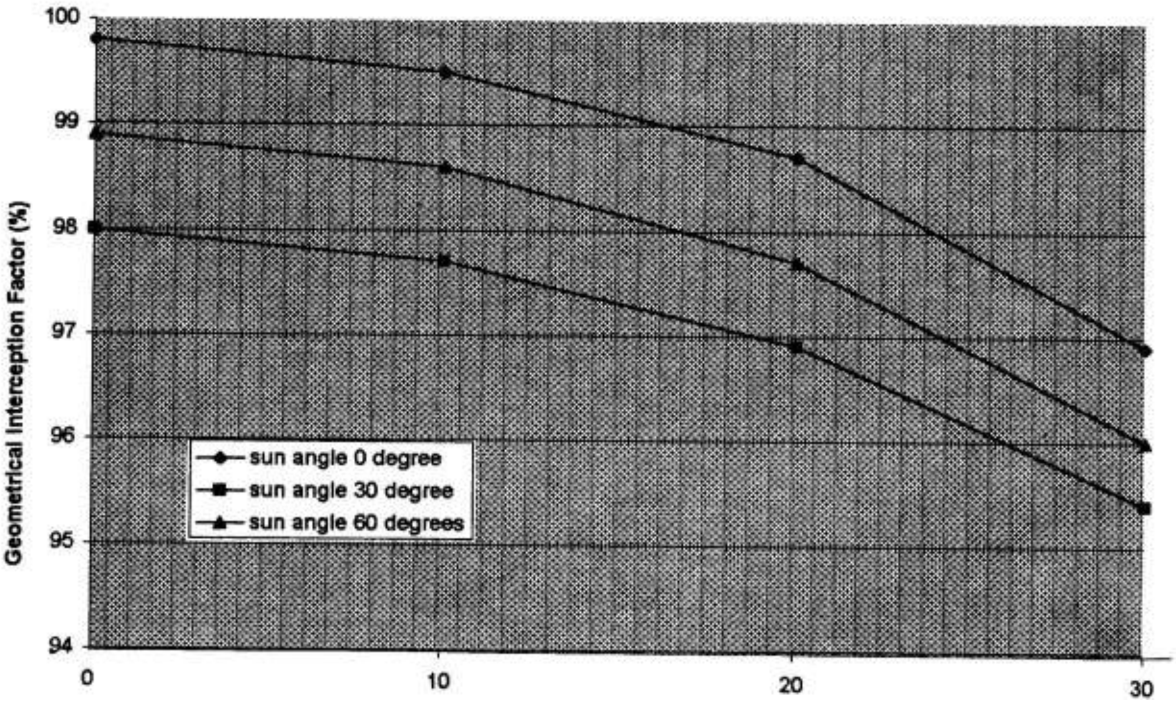
And the chosen dimensions of the outer surface of the receiver are the following:

• Cylinder BC:		Ø	0.23m
		Length	3.54m
• Cone HC		aperture diameter:	0.72m
		Aperture angle:	45.5°
		Length	0.24m
Total length			3.78m

These dimensions take into account the fact that the tip (lowest part) of the receiver is not touching the reflective surface. We decided to keep a gap of 2cm between them. We will fix on this tip a small and soft metallic brush extending down to 5mm of the mirrors in order to stop the reflected rays from arriving on this spot and thus prevent a hot spot problem (breaking mirrors because of excessive heat).



Shape of the selected receiver.



Mirror orientation error (minutes)

Curves showing the receiving characteristics of the final receiver

Influence of mirror orientation error and sun angle

For mirrors: 15cm x 15 cm; and a tracking error of 0'

If one replaces the tracking error 0' by mirror error 0' and calculate the influence of different tracking errors, one obtains exactly the same curves.

Sun angle 0° - Final receiver

	Mirror orientation error	Tracking error	Geometric interception
Bad case	15'	15	98.4
Average case	10'	10	99.3
Average case	5'	15	99.1
Excellent case	5'	5	99.6

Table showing the performances of our bowl

for different combined mirror and tracking errors.

It shows that the combined effect of the mirror orientation and tracking system errors is more important if these errors have very different values.

Follows a sample result sheet (translated from the French) of a PERFAC calculation. This sample result gives the harvesting characteristics of our final receiver for a 5' error in the precision of the mirror orientation and a 10' error in the tracking system positioning.

Translation from the French of a PERFAC computer printout

Page 1

Simulation of a faceted spherical collector

Angle between the sun and the axis of the collector: 0°

Repartition of the errors between the reflective surface and the sphere:

Angular error (‘)	Percentage (%)
4.00	5.60
12.00	19.60
20.00	27.90
27.00	28.20
33.00	16.50
38.00	2.20

Precision in the orientation of the mirrors (‘): 5.0’
Tracking accuracy (‘) : 10.0’

Reflectivity of the mirrors : 90%

Maximum diameter of the cylinder BC: .02674
Maximum diameter of the cone HC : .08372

Low concentration receiver

Slice No	Lower limit	Upper limit	Interception factors		Concentrations	
			Geom.	Energy	Geom.	Energy.
1	.00000	.04200	2.7877	2.5	19.	17
2	.04200	.08400	3.3132	3.0	22.	20
3	.08400	.12700	3.9455	3.6	26.	23
4	.12700	.16900	4.5818	4.1	31.	28
5	.16900	.21100	5.3093	4.8	35.	32
6	.21100	.25300	6.2696	5.6	42.	38
7	.25300	.29600	7.7097	6.9	50.	45
8	.29600	.33800	9.1843	8.3	61.	55
9	.33800	.38000	11.5224	10.4	77.	69
10	.38000	.41400	11.9318	10.7	98.	89

Translation from the French of a PERFAC computer printout

Page 2

Angular domain (degrees)	Interception factor (%)
0- 5	1.3
5-10	3.9
10-15	6.2
15-20	8.0
20-25	9.4
25-30	10.1
30-35	7.3
35-40	4.7
40-45	3.1
45-50	2.0
50-55	1.3
55-60	0.8
60-65	0.5
65-70	0.3
70-75	0.2
75-80	0.2
80-85	0.4
85-90	0.0

High concentration receiver

Slice No	Lower limit	Upper limit	Interception factors		Concentrations	
			Geom.	Energy.	Geom.	Energy.
1	.41400	.41700	2.4513	2.2	144.	130.
2	.41700	.42000	2.9339	2.6	143.	129.
3	.42000	.42200	2.3493	2.1	151.	136.
4	.42200	.42400	2.8068	2.5	164.	147.
5	.42400	.42600	3.5287	3.2	189.	170.
6	.42600	.42800	4.1713	3.8	206.	186.
7	.42800	.43000	4.3668	3.9	200.	180.
8	.43000	.43300	5.7615	5.2	162.	146.
9	.43300	.43600	3.3670	3.0	86.	78.
10	.43600	.43900	1.0471	.9	25.	22.
11	.43900	.44200	0.1221	.1	3.	2.

Translation from the French of a PERFAC computer printout

Page 3

Angular domain (degrees)	Interception factor (%)
0- 5	2.9
5-10	6.9
10-15	7.6
15-20	5.4
20-25	3.1
25-30	2.0
30-35	1.2
35-40	.4
40-45	.0
45-50	.0
50-55	.0
55-60	.0
60-65	.0
65-70	.0
70-75	.0
75-80	.0
80-85	.0
85-90	.0

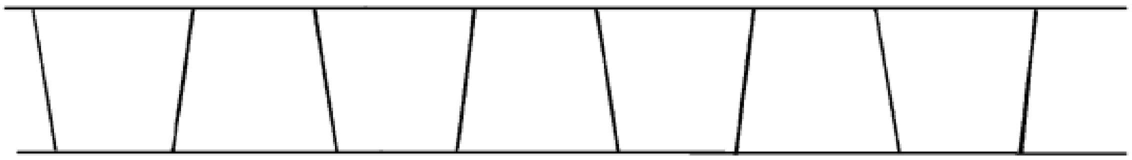
Interception Factor HC (%) :
: Geometrical: 32.9%
: Energetical : 29.6%

Interception Factor Total (%) :
: Geometrical: 99.5%
: Energetical : 89.5%

Percentage of simple reflection: 89.3%
Percentage of double reflection: .2%
Percentage of triple reflection: .0%

5.6.f. Facet pattern

In order not to have any gap between each facet of the spherical surface, the mirrors should not be square but trapezoidal. Trapezoidal facets were found to be very easy to cut and create also the least wastage.



Cutting trapezoidal mirrors with a minimum of wastage

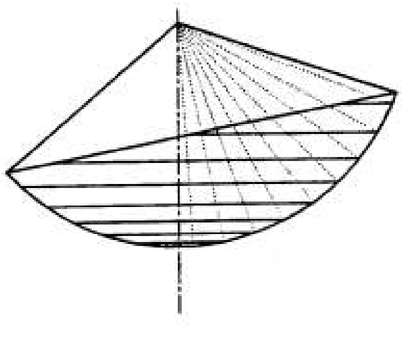
Facets would be simply laid row upon row. The next question was: Around which axis? The vertical axis of the bowl? Or its symmetry axis which is tilted by 12º? The main reason that made us opt for the vertical axis is that the circles along which the mirrors are laid are horizontal, and thus relatively easy to mark on the Bowl.

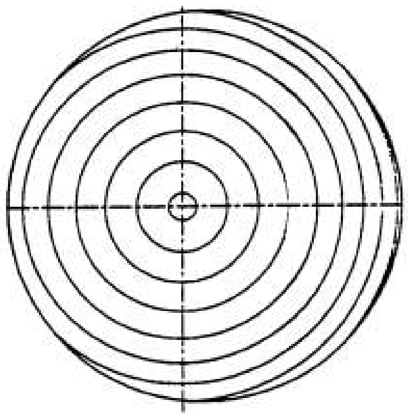
It was decided to use 10cm high trapezoids for the bottom rows as otherwise the gaps between the rows of faceted mirrors would become too large.

A very simple computer program was written to calculate the exact size and number of trapezoids needed. Listings were printed out.

However, when we started cutting the facets, we realized that the 15cm wide strips, which we had at first asked a mirror dealer in Pondicherry to supply us with, were not cut accurately enough. They thus needed to be re-cut to 14cm wide strips (it is too difficult to remove a strip of less than 8mm). To avoid re-calculating everything, we decided to use 14cm high trapezoids for the top 12 rows of mirrors.

The result of the parametric study done for square mirrors of 15cm side remains valid if the mirrors are trapezoids of 10 or 14cm height. The precision will be even better since the mirrors are smaller. We however did not decide to re-calculate the dimensions of the receiver because a reduction of one centimeter in its outer dimension would only lighten it by a few kg. We prefer to remain on the "safe side" to ensure a maximum interception of the sunrays by having a receiver slightly too big according to the theoretical calculations.





5.6.g. Methodology of the execution

- The external surface of the Bowl was painted with white cement.
- The inside surface of the plastered masonry shell was painted with 30 Kg of a liquid silicone sealant ("Nishiwa SH" from Sri Ganesh Chemicals, Chennai).
- All the mini-cracks were ground open and filled with a silicone adhesive (of the same brand as the one we used to fix the mirrors).
- 3mm thick "Modi" mirrors were procured in sheets of 4' x 6'.
- 2mm-thick "Modi" glass were procured in sheets of 2' x 3'.
- Araldite was procured in containers of (1 + 0.8) kg from the market in Chennai.
- A table equipped with a custom-made aluminum template was made to cut strips out of the sheets of mirror and 2mm plain glass.
- A second table equipped with two custom-made adjustable aluminum templates to cut the trapezoids to exact size was made.
- A third table was made to glue mirror and plain glass together; and also shelves to store the trapezoids while waiting to be glued to each other; and then to be glued on the bowl.
- The first table is used to cut the sheets of mirror and glass in strips (typical width: 15.0cm).

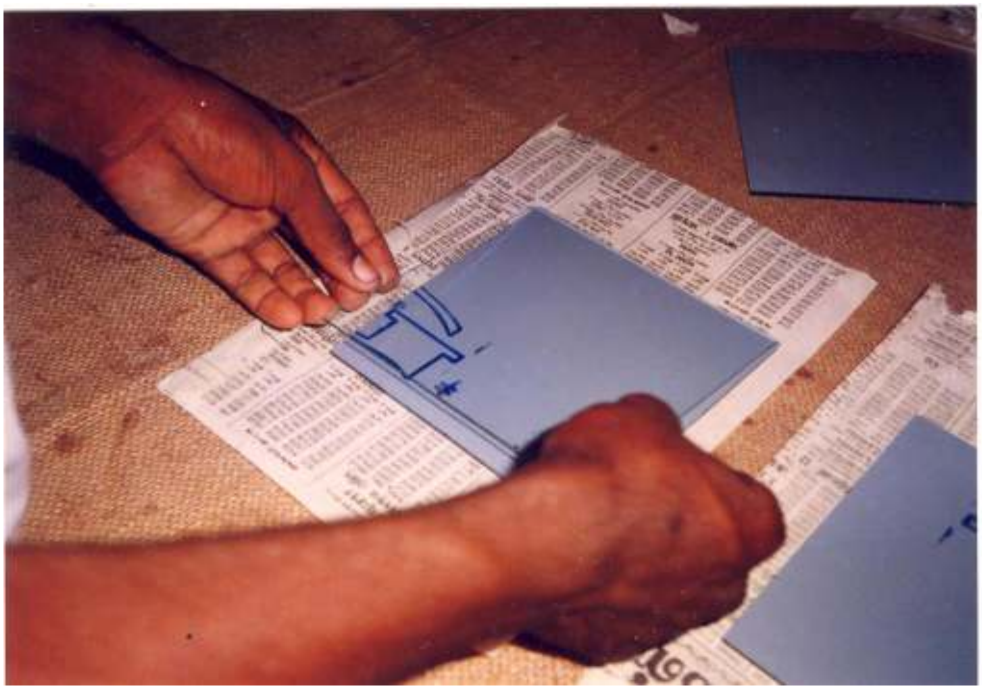
Using a template to cut strips of glass on the 1st table

- The second table is then used to precisely cut the strips of mirror and glass into trapezoids (typical dimension: 15.0cm high, 15.0cm wide at the top, 14.7cm at the bottom). The topside of these trapezoids is marked on the back using a permanent marker.

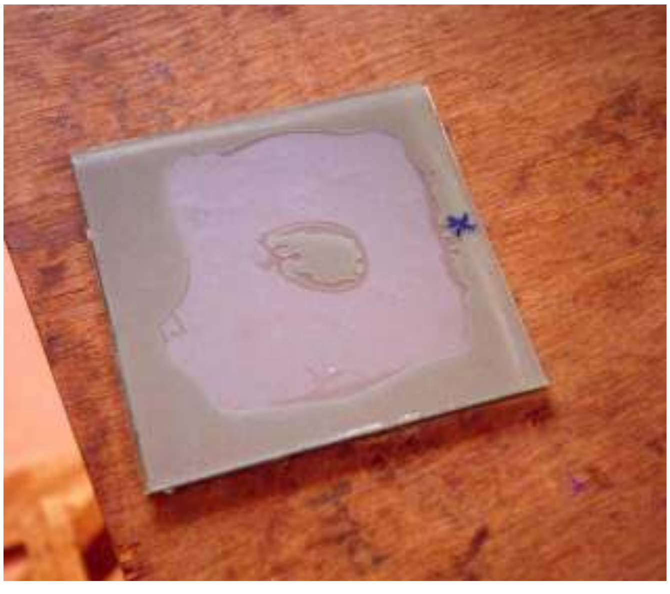
Using a template to cut trapezoids on the 2nd table

- Just before being glued together, each trapezoid (mirror and plain glass) is very carefully cleaned with soap and water and then dried; and then cleaned again with spirit to make sure that the Araldite will stick perfectly well.

- The mirrors to be stuck are laid on a table on newspaper pages with their back up. Araldite is then mixed and pasted on the back of each trapezoidal mirror using a wooden spatula. The plain glass is then placed very carefully on top of it. As the 2mm plain glass is transparent, it is possible to see how well the Araldite has spread. Great care is given that the Araldite spreads <u>continuously all around, up to the edge.</u> Usually, there is a bubble of air remaining in the middle and it does not appear to be possible to avoid it easily; but it probably does not matter as long as the sides are all sealed properly with Araldite.



Lamination of a trapezoidal mirror with a plain glass trapezoid



3mm mirror laminated with Araldite to a 2mm glass

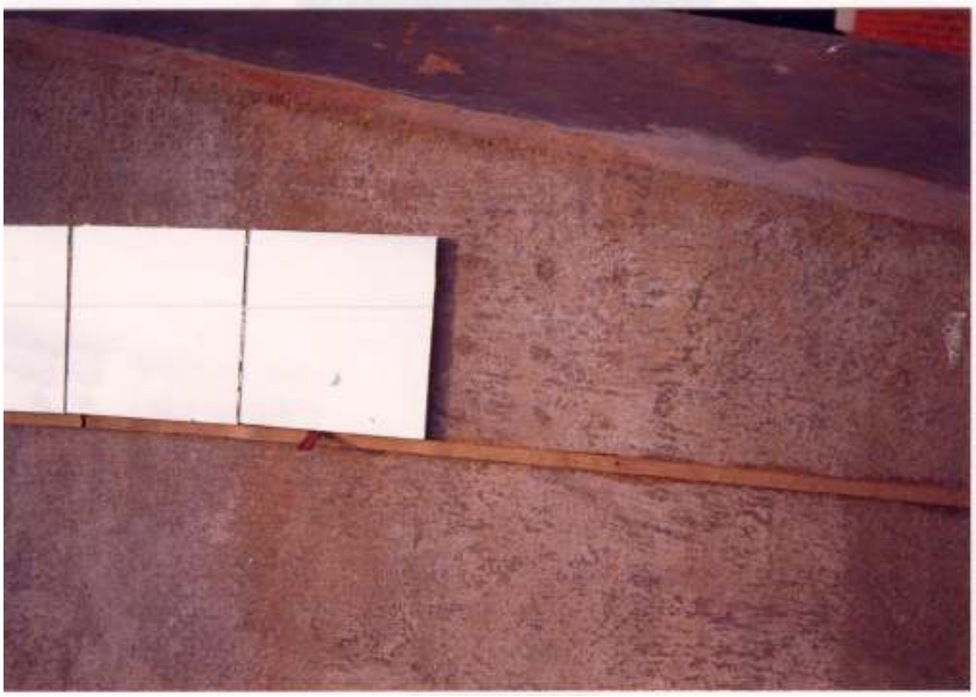
Removing the extra glue one day after laminating the mirrors

- Steel pipes and scaffolding clamps were used to erect a 2m x 2m wide temporary scaffolding tower around the temporary mast (without touching it) to allow an operator to work there without shaking the mast. A ladder was made on one side and wooden planks were placed on top to enable the operator to work with his eyes very near the center of the sphere.

- Casuarinas were then used to erect a wooden scaffolding inside the bowl to enable our team to stick the mirrors, starting by the top. Planks were placed at the suitable level along the surface of the bowl.

Tower, scaffolding & operator

- In order not to soil and damage the mirrors already laid, we had to start by the top. However, the mirrors tend to slip as long as the silicone hasn't hardened; hence the need to first stick a strip (3mm thick, 15mm wide) of cardboard below the line where the mirrors have to be stuck. In order not to repeat this operation for every row of mirror, we decided that once all the rows of mirrors would be laid above the line where we started, we would redraw an new line 1.2 meters (= 8 rows of mirrors) below this first line and stick all the rows in between. And repeat the operation again and again till we reach the bottom.



A first row of mirrors stuck in place resting on a strip of cardboard

- The pointing device described in paragraph 5.5.a. (p.45) is then used to orient properly each mirror.
- A team of 4 people is needed to stick and focus exactly some 20 mirrors per hour:
  - X holds a square cardboard (15cm x 15 cm) with a small hole at its center exactly where the mirror is to come.
  - Y, who stands with his eyes near the center of the sphere, orients manually the pointing device so that the dot of the laser pointer hits exactly this hole.
  - Z puts some 9 dots of silicone at the back of the mirror/plain glass sandwich and passes it to X.
  - X removes the square cardboard and places the trapezoidal mirror in position, and puts the cardboard over it. Y looks for the reflected dot and indicates to X on which side to press (and thus crush the silicone dots) to bring the reflected dot in the middle of the target. This is usually easily achieved. In the worse case, the error is of about 2'.
  - One more person is needed to carry and prepare the mirrors.

The red dot of the laser beam hits the centre of a mirror

The mirror-laying team at work
(laying on a second "first line" above a cardboard strip)

6. LOOP

From the outset, our project proposal stated that this bowl would be operational – and not an experimental one. This means that good promising solutions were not going to be sufficient for us; the adopted solutions had to be reliable with a proven track record in real situation. Solar systems being very specific; their solar components cannot be extrapolated from other non-solar thermal systems. We could therefore only draw experience from existing solar bowls, and also to a certain extent, from other concentrating devices such as solar dishes and troughs.

Besides their reflective surface (which has already been dealt with in this report), the other "exclusively" solar component of a solar thermal concentrating systems is the receiver at their focus. As said above, to design it, we can only refer to existing bowls.

The choice of the fluid that gets heated inside the receiver conditions the whole functioning of a solar bowl and could be the key to its success or the reason for its failure.

6.1. CHOOSING BETWEEN DIFFERENT FLUIDS

6.1.a. Water or heat transfer fluid

One has to choose between 3 options for the fluid used in the solar boiler and hence in the primary loop.

- A heat transfer fluid as used in the French bowl (PERICLES).
- Pressurized water as used in the American bowl (Crosbyton).
- Water and steam as used in Auroville Mini Bowl. (But no attempt had been made to control the process). The water is turned into steam in the solar boiler, as is the case in conventional (non-solar) boilers. Such diphasic systems are called DSG (Direct Steam Generation).

Theoretically, **di-phasic or DSG systems** seem to be the best and they are under study by some research laboratories for solar troughs. According to our information, there are still many problems to solve before they can be said to be well mastered and thus reliable. DSG systems are probably the solution for the future, but we believe it is still too early to use them now in an operational project.

To use **pressurized water**, one needs to feel confident to operate a high-pressure system. At 10 bars, water is transformed into steam at 179ºC; at 20 bars it is at 211ºC; at 30 bars: at 232ºC and at 40 bars: at 249ºC. As the designed output temperature of the boiler is 250ºC, we would have to work at a pressure of 40 bars minimum and we certainly did not feel confident to handle pressures of more than 20 bars in such an environment. Another option would be to limit the boiler's output temperature to 200ºC; but we thought it would be bad technically – and thus economically.

> The 20-meter diameter American bowl (at Crosbyton) used pressurized water for power generation; but it was finally abandoned after having been extensively tested for 2 years. The conclusion of its team of researchers was that it could only be interesting on a larger scale (60-meter diameter) and in the context of a developing country. As far as we know, the final results were never published.

Heat transfer fluid is the third option; the French team (PERICLES) used it. Their bowl was designed to produce heat for process – like ours. There are however some disadvantages in using heat transfer fluid rather than water. It is much more expensive and difficult to handle. It implies specific requirements for the design and operation of the system using it. It leaks much more easily than water. Beyond a certain temperature, the fluid may catch fire. However, all these problems seem to be now well mastered and heat transfer fluids are commonly used for many applications in India and elsewhere.

For us, the more convincing argument in favor of this solution was the fact that the PERICLES team had used it successfully. After being built and experimented with in Marseilles (France), the PERICLES bowl was dismantled and rebuilt in Recife (Brazil) where it was operated and maintained by non-specialists in a technically non-sophisticated environment. It worked continuously for two years without any problem. After that, a small leakage occurred. It would have been easy to fix it, but by that time the French Government had lost all interest in solar energy and the CNRS team could not do the servicing required for lack of financial support… The repair was never done and the bowl was abandoned. For us, this performance classifies this technology as a "proven" one.

In addition to this, we had a lot of printed information on the French bowl. Mr. John Harper (a member of our team and father of Auroville's Mini Solar Bowl) was already in contact with Prof. Authier (head of the PERICLES project) who even inspected John's bowl in Auroville. Some other member of our Auroville community had kept corresponding with Prof. Authier and when we re-contacted him for this project, he accepted to help us – though he is now retired. He however insisted that he could only help us if we would use also a heat transfer fluid, as he had no experience in the other systems. Prof. Authier provided us with more documents and advises and he introduced us to another member of his team: Mr. Jean Debilly who was the technician in-charge of putting the engineer's ideas into a concrete reality. It is Mr. Debilly who had to solve all the petty practical (but often crucial) problems and his advises have been extremely valuable to us as such problems are seldom mentioned in scientific reports.

The French team had done successfully what we ourselves want to achieve; they offered their help; we really felt we would succeed by following their advice.

Another advantage for us in such a system is the fact that we needed absolutely a heat storage tank; and it is fairly easy to include one in a system that uses a heat transfer fluid in its primary loop. The fact of using a heat transfer fluid in the receiver enables us to connect it directly with a heat storage tank full of the same liquid. This entire primary loop operates at a relatively low pressure – which is an advantage. If we had used water, we would have had to either include a heat exchanger to pass on the heat from water/steam to a heat transfer fluid and then a second one to pass it back from the heat transfer fluid to water/steam. Otherwise we would have had to store steam (or pressurized water) at a high pressure.

After operating the system for many months, it appeared that the problems of leakage are indeed difficult to fully solve. Tiny leakage on welding may occur and it is almost impossible to weld on it; the presence of heat transfer fluid seems to prevent the welding cordon to really stick. Flanges with suitable gaskets do not leak. Threaded joins on the pump leak and valves leak along the shaft of their wheels; fumes come out with a strong smell. We have not found as yet a way to fully solve this question.

6.1.b. “Therminol 66” versus petroleum products

We chose the same heat transfer fluid used in the PERICLES bowl and in most other solar projects. It’s producer Mosanto (it is now marketed by ”Solutia”) calls it now “Therminol 66” (earlier it was known as “Gilotherm”). Despite its price this fluid has been preferred to much cheaper ones that are produced from petroleum products for the following reasons:

- The lifetime of Therminol 66 is about 20 years, as against 2 to 4 years for other heat transfer fluids.
- Petroleum products create an important scaling of the circuit that needs to be cleaned out every two years. This cleaning done after thoroughly emptying the loop is a difficult and tedious affair. Therminol is said not to provoke any scaling or deposit inside the pipes.
- Contrary to that of others the thermal stability of Therminol 66 is well proven and very much appreciated by its users.
- As Therminol 66 hardly evaporates, it doesn’t need to be replaced, only a little bit of re-filling once in a while.

All these reasons make Therminol 66 cheaper in the long run, which is why so many users opt for it.

> All the polyester industries in India are said to use it, though many of these industries are actually owned by petroleum companies which manufacture their own heat transfer fluid.
>
> Therminol 66 is also the most commonly used fluid in solar thermal concentrating systems working at temperatures around 250ºC. In particular, it is used in the solar troughs of the 350Mwatts SEGS power plant (previously known as “Luz”) in the Mojave Desert in California.

Therminol 66 physical, chemical and thermal characteristics are given in Annexure C.

6.1.c. Basic principle of the loop of Auroville Solar Bowl

Our loop actually consists of 2 loops linked by a common element, a heat exchanger, which is a coil placed inside the heat storage tank.

- The primary loop is filled with Therminol 66; it includes the solar receiver, the heat storage tank cum heat exchanger, an expansion tank and a pump.
- The secondary loop is fed with softened water. A piston pump sends this water through the coil of the heat exchanger cum heat storage tank, where it becomes steam; it then passes through a steam separator and heads towards process where it condenses back into water in double-jacketed steam cooking vats. This condensed water then returns to a “condensate tank”, which feeds it back to either of the two boilers.
  The system is hybridized, which means that in parallel to this secondary loop, there is a diesel-fired boiler with its own water pump, which is also fed with softened water. The steam produced by this boiler goes though a second steam separator and a pressure reducing valve.

6.2. HEAT STORAGE TANK cum HEAT EXCHANGER

(The element linking together the two loops).

The capacity of the heat storage tank cum heat exchanger is such that it can store some 60 minutes of peak energy production; it is a well heat-insulated cylindrical container and holding some 1,100liters of heat transfer fluid. It is made of 6mm thick Mild Steel.

To produce steam, we opted for the simplest method by placing a coil inside the heat storage tank to create a heat exchanger. Water is pumped through this coil, where the ambient heat turns it into steam. A simple pressure controller adjusts the flow. The problem with this technique lies in the risk of having a water hammer effect and a very serious problem if ever steam would leak inside the heat storage tank.

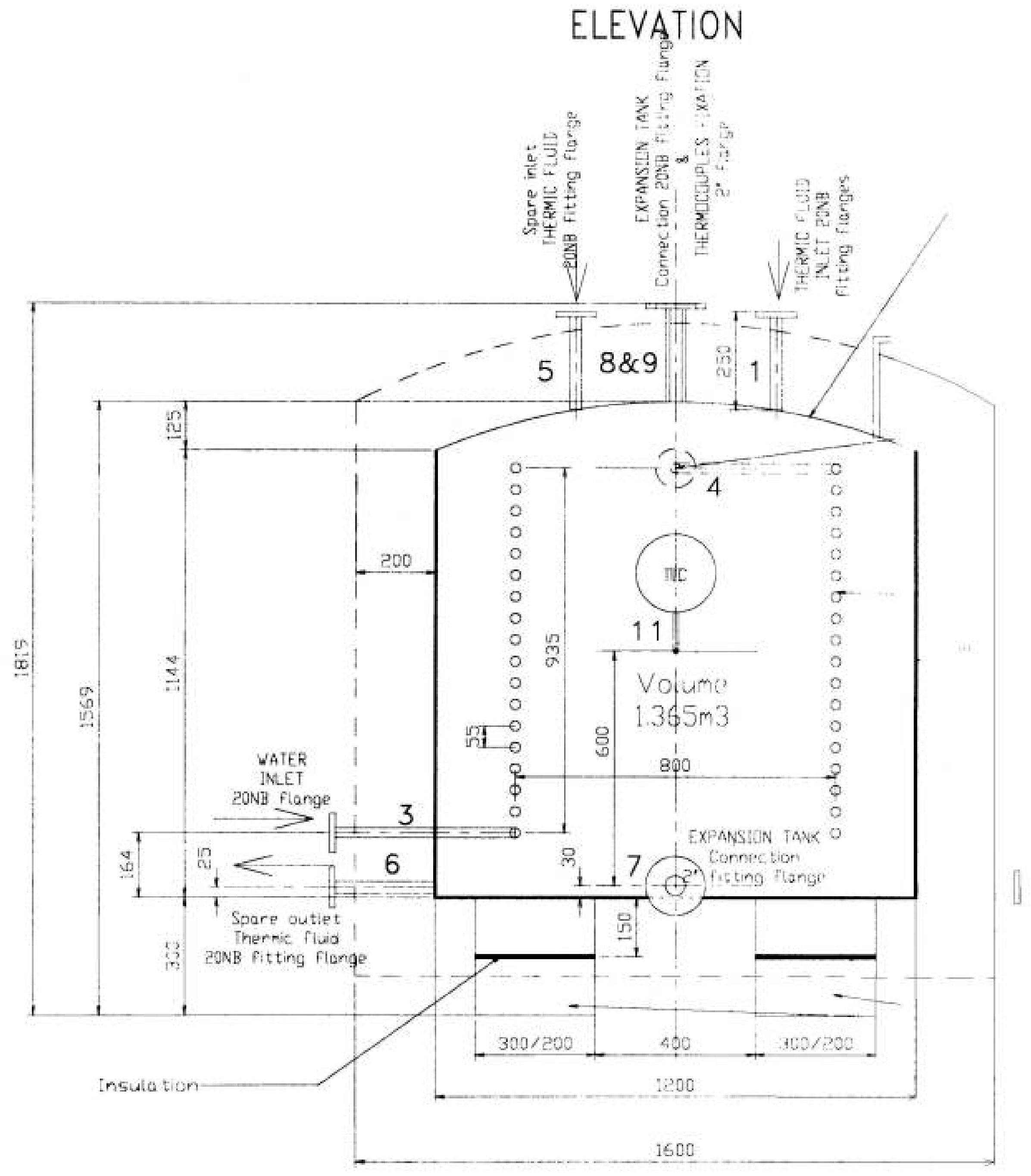
Another option would have been to add another vessel kept full of water pressurized at 2 bars and have coils (or plates) submerged in it and pump hot heat transfer fluid through these to produce steam. In this concept, the level of steam production can be freely chosen, within limits set by the available oil temperature.

This option is costlier in terms of equipment and running costs. I.e.: gear pumps capable of pumping fluids at high temperature are very costly and running this 2nd gear pump would also consume energy.

<u>It is absolutely essential to avoid any possibility of leakage that would put the heat transfer fluid in contact with water – or steam</u>. As the high temperature steam could eventually corrode the coil, and create a leak in this crucial area, we decided to use a stainless steel coil for the heat exchanger – though in terms of heat transfer Mild Steel would have been better. Special attention has been paid to the way this coil is welded. Our calculations showed that if we opted for a ¾" stainless steel pipe, it had to have 18 rounds. This coil was bent using a hydraulic pipe bending tool, but after doing the first trials at 200°C, it developed some cracks which resulted in dozens of pin holes through which the heat transfer fluid leaked inside the coil – which is naturally totally unacceptable. We thus had to change the coil and decided to make another coil winding 40 rounds of ½" SS pipes.
The heat storage tank is equipped with a thermo-couple placed in a side pocket near its centre. Another 8 pockets placed at the top have been provided to enable us to place thermocouple at different levels and study the heat stratification.
Naturally, the heat transfer fluid is pumped from the bottom of the tank and after being heated up in the receiver returns in the tank by its top.

Heat Storage Tank
(prior to its insulation)

Coil of the Heat Exchanger
(The one that had to be replaced)



1 Thermic fluid inlet	- 20Nb – fitting flange
2 Thermic fluid outlet	- 20Nb – fitting flange
3 Water inlet	- 20Nb – flange
4 Steam outlet	- 20Nb – flange
5 Spare thermic fluid outlet	- 20Nb – fitting flange
6 Spare thermic fluid outlet	- 20Nb – fitting flange
7 Connection expansion tank	- 2" – fitting flange
8 Connection expansion tank	- 1" – fitting flange
9 Pockets for thermocouples	- 2" – flange
10 Temperature indicator	- 15NB - open
11 Temperature indicator & controller	- 15NB - open

Plan of the Heat Storage Tank cum Heat Exchanger

6.3. SECONDARY LOOP

In the secondary loop, there is only water and steam.

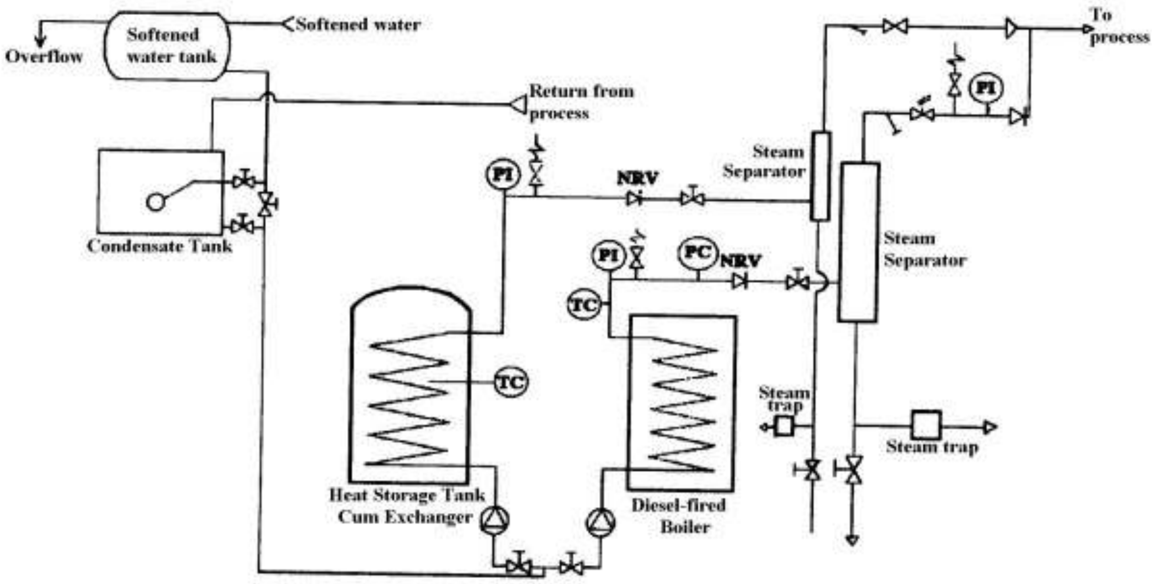


Diagram of the secondary loop

6.3.a. Water softener & accessories

In order to reduce considerably the risk of scale formation in the coils of the diesel-fired boiler and of the heat exchanger, the whole circuit is fed only with softened water.

As the pressure from the overhead pump is sufficient, there is no need of a centrifugal pump to force water through the **water softener** (Ion Exchanger) and fill a (700liter capacity, plastic) **softened water tank**. The pump is controlled by a level-switch fixed in the softened water tank.

A **dosing tank** in plastic holds the chemicals that are necessary to soften the water (caustic soda and sodium sulfite, or replace both by sodium hexometaphosphate). A dosing valve controls the flow of chemicals.

6.3.b. Condensate tank & accessories

The softened water tank fills a **1,000liter capacity hot water tank** (also called condensate tank) that is in stainless steel to avoid corrosion and (will be) heat insulated with 5cm of rockwool covered with an aluminum foil.

This tank is filled from above with hot water that comes from the steam that condensed back into water inside the steam cooking vats and is released in the condensed water line by a steam trap. Though the cooking vats are lower than the condensate tank, there is still enough pressure in the condensed water line for this water to reach the condensate tank.

(Note that the hot water that comes out of the two steam separators is not recycled.)

This tank is also filled at mid level with water coming directly from the softened water tank. Part of the water that is pumped into the loop evaporates and thus doesn’t get recycled; it therefore needs to be replaced with softened water. This inlet is at mid-level only and controlled by a float valve to make sure that 1) there is always sufficient water in the hot water tank and 2) there is always sufficient place in this tank for the condensed water to come back without making it overflow.

Water softener (bottom right), (plastic) softened water tank (top), (stainless steel) condensate tank (prior to its insulation)

6.3.c. Heat Exchanger, its pump and controls

The Heat Exchanger itself has been described in 6.2.

Pump of the Heat Exchanger

The heat exchanger is fed by softened water coming from a pump that is capable of pumping 100liters per hour of hot water (80ºC) at a pressure of 15kg/cm². This pump is similar to the one of the diesel-fired boiler to make maintenance easier.

A 1HP 3-phase motor powers this pump.

A temperature controller allows the pump to work only if the temperature inside the heat storage tank is high enough.
A pressure controller placed on the steam outlet of the heat exchanger controls the pump in the same manner as the pump of the diesel-fired boiler is controlled.

The mixture water/steam coming out of the heat exchanger goes through its own steam separator after passing in front of a safety valve calibrated at 3bars. Steam naturally goes to process; but the small amount of waster that comes out of the steam separator goes is not recycled.

6.3.d. Diesel-fired Boiler

Diesel-fired Boiler
(Revomax RXA-02 from Thermax)

The diesel-fired boiler that has been installed is a "Revomax 200" from "Thermax", a fully automatic non-IBR boiler capable of evaporating 200kg of water an hour.
(Non-IBR means that the specifications of this boiler are such that the tough provisions of the "Indian Boiler Act" don't apply to it, because it is not dangerous).

Its two motors (blower and pump) require a 3-phase electrical connection.

It works intermittently and is controlled by a pressure controller.

A 100-liter diesel tank placed at a high point in the technical room feeds the boiler by gravity. This overhead diesel tank is filled with a small ordinary centrifugal pump, which works fine – though it starts with some difficulty due to the viscosity of the diesel.

6.3.e. Controls of the hybrid boiler

As said, if the temperature in the heat storage tank is high enough (i.e.: 180ºC), the water pump of the heat exchanger is allowed to work. A pressure controller placed just after the heat exchanger keeps the pressure in the pipeline between 2 and 2.5 bars.

If ever the pressure falls below 2 bars (this happens when the heat exchanger produces less steam than required), the pressure reducing valve placed on the steam line coming from the diesel-fired boiler will let steam coming from go through and deliver the balance amount of steam.

(A pressure controller keeps the pressure of the steam coming out of the diesel-fired boiler between 5.5 and 7.5 bars. This steam goes through a steam separator and then through a pressure reducing valve, which lets steam go through it as long as the pressure in the steam line after that valve remains below 2 bars.)

Note that the primary loop functions independently and heats up the heat storage tank – if there is sufficient (direct) solar radiation.

6.3.f. Process

The Solar Kitchen is presently equipped with:

- 1 No. 5-door rice/idly cabinet,
- 3 Nos. 75-liter capacity double jacketed vat,
- 1 No. 100-liter capacity double jacketed vats
- 2 Nos. 250-liter capacity double jacketed vats,
- 1 No. hot water tank,

6.3.g. Pipe connections

Water from the hot water tank flows by gravity to both the pump of the diesel-fired boiler, and that of the heat exchanger. All pipes are Mild Steel ¾" "Tata" "C" Class. They all received a layer of thermal insulation material (mineral wool) covered by an aluminum foil.

Expansion Tank installed on the roof

6.4. PRIMARY LOOP

The primary loop is that part of the loop that is filled with heat transfer fluid. It consists of two different sets of pipe connected to the heat storage tank:

- A 1st set of pipes is used to bring heat harvested from the sun to the heat storage tank:
  Heat transfer fluid comes out of the bottom of the heat storage tank. It then passes through a strainer and then a (gear) pump that pushes it up to the top of the mast, down to the bottom of the swinging arm and then up though the coil of the receiver (or solar heater). After that, it goes back to the top of the mast before returning to the top of the heat storage tank. Air vents are provided at each one of the 3 high point.

- A 2nd set of pipes is needed to deal with the problem of expansion of the heat transfer fluid with the rising temperature:
  As heat transfer fluids expand a lot; approximately 7% per 100 °C; an **expansion tank** placed above the Heat storage tank is therefore necessary. It is placed on the roof of the kitchen (above the first floor), a little higher than the highest point of the loop (the top of the mast) so that the fluid simply flows by gravity to every part of the loop.
  To prevent any risk of oxidation of the heat transfer fluid, we kept the option of nitrogen blanketing – in which case the expansion tank will be connected to a nitrogen bottle that will also keep the pressure at the correct level (approx. 1 bar).

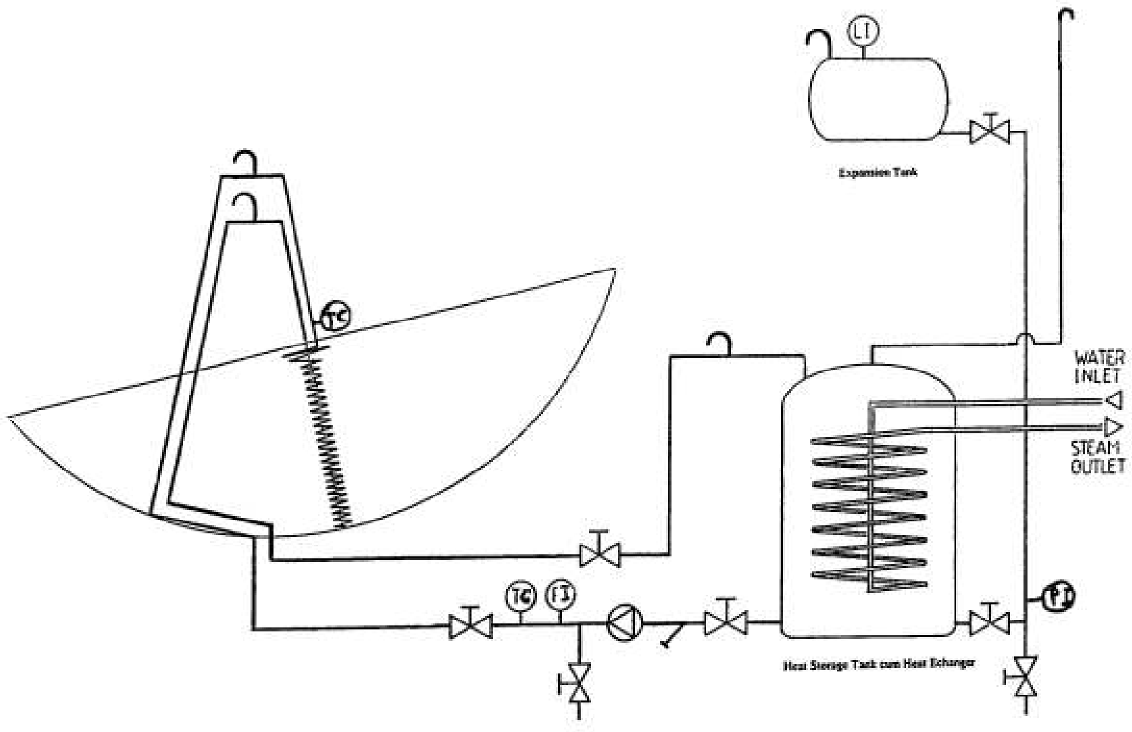


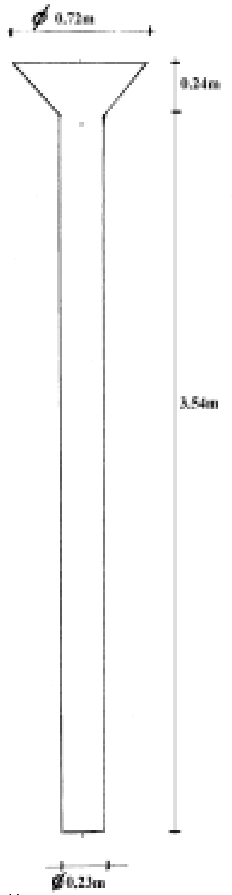
Diagram of the primary loop

6.4.a. Receiver

The surface temperature of the solar heater (receiver) may reach 600 °C; and the working temperature will be in the range of 30 to 300 °C.
The pressure always remains a little above 1 bar, even at the first start when cold.

1. Design of the receiver

As said earlier, we used the PERFAC computer program to optimize the geometry of the receiver. The parametrical study and process used to define the final shape of the receiver is described in Annexure B.



As said earlier, the result is a receiver of 378cm length that is the addition of two different elements:

- The lower portion, where the concentration is low, and which is almost touching the reflector, is a cylinder with a diameter of 23cm and a length of 356.04cm
- The upper portion, where the concentration is high, has the shape of an inverted truncated cone with a minimal diameter of 23cm and a maximum diameter of 72cm; its length is 24.08cm.

Geometry of the final Receiver

According to PERFAC's calculations, the geometric interception factor (% of the reflected rays hitting the receiver) varies between 97.7 and 99.3% according to the angle of the sun for an average error of 10' in the mirror orientation and 10' error in the positioning of the receiver by the tracking system. The geometrical concentration ratio varies from 18 to 99 in the low concentration part (cylinder) and raises up to 212 in the high concentration part (inverted truncated cone). The receiving characteristics of this receiver are detailed in Annexure B.

The PERICLES team used a receiver made of two concentrical cylinders. Between these two, a square thread (of 6mm side) was welded around the inner cylinder, thus creating a vein where the heat transfer fluid circulated. The thread also needed to be welded inside the outer cylinder; therefore a steel foil was cut at the same width as the vein and then welded on both sides to the square thread. This receiver worked fine, but when the PERICLES team made the study of a 40meter diameter solar bowl, they came up with another technique to realize its receiver: to simply wrap around a sleeve a set of several parallel pipes. We hesitated between these two techniques.

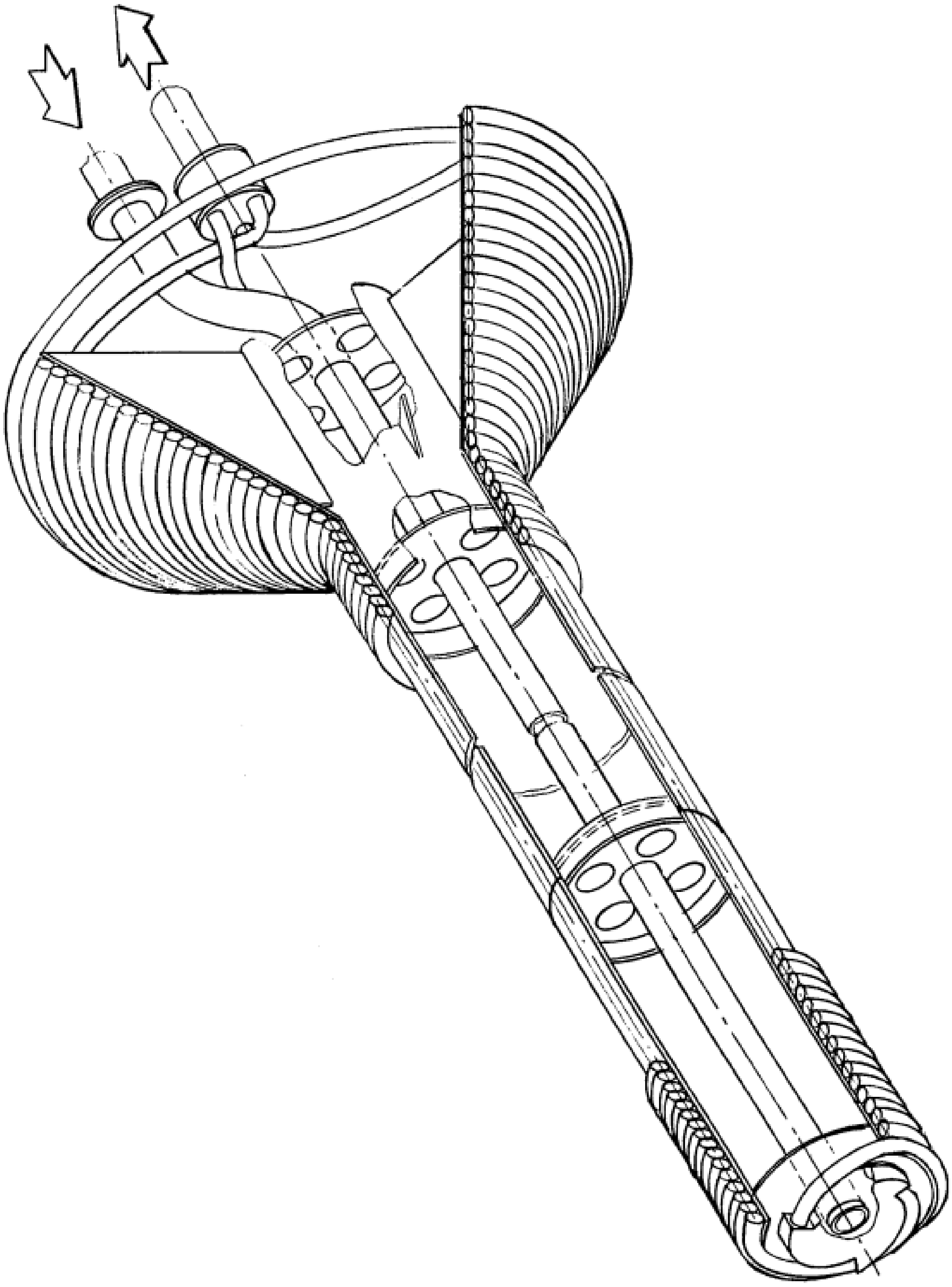
In the first one, a thin steel sheet (1mm thick) is used as outside cylinder therefore facilitating the heat transfer to the fluid. But it requires a great length of welding of a very thin foil on a small thread. We thought that it would be prone to leakage of heat transfer fluid (at 300°C just above the mirrors… No thank you!) Actually, new techniques are now available to weld a foil on a supporting steel element without having to cut it. Once completed, the welding is controlled by radiography. These techniques are not available to us – at least not easily; and would somehow defeat our purpose which is to try and realize a rather low-tech, easy to maintain bowl. Considering all this, we opted for the second technique: wrapping several small parallel pipes around a supporting sleeve. A computer study, which is included at the end of this chapter, has shown that 3 parallel pipes were more suitable than 2 or 4.

The receiver is designed in such a way that it is easily detachable from the swinging arm and disconnected from the pipes. Once detached, it is lowered (through a 0.8m diameter hole in the reflector) into a cylindrical hole that has been specially made under the bowl. This is to avoid doing acrobatics above the mirrors.

2. Thickness of the cylindrical steel sleeve around which the pipe is wound

According to Mr. Debilly (the member of Dr. Authier's team who actually made the French bowl), a sheet of 2mm should form a good enough sleeve for the receiver to remain absolutely straight.
Finally, we decided to use a 1.6mm thick steel sheet only, but we introduced in it stiffeners in various places. Like this, it should retain its shape while the 3 pipes are being around it and it should not bend when the whole receiver is being tilted while in use and thus full of heat transfer fluid. (Any deformation would be detrimental to the spreading of the flux on the receiver).

Supporting structure of the Receiver
(Note the stiffeners)



Isometric view of the receiver
(Note the stiffeners and the distribution boxes for the heat transfer fluid)

3. Sizing the pipe used as coil for the receiver

As said earlier, the receiver consists of 3 MS pipes wound around a cylindrical sleeve made of steel sheet; and these **each turn of these 3 pipes touches the previous one**.

In order to arrive at the best possible choice for the pipe of the receiver, we conducted a comparative study between several pipes we found on the market.

S. No	Type of pipe	Inner/outer diameter	*Thickness*
1	ERW pipe	17.45/19.95 mm	1.25mm
2	ERW pipe	16.75/19.95 mm	1.6 mm
3	IS 1239: 1968 BS 1387:1967 Light *3/2	13.50/17.10 mm	1.8 mm
4	IS 1239: 1968 BS 1387:1967 Light *3/2	17.00/21.00 mm	2.0 mm
5	***Seamless pipe, imported***	15.40/20.00 mm	2.3 mm
6	Seamless pipe, imported	15.85/19.05mm	1.6 mm
7	The ideal pipe; but as yet we haven't found it on the market	15.00/18.00 mm	1.5 mm

Note:

- "ERW" stands for Electric Resistance Welded. A thin welding line can be seen inside the pipe; but it doesn't hinder the flow of the fluid.
- "Seamless pipes" are extruded and not welded. There is therefore no hindrance to the flow of the fluid.
- "IBR quality pipes" are sold with a certificate issued by a Government Agency stating that this pipe conforms to the provisions of the Indian Boilers Regulation Act. This certificate is only issued for pipes manufactured in India and the smallest such pipe manufactured in the country seems to have an OD of 32mm.

Several considerations intervene in the selection of the pipe used for the coil of the receiver:

1st consideration: Thickness of the pipe:

First, it is essential that the layer of steel that separates the heat transfer fluid from the rays of the sun be **as thin as possible** so that the maximum solar energy is absorbed by the fluid and as little as possible is used to heat up (and keep hot) the layer of metal.

The difference of temperature between the two surfaces of the pipe wall is given by the formula: Δ Twall = e. φ/λ with: e = Wall thickness

φ = Heat flux intensity

λ = Thermal conductivity

For: $\varphi = 800 \times 150$ W/m²

e = 10^{-3} m

λ = 35 W/m °K

We find a temperature difference of Δ T = 3.5 °K; therefore, for each 1mm of added thickness, there is a temperature drop of 3.5 °C

Second, if one uses a coil made of pipes, one cannot take too thin ones as there is a **risk of flattening the pipes while bending them** in a coil around the supporting structure (a cylinder of 19cm diameter ending by a cone whose maximum diameter is 68cm). Experts told us that pipes as thin as 1.5mm thick can be bent without being flattened provided one fills them with sand before bending them. We actually tried bending a 15.85/19.05mm (that is 1.6mm thick) around a 19cm diameter sleeve and we found that it flattened only by 1mm approximately, which we found acceptable.

Third, the thicker: the pipes, the heavier the receiver.

S. No.	**Pipe thickness**	**Weight of the pipes**	**Supporting structure (2mm thick)**	**Acces- -sories**	**Total weight**
1	1.25 mm	75.1 Kg	36.8 Kg	20 kg	132 Kg
2	1.60 mm	94.4 Kg	Id	id	151 Kg
3	1.80 mm	98.0 Kg	37.7 Kg	id	156 Kg
4	2.00 mm	119.0 Kg	36.3 Kg	id	175 Kg
5	2.30 mm	130.8 Kg	36.7 Kg	id	188 Kg

("Supporting structure" = cylindrical steel sleeve around which the pipe is wound).

To calculate the weight of the receiver, we added to the weight of the coil the weight of the supporting structure and we estimated at 20Kg the weight of the accessories. The accessories are: metallic brush and protection plate at the bottom of the receiver; protective cone on top; a connecting device with the arm; a feeding pipe from top to bottom (a 21/27 pipe of 3.78m long weighs 6.4Kg) and a collector at the bottom to distribute the fluid between the 3 coils. And a second collector to bring back the 3 pipes together. The weight of the heat transfer fluid has to be added to this.
Conclusion: **1.5mm thickness seems to be the best compromise** between thermal and mechanical considerations, provided it can be found on the market.

2nd consideration: Inner diameter of the pipe:

Inside the pipes, the flow needs to be turbulent to ensure a good heat exchange with the pipe walls. The "CHAUDIER" program (another program written by the PERICLES team) checks the "Reynolds" number according to flow rate and pipe diameter. The flow is assumed turbulent if Reynolds' number is higher than 4,000.
We opted for a "nominal" flow of 0.6 Kg/s; this flow is suited for a "Solar Constant" (an expression used by the PERICLES team) of 747W/m², that is to say for the "normal" direct solar radiation at noon on a clear day.

- The smaller the inner diameter of the pipes will be, the greater the friction losses will be within the receiver. These friction losses need to be kept at a low level in order to reduce the energy consumption of the pump.
- The greater the speed of the fluid will be, the less high the temperature will get – which is favorable.

Those two last factors are such that the global thermal performances increase while the inner diameter gets smaller.

Conclusion: The inner diameter should be as small as possible within the limit of having acceptable friction losses. **A 15mm inner diameter seems ideal in our case.**

3rd consideration: Outer diameter of the pipe

This characteristic has no incidence on the results. The supporting structure is to be designed in such a way that the outer dimension remains in any case 23cm diameter for the cylindrical part BC and 72cm aperture for the conical part HC. For example, for pipes with an outer diameter of 18mm, the supporting structure (cylindrical sleeve) will have a diameter of 23 - (2 x 1.8) = 19.4cm. One should recall that the outer diameter has been defined according to optical criteria in order to ensure an optimal reception of the reflected rays of the sun.

4th consideration: Head losses

Having selected the size of the pipe, we run the "CHAUDIER" computer program to calculate the head losses for different pipes, smooth or rough inside.

We have reproduced hereunder a sample calculation done by the PERICLES team in the case of a boiler designed for a 40-meter-diameter solar bowl:

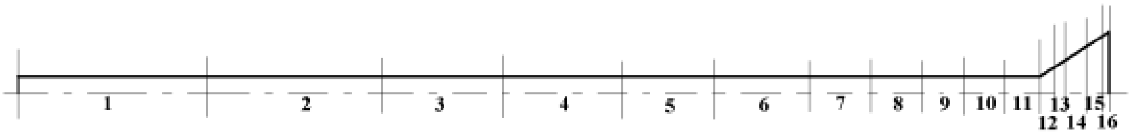
The PERICLES team calculated the following head losses:

	Average height of the asperities	**Head losses**
Smooth pipe with no asperities	None	2.79bars
Pipe with homogeneous asperities	0.02mm 0.10mm	2.90bars 4.59bars
Pipe with heterogeneous asperities	0.02mm 0.10mm	3.43bars 4.67bars

We see that friction losses increase by 67% between the best and worse cases; so we obviously have to find pipes (ERW or seamless) that are perfectly smooth inside.

5th consideration: Temperature distribution along the receiver:

To do this analysis, we run the computer program "CHAUDIER". The receiver is virtually split in 16 "slices" characterized by their height and upper limit (counted from the bottom of the boiler, near the mirrors). The table hereafter shows the temperature distribution for these different sizes of pipes: 17.45/19.95, 16.75/19.95, 15.85/19.05 and the more ideal 15.0/18.0



Slicing of the receiver

Slice No.	Upper limit	*Height*	Concen- -tration	T max (°C) (for Sc = 747 W/m²)			
	Cm	**Cm**		**Case No 1 17.45 /19.95**	**Case No 2 16.75 /19.95**	**Case No 6 15.85 /19.05**	**Case No 7 15.0 /18.0**
1	68.4	68.4	22	171	171	171	171
2	128.1	59.7	28	190	189	189	188
3	170.1	42.0	34	202	201	201	200
4	211.3	41.2	40	214	214	213	212
5	243.0	31.7	48	225	224	223	223
6	275.5	32.5	58	237	236	234	234
7	297.1	21.6	66	245	244	242	241
8	314.1	17.0	73	251	250	248	247
9	328.5	14.4	80	257	255	254	252
10	342.1	13.6	90	263	262	260	258
11	354.2	12.1	99	269	267	265	263
12	359.5	5.3	144	284	281	278	275
13	362.9	3.4	163	290	286	283	280
14	370.5	7.6	212	317	312	306	301
15	375.4	4.9	160	300	296	292	289
16	378.0	2.6	21	249	249	249	249

T max. is the highest temperature reached of the corresponding slice, for a given "solar constant" (in this case 747W/m²). To protect us from any bad surprise, we have taken in consideration for each slice, not the average value of the solar concentration, but the maximum value for a particular slice. Thus, along slice 14 - the most critical one - (a 7.6cm-high portion of the cone HC), the concentration varies in fact from 212 to 163.

- Case No1: is the worst in terms of temperatures because the inner diameter is the largest.
- Case No 6: is the best of the 6 possible solutions with the pipes available on the market.
- Case No 7: pertains to the most ideal pipe, which we could not find on the market.

Note: One should not worry about these values of T maximum as the characteristics of Therminol 66 given by its manufacturer, Mosanto, are:

- Maximum temperature within the vein of the fluid : 345°C
- Maximum temperature in contact with the hot wall: 375°C

Therefore a temperature of 306°C (for the 15.85/19.05 pipe) is perfectly acceptable. PERICLES had a nominal output temperature of 300°C with the same heat transfer fluid.

If we take a "Solar Constant" of 1,000W/m², (such intensity may be happening only once every 10 years in Auroville), the values will be:

	Case No.1	Case No.2	Case No.6	Case No.7
T max (section 14)	341°C	335°C	328°C	321°C

These temperatures are all acceptable as they remain below 345°C. But one sees that in Case No 1 (inner diameter 17.4mm); the safety margin becomes too small. Even in Case No 2 (inner diameter 16.75mm), one sees that it would be advisable to reduce the inner diameter.

In any case, it is not interesting to have a temperature too high. What we require is an output temperature of 250°C. Working with higher temperatures would be a waste of energy; this is why the global thermal performances are much better when the temperature raises less beyond 250°C inside the receiver.

<u>6th consideration: Evaluation of the thermal performances over one year operation:</u>
Having reached that stage of our calculations, we run "THERMIQU", a third computer program written by the PERICLES team. THERMIQU evaluates the thermal performance of solar bowls over an ideal year of operation. The ideal climate as defined means no clouds, 1,000W/m² at solar noon, solar angle calculated for the latitude (that is 12˚ in Auroville) for one average day each month.

We give hereunder sample calculations done with this program. To compare with the overall thermal performances of the bowl, we run the program with 6 different sizes of pipes used for the coil of the receiver. The first six figures correspond to pipes that we found to be available on the market; the seventh one is an "ideal" pipe.

	Pipe inner & outer diameter mm	Weight of the receiver Kg	Friction losses Bar	T max °C	Thermal losses kW	Energy spent MWh	Energy harvested per year MWh	Thermal efficiency
1	17.45/19.95	116	0.33	317	15.45	0.12	248	0.792
2	16.75/19.95	135	0.40	312	15.35	0.12	249	0.795
3	13.50/17.10	148	1.30	294	14.71	0.13	251	0.801
4	17.40/21.40	160	0.31	315	15.81	0.12	246	0.788
5	15.40/20.00	173	0.59	303	15.17	0.12	249	0.796
6	15.85/19.05	151	0.54	306	14.46	0.13	251	0.804
7	15.00/18.00	130	0.75	301	15.00	0.12	250	0.798

Even if the differences between the energy harvested do not appear to be enormous, they are still highly meaningful as they are expressed in megawatt-hours; that is to say in thousands of kW-hours.

Conclusions:

Pipe No1 17.45/19.95 non acceptable

- Thickness 1.25mm: Okay if the coil can be made without flattening the pipes.
- Inner diameter: too big, resulting in too high temperatures and poor performances.

Pipe No.2 16.75/19.95 Okay if the steel quality is good, in which case it is the best of this list, except for pipe No.6 (the ideal pipe)

- The fact of taking a thickness of 1.6mm is a bit too much according to the solar criteria, but it makes it easier to make the coil without flattening the pipe.
- The inner diameter is a bit large, but is acceptable.

An added advantage in this case is that the pipes are without asperity inside.

Pipe No.3 13.50/17.10 non acceptable

- Inner diameter too small, hence the friction losses will be too high; moreover the table shows that the energy utilized increases by 10kWh. The consumption of the pump is a key factor as the economic viability of the bowl would be in jeopardy if the energy consumption to operate it would be too high.
- Thickness 1.8mm: a little too thick

Pipe No.4 17.40/21.40 non acceptable

- Thickness 2mm really too high.
- Inner diameter too high.

Pipe No.5 15.40/20.00 not really good, but acceptable

- Thickness 2.3mm is far too high and increases unnecessarily the receiver's weight.
- Inner diameter okay.

Pipe No.6 15.85/19.05 very good

- Thickness 1.6mm and inner diameter 15.85mm represent the best compromise allowing us to satisfy all the criteria (thermal and mechanical).

Pipe No.7 15.00/18.00 ideal, but could not be found

- Thickness 1.5mm and inner diameter 15mm would be even better.

We opted for a 15,85/19.05mm imported seamless pipe.

As said earlier, we checked by calculation that three (rather than 2 or 4) parallel pipes give the best compromise for the friction losses and the highest temperature reached inside the receiver. Sample result printouts issued by the program CHAUDIER and THERMIC in the "ideal" case (15/18) are given on the next page and more can be found in Annexure D.

Compilation & translation from the French of 4 Output files for a "Chaudier" calculation

Length of the receiver	:	3.78m
Diameter of the low concentration portion	:	0.23m
Maximum diameter of the high concentration portion	:	0.72m
Surface of the receiver	:	3.10m²
Input temperature	:	150°C
Output temperature	:	250°C
Highest acceptable temperature	:	370°C

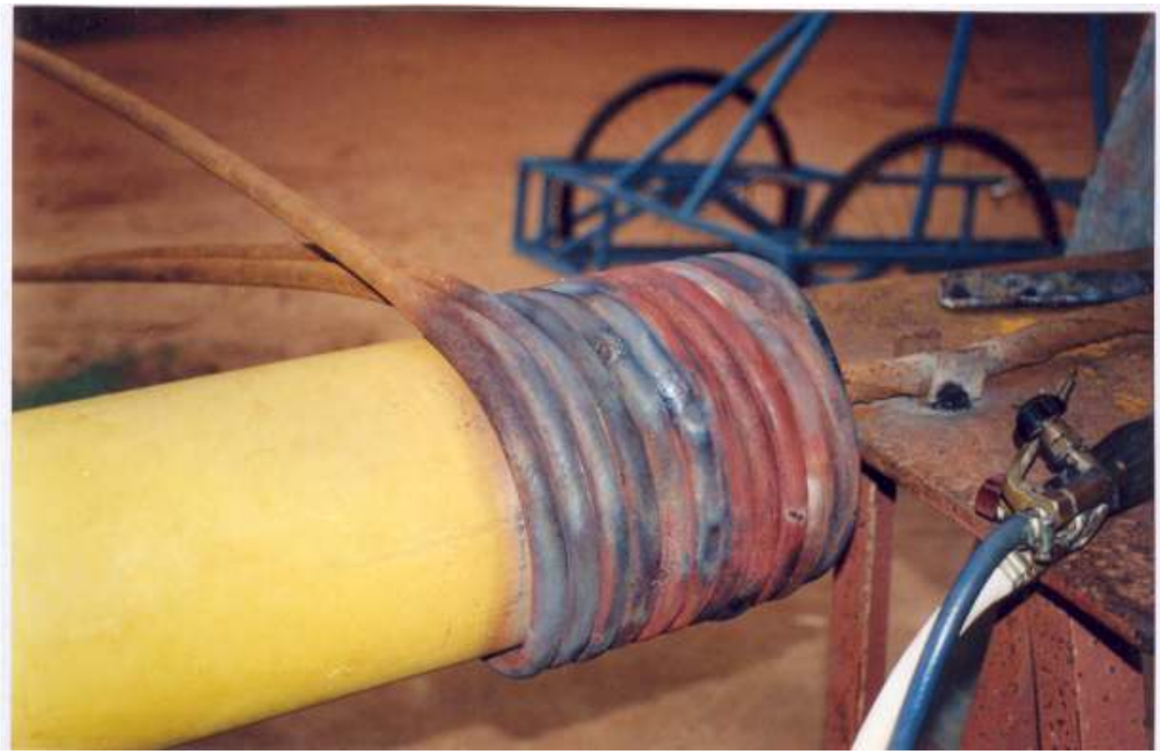
Solar constant is 747W/m² in all cases, except for 6 veins for which we took 1kW/m²

Slice No.	Inner dia mm.	Outer dia Mm.	Maximum Temperature (°C)			
			3 veins (flow/vein = 0.20kg/s)	4 veins (flow/vein = 0.15Kg/s)	5 veins (flow/vein = 0.12Kg/s)	6 veins (flow/vein = 0.10Kg/s)
1	12.40	14.40	170	170	171	174
2	12.40	14.40	187	188	188	193
3	12.40	14.40	199	200	200	205
4	12.40	14.40	211	212	213	218
5	12.40	14.40	221	222	223	230
6	12.40	14.40	231	233	234	242
7	12.40	14.40	238	240	242	251
8	12.40	14.40	244	246	248	258
9	12.40	14.40	249	251	253	264
10	12.40	14.40	254	257	259	271
11	12.40	14.40	159	261	264	277
12	12.40	14.40	268	273	277	295
13	12.40	14.40	272	277	281	302
14	12.40	14.40	288	296	303	333
15	12.40	14.40	279	285	290	312
16	12.40	14.40	249	249	249	251

Head losses if the inside of the pipes is smooth:
(Combined total flow: 0.60 Kg/s; Weight of the pipe: 71 Kg; Volume of fluid: 26 liters)

No of veins	3	4	5	6
Head losses	2.31	1.05	0.57	0.38

Conclusions for a pipe of 12.40/14.40:
Temperature is maximum in slice No 14. When there are 3, 4 & 5 veins it is acceptable, but it is too high when there are 6 veins.
Head losses are too high for 3 veins and a bit high for 4 veins; acceptable for 5 & 6 veins.



Bending in shape the coil of the receiver
by heating up its 3 pipes with an oxy-acetylene torch
(A DC welding set was used to join the pipes end to end)

6.4.b. Pump for the heat transfer fluid and flow control

According to our calculations, the maximum flow of heat transfer fluid will be of 0.6kg/second; that is 06/0848 (density of Therminol 66 at 250°C) = 0.707liters/second = 2,547liters/hour. Therefore, this pump should be able to pump a little more than 2,500liters of Therminol per hour and accept temperatures of 300°C and a little above.

We opted for a gear pump from "Matz". Its specification is given in Annexure E.

It is rated as pumping 2,500liters/hour (42liters/min) at 1,440tr/min and can function up to 450°C. Both the inlet and the outlet have a 40mm diameter. To select the motor that powers this pump, the main problem is that this "nominal" flow-rate is likely to change often because of passing clouds for example; and first of all, at the start in the morning.

"Matz" pump and its motor

(the strainer is placed just before it)

Selection of a motor for this pump:

This motor has to be powerful enough to be able to start the pump when the fluid is cold (and thus difficult to move).

The <u>viscosity of the pumped fluid</u> is changing with the temperature. This creates an important problem in the morning at the beginning of bowl operations. The cinematic viscosity is of 55.5mm²/s at 30°C; of 1.65mm²/s at 150°C and of 0.67mm²/s at 250°C. So, the viscosity is 30 times bigger at the first start than during normal operations.

We concluded that a 1 HP motor would be sufficient and we were proven correct.

Flow control:

Usually, to adjust the flow to the required flow rate, a proportionate valve is installed immediately after the pump to send back to the pump part of the fluid, via a by-pass of the pump. This technique is simple; but the pump would be working at full speed even when the required flow-rate is very low. By doing so, we would be wasting electricity, which is not acceptable in a solar system.

To feed this 1 HP pump we use a (Japanese made) frequency variator (imported in India by Larsen & Toubro).

Frequency variator

This frequency variator is fed with single-phase current (240V).

This is an advantage because it is absolutely crucial that this pump doesn’t stop in case of power cut (which are very frequent in rural Tamil Nadu). A large battery bank (submarine batteries on loan from the Indian Navy) was already available with us, and also a single-phase inverter; but 3-phase inverters being very costly, we were happy to be able to save this additional expense.

This frequency variator produces three-phase current (240V between phases).

As one can only find on the market motors using 380 volts between phases, **we installed a motor rotating at 1,400rpm and rated at 1.5HP when supplied with 380V at 50Hz**. As it will be fed with 240V only, its power will only be of 1 HP.

This frequency variator produces three-phase current whose frequency can be made to vary as programmed from 2 to 60Hz. This means that:

- at 50Hz, the flow will be of 2,500 x 1,400/1,440 liters/min = 2,430liters/min
- at 2Hz, the flow will be of 2,430/25 = 98liters/min
- at 60Hz, the flow will be of 2,430 x 60/50 liters/min = 2,916liters/min

The range of flow is thus sufficiently wide and is thus satisfactory.
The frequency variator s controlled by a 4 set points controller connected to a temperature gauge placed in the pipeline just after the receiver. It is presently programmed as follows:

- below 100°C: 10 Hz
- Between 100 and 200°C 20 Hz
- Between 200 and 280°C 35 Hz
- Above 280°C 50 Hz

6.4.c. Pipeline, valves, heat insulation

- The line from heat storage tank to receiver and back, as well as the line from the top of the heat storage tank to the top of the expansion tank are in Mild Steel 1¼" "Tata" "C" Class.

- The line from the bottom of the heat storage tank to the bottom of the expansion tank is in Mild Steel 1" "Tata" "C" Class.

- All lines are insulated with 10cm of mineral wool clad in an aluminum foil as thermal insulation. The two lines to the expansion tank are only insulated on that part oft heir length where they are getting hot.

- Three air vents (SS valves ½") were installed at the three high points of the loop: On top of the mast (one on each line), and one on the return line, above and just before the heat storage tank.

- Valves are provided just below the expansion tank (on the line linking the bottom of both tanks) and also next to the heat storage tank on the three lines:
  - To receiver
  - From receiver
  - From bottom of heat storage tank to bottom of expansion tank.
    Purposely no valve has been installed on the line linking the top of the two tanks as closing all 4 lines could lead to an explosion (or severe damage) of the heat storage tank in case the temperature there would vary and with it the volume of the fluid.

- There are purges at the lower points of each of the 3 lines. None of these are equipped with valves, but with stoppers (end-caps).

- There is a possibility to fill the expansion tank with Nitrogen in order to protect the fluid from corroding at high temperature.

- Three temperature sensors have been installed: just before the pump, just after the receiver and in the middle of the heat storage pump.

- Two pressure gauges have been installed: one just after the pump to check the pressure when pumping at low temperature, one on the line linking the bottom of both tanks in order to check the oil pressure/level in the line. It gives a good indication of the heat stored in the loop.

- The supports of the pipes are designed in such a way that they allow the pipes to expand with the rise in temperature.

- Stainless steel hoses were used next to the articulation and also to compensate for the expansion of the pipes with the rise in temperature.

Recommendations for pipeline filled with high temperature "Therminol 66"
(as advised by the PERICLES Team)

Therminol 66 gets highly fluid at high temperature. A certain number of precautions are thus necessary:
The experience acquired by the PERICLES team while building and operating a Solar Bowl using Therminol 66 has brought them to suggest some technological constraints for the realization of the primary loop of a Solar Bowl.
This document does not take into consideration the local regulations, which should be abided to by the builder of a bowl.

1. Pipes

- They should be painted with a high temperature resistant anti-rust paint.
  Aluminum paints resisting temperatures of more than 350°C are available on the market..
- In order to avoid thermal losses, asbestos millboard at least 40mm thick need to be used inside the clamp, which support the pipes.
- The design of the pipeline has to be such that the flanges should always be in a vertical plan so that if ever there is a leakage, the Therminol 66 doesn't get into the insulation material. Therminol 66 is auto-inflammable at a temperature of 280°C in a confined atmosphere.
- The bolts of the flanges will be in stainless steel; or at least in GI and covered with high temperature grease, or covered with a product based on MoS^2.
  i.e.: "ServogenHT" high temperature grease.
- The nuts of the bolts of the flanges will be tightened using a torque spanner until one reaches the suitable crushing of the gasket. This crushing is to be determined in agreement with the manufacturer because of the thermal shock.
  It is provoked at a pressure of 3Kg/mm² for SPZ caskets supplied by "Trouvay Cauvin" (France), and 5Kg/mm² for "Klinger Oilit" gaskets.
  It is essential to have an adequate positioning and number of spring washers.
  We used "Champion Oil 59" gaskets.
- The design of the pipeline will be such that it can compensate for fast dilatation under frequent thermal shock. The pipeline of a solar system is expanding at least once a day. The efforts created by the dilatation of the pipeline cannot be taken by elements which are anchored (Heat Exchanger, pumps, etc.). One should include some device to absorb this expansion and maybe some buttress for the pipeline).
  We used stainless steel hoses in bends.

2. Valves, etc.

- These elements will have to be made of steel. Bronze is prohibited in contact with hot Therminol 66 and cast iron is usually porous with Therminol 66.
- The valves will allow the passage of fluid as direct as possible (head losses) and will have a SS bearings, because of the very high fluidity of Therminol 66 at high temperature.
- The air vents and the drains, though they are not in contact with the hot vein, should be able to bare a temperature of 340°C. Ball valves on PTFE bearing are not acceptable.

3. Safety elements:

- The safety valves should be – if possible – of the lever type to make the checking easy, and will also have a sealed outlet.
  As we have an expansion tank, we did not include any safety valve on the primary loop (there is no pressure).

- The safety valves will be connected to small recuperation tanks that will collect the hot Therminol 66 in case of leakage.
  Note: Depending to the local regulations, these tanks will be dimensioned according to either the recuparation of the safety valves (a few liters), or the complete drainage of the whole installation (1,300 liters).

4. Heat Insulation:

The flanges, and other junctions, will be – as much as possible – heat insulated. On the Mini-PERICLES, a mattress of asbestos and glass wool was used.

Below each flange, there was a small steel cup filled with some absorbing product to recuperate the Therminol 66 in case of leakage. This system enabled the PERICLES team to also check that the joints were well sealed.

Mast & Swinging Arm

Anchoring of one of the guy pipes

7. MAST, ARTICULATION & SWINGING ARM

7.1. MAST & ITS GUY-WIRES

The structure supporting the articulation, the tracking system and the swinging arm is single legged; it is a mast that rests on a steel base plate placed inside the bowl, but more than one meter outside the trajectory of the receiver (to the South).

This steel base plate is supported by (and anchored to) a RCC foundation, which is attached to the RCC beam that tops the larger of the two cylindrical walls on which, the bowl is resting.

The mast is tilted towards the North and needs to be held back. The Texas Tech University designed a similar tilted mast for the Crosbyton Bowl and held it back with two pipes whose diameter was big enough for them not to bend or vibrate in the wind. We thought of using simply two over-dimensioned steel guys, but finally opted for 2 thin 3D-truss beams to reduce both the shadow and the possibility of vibration for the guys and mast. These 3D-truss guys are attached to two anchoring hooks, which were purposely incorporated in the RCC slab of the terrace.

Along this mast, run the two insulated pipes bringing thermic fluid from the receiver to the heat storage tank and back. The total width of the aluminium cladding that contains both insulated pipes is nine inches (2" + 1¼" + 2½" + 1¼" + 2").

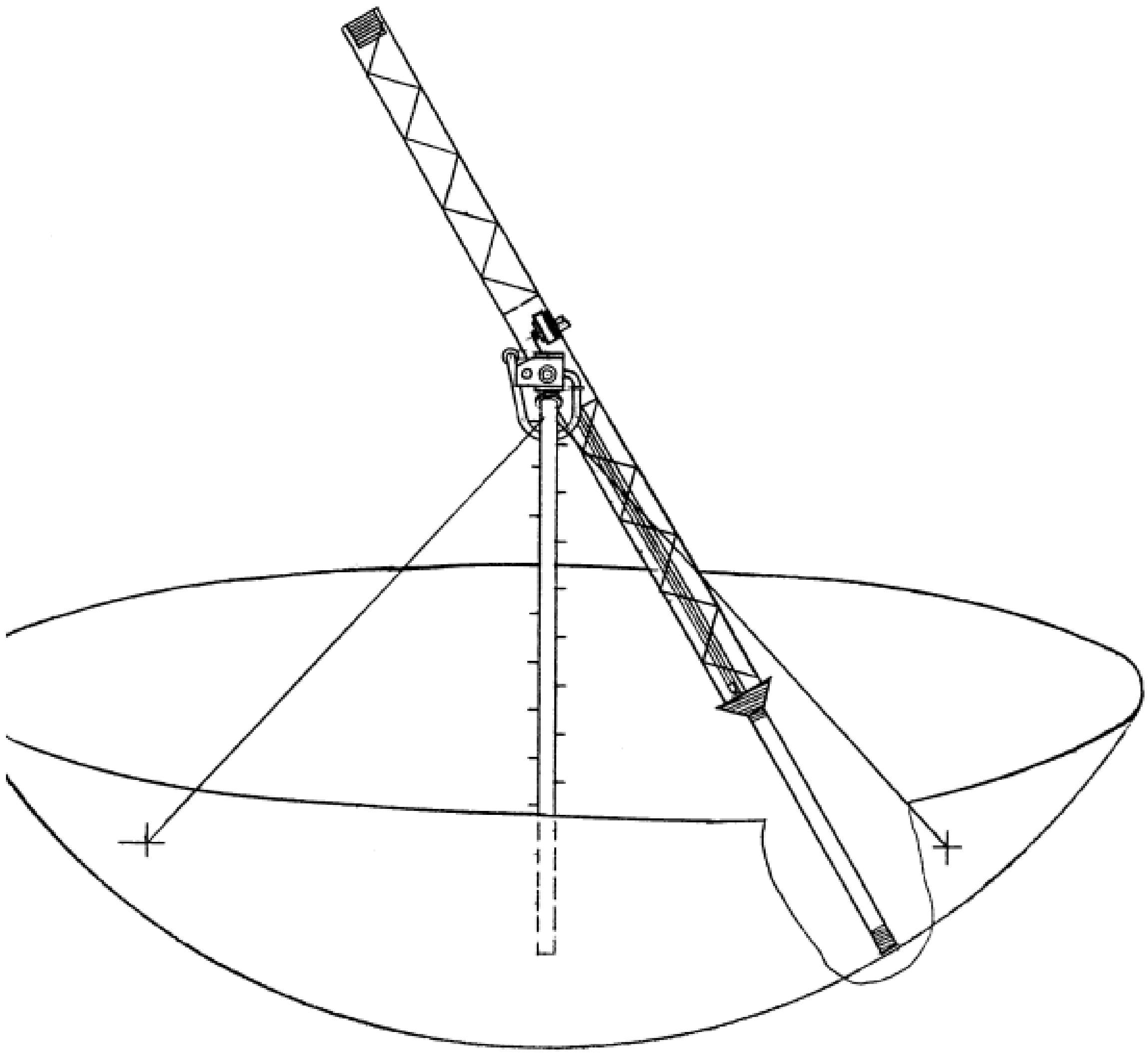
For the mast, we finally opted for an 8" GI pipe (4mm thick), rather than a 3D-steel truss for two reasons:

1) We wanted to minimise the shadow cast on the bowl by the mast. However, as there are already two insulated pipes (9" together) running along the mast, even an 8" pipe would not add much to this shadow. A 3D-truss would actually cast a greater shadow because its section would have to be larger than that of a single pipe, and only few rays of the sun would have been able to pass through the truss.
2) The mast does not have to take moments (the main advantage of a 3D-truss) because we want the mast to simply rest on the base plate, rather than being anchored in it. This because we did not want the foundation to take any moment (it would have had to be too massive and there would have been more risks of leakage).

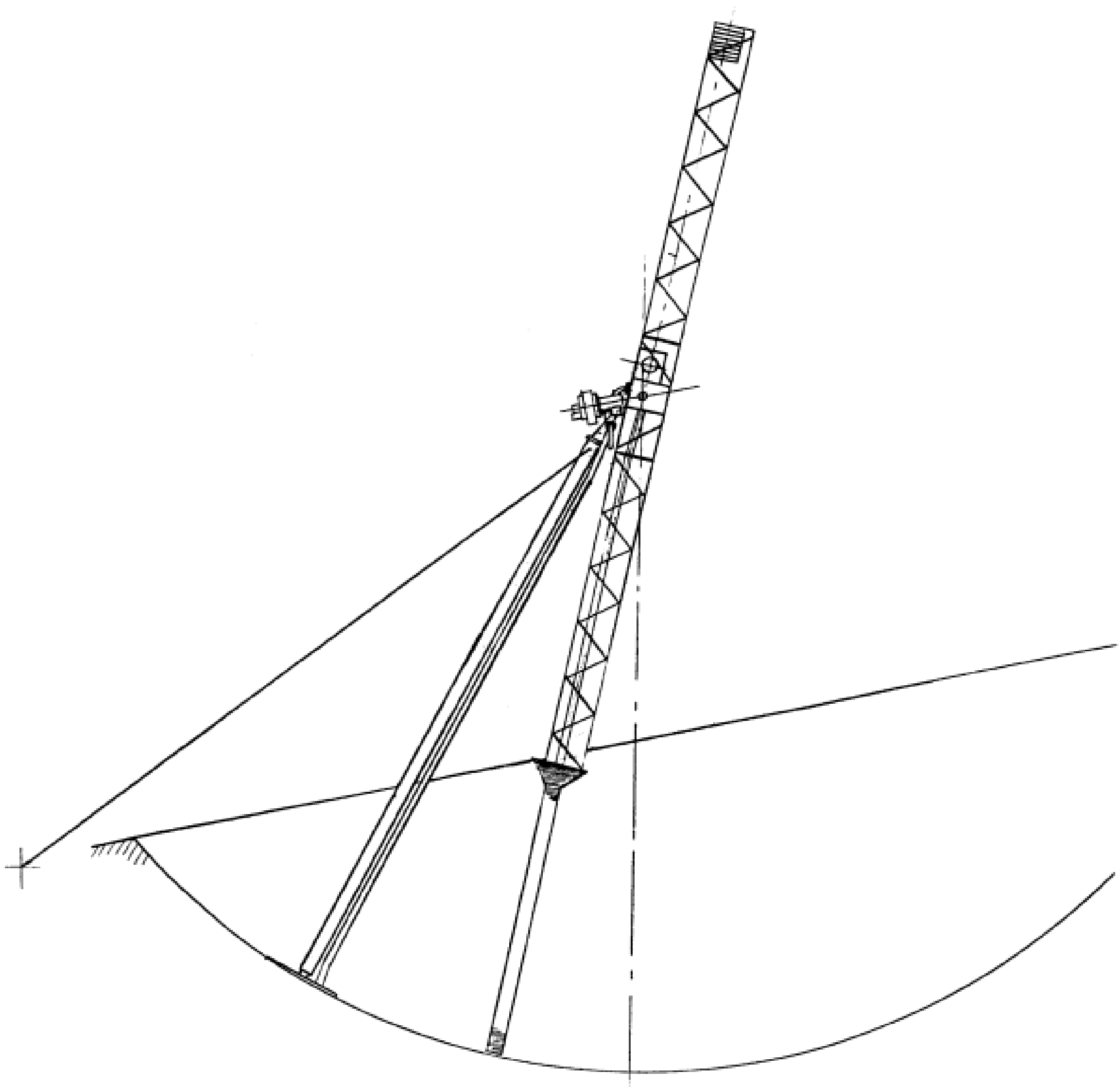
16mm rods stick out on both sides of the pipe to create a ladder. One horizontal pipe has been added at the top to improve the accessibility of the air vents, stepper motors and encoders. The diameter of this pipe is the same as that of scaffolding pipes so that, in case of need, scaffolding could be attached there. Every meter, below the mast, there is a steel device to hold in place the two insulated pipes.

Thanks to a pair of flanges, the mast supports an element that supports the double axis articulation and the tracking system.
The mast will normally never have to be removed once in place; but this element may have to go back to the workshop for improvements. Therefore, the guy-wires are attached to the mast and not to that element.

We used 2" "C" class GI pipes as **guy wires**. We rigidified them with some more pipes.



Mast & swinging arm seen from the South



Mast & swinging arm seen from the East

Erection procedure: As we could not afford to damage the reflective surface, it was very important to take the erection procedure into account right from the designing process. After much thought, we arrived at the following:

1) The mast was brought from the South (the lowest side of the bowl) on the terrace and had its base rest on the base plate.
2) The mast was made to pivot on top of the base plate till it reached its (approximate) position. **We therefore decided to link mast and base plate with a pivot that enabled this rotation to take place**. This pivot allows however the mast to also resist torsion.

Small scaffolding had to be erected in the middle of the sphere rising up to the counterweight.

The elements were then raised through the hole at the bottom of the bowl in the following succession:

3) The element holding the double axis articulation with diurnal gearbox in place is lifted and bolted in place.
4) The swinging arm is lifted and bolted in place (this is done in sections).
5) The receiver is lifted and bolted in place.
6) The counterweight is lifted in place element by element. (Actually, to add some more 16kg elements of the counterweight at a later stage, we placed a solid plank horizontally across the arm at its very top and two men sitting on that plank lifted and bolted in place these additional elements.

The **function of the mast** is to support the two-axis articulation and the tracking system, and keep the whole thing positioned very precisely when the 900kg swinging arm (complete) moves. It is therefore absolutely essential that some adjustments enable us to:

1) Bring <u>exactly</u> the centre of the articulation at the centre of the sphere; and
3) Orient the articulation's polar axis exactly parallel to that of the earth.

The entire supporting system is naturally designed and manufactured as accurately as possible to serve this purpose, but it doesn't suffice; fine adjustments are still required in several places:

<u>Superposing the centres of the articulation with the centre of the sphere is done by:</u>

- Adjusting the length of the mast. But once this is done well, it doesn't ever have to be modified. This adjustment could have been done in three different places: 1) between the base plate and the bottom pivot, 2) between the bottom pivot and the mast, 3) in the higher part of the mast.

  We opted for the first solution. We have a second base-plate separated from the first one by a gap that is filled with cement mortar once the height is adjusted precisely. Four bolts allow us to adjust the distance between the two base plates.

- By adjusting the length of the two guy-wires, we are able to bring the centre of the articulation exactly to the centre of the sphere.

<u>Orienting accurately the polar axis is done by </u>allowing the element supporting the double axis articulation & tracking system to itself pivot along two axes on top of the mast:

- It pivots around the axis of the mast thanks to oblong holes drilled in the flanges that hold it to the mast. (The two flanges are perpendicular to the 8' pipe).
- Two large bolts allow an adjustment of this element around a horizontal axis. Actually it won't remain exactly horizontal after rotation of the two flanges, or adjustment of the guy wires, but it doesn't matter.

(Above:)

Mast & Guy wires in place,

Getting ready to lift the arm – one section at a time.

(Left)

Everything is now installed, the scaffolding is about to be removed.

7.2. ARTICULATION

For the swinging arm to be able to move in all directions, it must rotate around two axes. **As is usually recommended, one axis is polar (parallel to the earth's polar axis), and the other one is perpendicular to the first one.**

- The swinging arm needs to rotate around the polar axis by a little more than 60º towards the east and by more than 60º towards the west (counted from the symmetry axis of the bowl).
- The swinging arm has to be able to rotate around the second axis by 23.42º towards the north, and by 23.42º towards the south (counted from the symmetry axis of the bowl).

Note: the symmetry axis of the bowl forms a 12º angle with the vertical.

As seen in the previous paragraph, an element bolted to the 8' pipe supports the double axis articulation and the tracking system. Great care was taken so that:

- The double axis is brought very precisely in the proper position (see previous paragraph).
- The entire supporting structure resists the efforts it is subjected to without movement, deformation or vibration.
- The swinging arm is easily removable from its position, and easily de-connectable from the tracking system.
- The two encoders (measuring exactly the two angle of rotation of the arm) are placed directly between axis and the swinging arm. This is to ensure the best precision possible.

The polar shaft is designed in such a way that it remains attached to the element on top of the swinging arm. A pipe attached indirectly to the swinging arm comes around this polar shaft and is clamped to it (with a possibility to de-clamp it and allow it to rotate around the pipe). This pipe (which serves also as polar axis) is welded perpendicularly to the second shaft which rotates inside two bearings fixed on the 3D truss of the swinging arm.

(Standing on the gear box of the diurnal movement) **Andres tests his design**

7.3. SWINGING ARM & ITS COUNTERWEIGHT

The swinging arm is a 3D steel truss with a triangular section. The rationale for using a 3U truss rather than a pipe is that for the same weight, a 3D truss is more rigid (an essential factor). As the swinging arm (when in operation) remains always in line with the sun, it won't cast any additional shadow on the spherical reflector - provided its triangular section fits within a 72cm circle (maximum diameter of the inverted truncated cone of the receiver).

The two insulated pipes (conveying back and forth the thermic fluid to the receiver) are installed just outside the triangular section of the swinging arm, but within the 72cm circle – so as not to increase the shadow.

The counterweight is made of cast iron and it is held at a distance of 4 m from the articulation. Each element weights 16kg and is bolted in place. A detachable hook allows it to be lifted easily with a rope.

Swinging arm & Counterweight

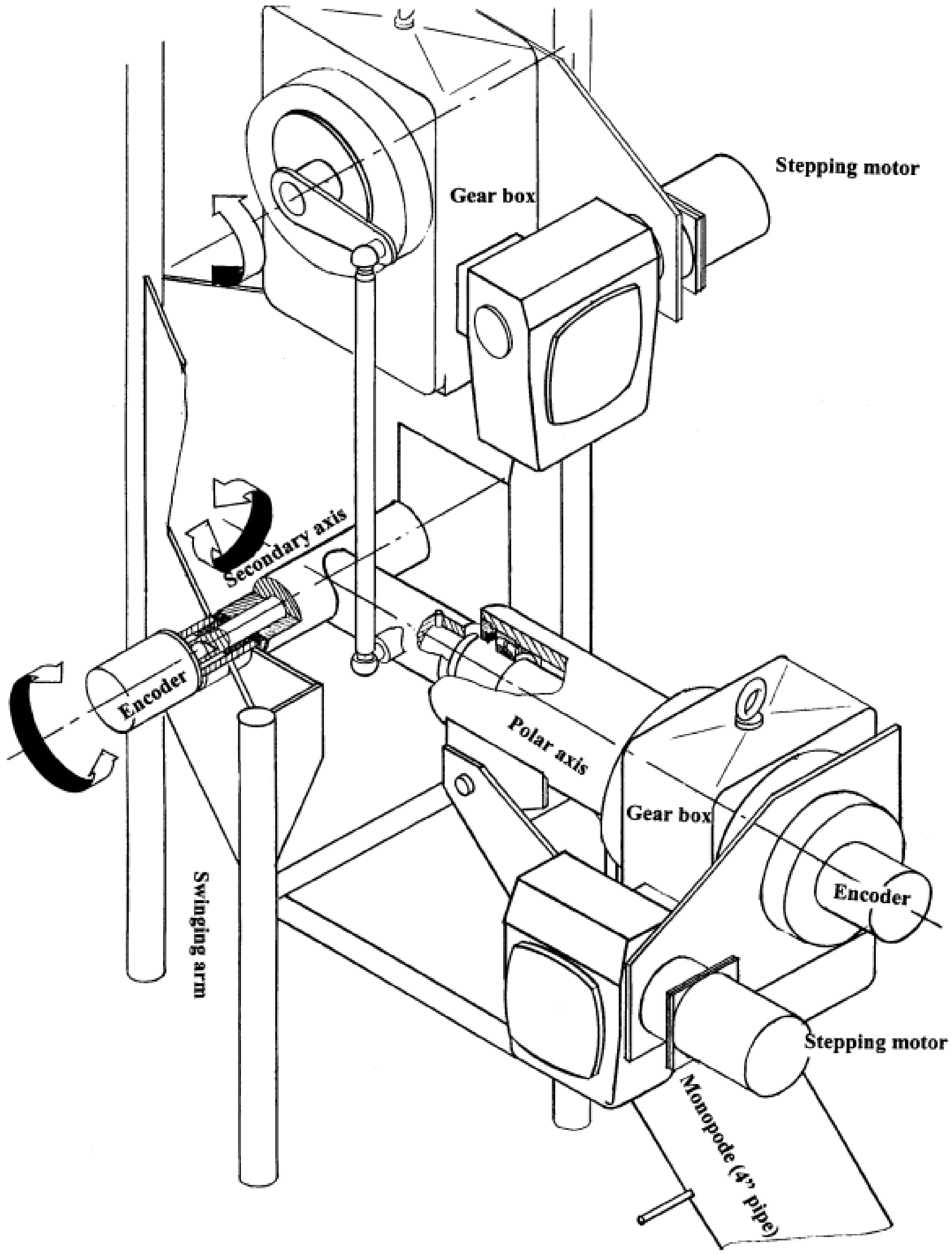
7.4. FLEXIBLE PART OF THE PIPE LINE

The flexible part of the pipeline poses a particular problem as such pipes can be bent in one direction, but do not like torsion. Moreover, as this is the highest portion of the entire loop, an air-vent needs to be placed exactly at the highest point to remove the air while filling the entire loop.

Articulation seen from South and from East

(Note the flexible hoses at the 2 articulations)

Mast & lower portion of the arm seen from East and from North



Tracking system mechanism

8. TRACKING SYSTEM

8.1. COMPONENTS OF THE SYSTEM

The tracking system is controlled by a PC; its home-written software:

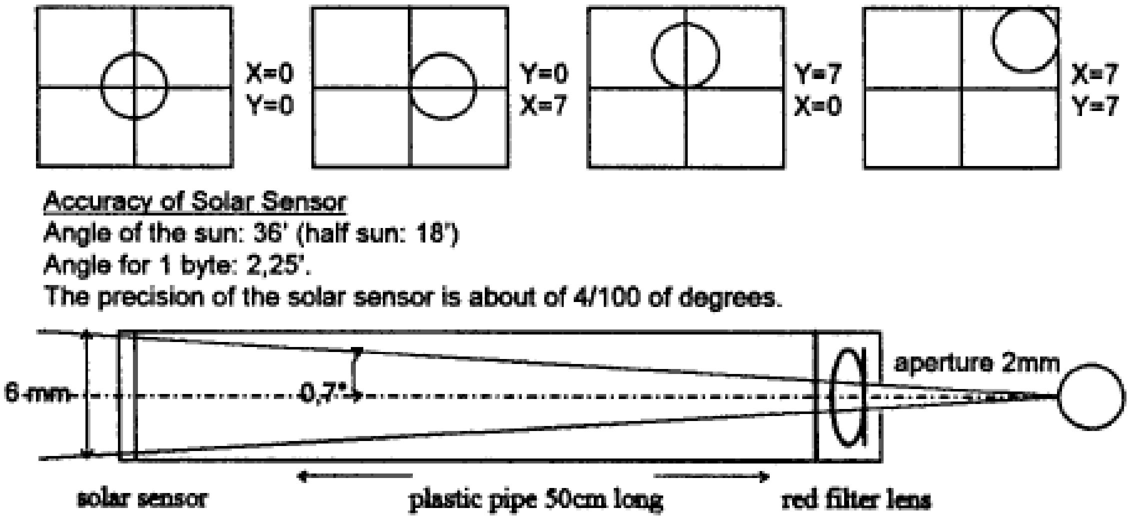
1) Receives information from:

- A keyboard used by the operator to give his instructions.
- Two "encoders" (fitted respectively on the two axis of the articulation) that give the exact position of the arm.
- A computer software that gives the exact position of the sun at any time of the day, and of the year.
- A temperature gauge fitted just after the receiver. (When this temperature is too high, it launches an emergency procedure).

And at a later stage, it will also receive information from:

- A small system with a lens and four photocells, in which the intensity of the light received by each of the cells, is compared. (If the arm is accurately aligned with the sun, each photocell receives the same amount of light and thus produces the same amount of current. If not properly aligned, the photocells produce a different quantity of energy, which indicates in which direction the sun, is, and how far off the arm is). Such as system, made in Italy, is working to our full satisfaction since years to orient a heliostat located on top of Matrimandir in Auroville.
- An anemometer. (Beyond a certain wind velocity, it will launch an emergency procedure.) This does not seem to be necessary.

2) Instructs two stepper motors to move the swinging arm in a certain direction and at a given speed - or to a specific point.



Principle of the 4-cell photo-electric sensor

8.2. FUNCTIONING OF THE SYSTEM

As said earlier, the swinging arm is pivoting freely around a two-axis articulation bolted at the top of the mast.

In the office of the technician operating the Solar Bowl and other systems of the Solar Kitchen, there is a (personal) computer ("pentium" because their in-built clock is sufficiently precise for our purpose) and an old computer box. In this box we have fitted the drives of the two stepper motors and the hardware that is necessary between these drives and the computer and between the encoders and the computer.

The system is equipped with a remote control with the following press-buttons:

- Auto/manual
- Fast/slow
- Diurnal movement: Eastwards/Westwards
- Seasonal movement: Northwards/Southwards

Every minute, the computer:

- reads the encoders
- calculates the exact position of the sun
- calculates how many steps each of the two motors has to do and in which direction.

Then the monitor displays this information and the drives send the number of impulsions required to the stepper motors. For the time being the maximum speed has bee set at 420steps/minute (that is approximately 2rpm) – which seems to be sufficient.

Before operating the system for the first time, one needs to enter the exact latitude and longitude, the precise time and date, and also the readings of the encoders when the arm is vertical. In addition to displaying the exact position of the sun, the monitor indicates also at what time the sun rises, at what time is solar noon and at what time the sun sets – on that day.

The software has been written so that the system may work with – or without encoders (an easy procedure disables them).

When one switches on the computer, if one wants to operate the system, one has two options:

1. Press "Position Search Mode"
   The computer will then automatically bring the arm to the focus and then start tracking automatically.
2. Press "Manual" and then use the remote control to bring the arm exactly where one wishes. It is easy to bring it in the focus because its (moving) position in the bowl is highly remarkable. If one wants, once one has reached the focus, one can press the "auto" switch and then the computer will start tracking without using the encoders. It will understand that the arm is in the focus and will continue to track. The encoders are thus not indispensable.

An "Excessive Heat Emergency" mode will be triggered by the 4-set points controller (that is connected to the thermal gauge just after the receiver) and will move the arm backwards at full speed using both motors (diurnal and seasonal).

> This mode move as fast as possible the arm forwards (meaning eastwards) till the receiver is fully out of focus (that is some 10° off focus). This mode rings also an alarm bell to call for the operator's attention.
>
> The receiver being brought taken out of the focus, the temperature will quickly go down. Normally, the operator would decide what to do next. If the operator does nothing, the receiver will come slowly in focus again and if ever the temperature rises again too high, the emergency mode will be triggered again.

8.4. ANGULAR SPEED AND CORRESPONDING MOVEMENT OF THE ARM.

The earth spins around itself in 24hours = 24 x 60minutes = 1,440minutes.

To compensate this movement, the arm spins around the polar axis at a speed of: 1/1,440rpm = 0.000694rpm. As our double reduction worm gear has a ratio of 1:3000, it means that the stepper motor has to rotate at 2,08rpm

Presently at full speed, the stepper motors make 420 steps/minute; that is approximately 2rpm.

A circle of 8.60m radius has a circumference of 2 x 3.14 x 8.60 = 54.008m

Which means that each time the arm moves by 1 angular minutes, it describes an arc of 54.008/360 x 60 = 0.00252m = 2.50mm.

The arm would do a full lap in: 24 x 60 x 60 = 86,400 seconds;

And describe 1 angular minute in 86,400/360 x 60 = 4 seconds

Therefore, at the equinox:

Period of time **in seconds**	**Angle of rotation of the sun; and arm** **in arc-minutes**	**arc described by the tip of the receiver** **in cm**
4	1'	0.25cm
16	4'	1.00cm
32	8'	2.00cm

<u>Note:</u> At all other periods of the year (other than the equinox), the angle described by the receiver will be (a little) less than this. This is because, though the arm will indeed pivot around the polar axis by the same angle, the arm won't be perpendicular anymore to the polar axis.

8.5 CONTINUOUS OR INTERMITENT MOVEMENT ?

In “tracking mode”, the arm has to swing at 1round per day. In the Excessive Heat Emergency Mode, the arm has to move at least 50 times faster.

Which type of motors can provide us with such a wide spectrum of speed?

- Stepping motors have an even larger spectrum of speed; but they are costly and their drive may not be 100% reliable.
- 3-phase motors fitted with a frequency variator are cheaper and very reliable. Their drives are simple; but they have a speed range of 1:25, which is absolutely not sufficient. To utilize such motors in “tracking mode”, one would have to run intermittently the motor at low speed (2Hz, or 60rpm). To utilize the motors in “Emergency Mode”, one would run the motor at 50 Hz, that is at 1,500rpm.

The table above (paragraph 8.4.) shows that if the acceptable accuracy in positioning the arm is of (say) ±4arc-minutes, then the arm can only remain immobile during 32 seconds.

We opted for continuous movement - and stepping motors - because the accuracy is thus much better and because intermittent movement would have strained the whole mechanism.

8.6. ACCURACY OF THE SYSTEM

We have already seen in paragraph 4.6.d. how (with the help of “PERFAC”) the size of the flat facets of the reflector was defined - and also the geometry of the receiver.

According to PERFAC, a 5’ angle between the actual position of the swinging arm and the real focus is good; and if this angle reaches 10’; it is still acceptable.

This acceptable angle (10’) is actually a combination of two angles (North-South and East-West). Let us say that we wish to share equally this approximation between these two angles. As the angle is very small, one can say that 10’ is the combination of two angles of 7’(one angle in each direction). However, as statistically, there is very little chance for the two approximations to be at their maximum at the same time, **we can safely accept angles of 8’ and probably even more in both directions (N-S & E-W).**

The angle between the actual position of the swinging arm and the ideal one is the result of the combination of two approximations:

1. The approximation of the information received by the computer.
2. The approximation in the system’s ability to position the receiver where instructed.

In both directions (N-S & E-W), we have to see that the combination of these approximations does not go beyond 8’. Actually, the first 2 approximations are not to be added, but again combined, as statistically there is very little chance that the two extremes take place at the same time – and in the same direction.

8.6.a. Accuracy of the information received by the computer:

- **Computer program (giving the position of the sun):** Its accuracy is so good that its inaccuracy can be neglected. The accuracy of the information received by the computer is thus that of the encoder and/or of the photoelectric sensor.
- **Encoders:** We selected two Nos. 12 bits encoders; that is with 4,096 partitions. In other words their precision is of **± 2.6’**, which is equivalent to an arc of 0.8 cm on our sphere. (see attached pamphlet, Annexure H)

  To this inaccuracy, one must add other inaccuracies due to:

- **The inaccuracies in the orientation of the polar axis.**
- **The inaccuracy in the positioning of the centre of the two-axis articulation at the centre of the sphere.**
- **The inaccuracies in the "zero" setting of the encoders (in the vertical position).**
- **The play between the shaft on which the encoder is mounted and the movement of the arm.**
- **The deformation of the arm due to bending and sliding along a shaft.**

Each of these other inaccuracies are very difficult to evaluate on the drawing table. However, they had to be kept in mind while designing the system.

- **Photoelectric sensor:** The photoelectric sensor will only function if there is sun and if the arm is continuously kept within a few arc-minutes of the ideal position. As this is not always the case, encoders will still be required when a photoelectric sensor is installed. The photoelectric sensor we are presently using at Matrimandir was made especially for us in Italy some years ago. It's precision is very high (approximately four hundredth of a degree).

  In this case, the only accuracies that needs to be added are:

  - **The inaccuracy in positioning the centre of the two-axis articulation at the centre of the sphere. (this can be checked regularly optically)**
  - **The inaccuracy in the parallel alignment of the axis of the photoelectric sensor and the swinging arm. (Should not be difficult to adjust in practice).**
  - **The deformation of the arm due to bending and sliding along a shaft.**

8.6.b. Accuracy of the system ability to position the arm as instructed.

The movement will be continuous and due to stepping motors. The accuracy then depends on how many steps per second the motors will have to do. As will be seen later, the gearboxes we opted for provide a reduction of 1:3000; and the stepping motors do 200steps/round. In other words, one step will correspond to 1:600,000rounds of the arm; that is 360 x 60/600,000 = 0.036 arc-minutes. Which is so low that it doesn't play a determinant factor.

8.7. SPEED OF THE "EXCESSIVE HEAT EMERGENCY" MODE

Our problem here is to know:

- How fast the "Excessive Heat Emergency" mode needs to be able to move the arm away from the focus, so as not to damage the heat transfer fluid?
- How fast are we really able to move the arm?

If we were not able to move the arm fast enough, then we would have to envisage either of the following solutions:

- Exploding bolts freeing the arm from the gear and let it be carried away thanks to a counterweight.
- Letting a shield come down (with a counterweight) from above the receiver and cover at least the truncated cone and part from the cylindrical receiver.

8.7.a. Angle by which the receiver should be moved out of focus.

- Angle by which the bottom of the receiver needs to move to be fully out of focus;

Period of time **in seconds**	**Angle of rotation of the sun; and arm** **in arc-minutes**	**Arc described by the lower tip of the receiver** **in cm**
16	4’	1.00cm
368	92’	23.00cm

This means that to get the lower part of the receiver fully out of the focus, the arm (or the focus) has to move by 92 arc-minutes; and that if the arm remains immobile, this will happen in 368 seconds, or in little more than 6 minutes.

- Angle by which the top part of the receiver (truncated cone) needs to move to be fully out of the focus:
  The bottom part of the receiver is at 8.60m from the centre of the sphere.

  The top part of the receiver is at 4.60m from the centre of the sphere.

  Which means that to get the to part of the receiver out of focus, the bottom part has to move by: 72 x 8.6/4 = 154.8cm

Period of time	**Angle of rotation of the sun; and arm**	**Arc described by the lower tip of the receiver**
16 seconds	4’ arc minutes	1.00cm
2,477 seconds = 41.28 minutes	619.2 arc-minutes = 10°	154.80cm

This means that to get the upper part of the receiver fully out of the focus, the arm (or the focus) has to move by 10°, and that if the arm remains immobile, this will happen in 41.28 minutes.

8.7.a. Speed at which the receiver should be moved fully out of focus.

We have not made this calculation, as it is quite complicated. We would have to assume that the gear pump doesn’t work at all, that the solar radiation is maximum (clear day at noon). The top speed is not the only factor; acceleration is also very important. This acceleration is limited by the inertia of the whole system (the weight of the swinging arm is in the range of 1 ton), the frictions and the performances (torque) the stepping motor and its drive are actually able to pass on to the arm.

8.7.c. Speed at which the receiver can be moved fully out of focus.

Only experience will tell us about the inertia of the whole system (the weight of the swinging arm is in the range of 1 ton), the frictions and the performances (torque) of the stepping motor and its drive are actually able to pass on to the arm.

At present, we can only say that at full speed, the receiver would be fully out of focus in (41.28/100 =) 0.4minutes (that is 24 seconds). One has the impression that it would probably suffice…

8.8. EQUIPMENT

Stepping motors

In paragraph 8.5. we explained why, because of the wide spectrum of speed required, we had to opt for stepping motors rather 3-phase motors with frequency variators.

We acquired 2 Nos stepping motors from Srijan Control Systems. (see Annexure F).

Other types of motors and other brands of stepping motors are available on the market, but Srijan is well priced and we are already using stepping motors of this brand for the heliostat of Matrimandir, so we won't have to re-write this part of the software.

Encoders

In paragraph 8.6.a., we said that in order to have a sufficient accuracy, we had to opt for 12 bits encoders; that is with 4096 partitions.

We acquired 2 Nos single-turn encoders made in Germany by Hohner, and marketed in India. (see Annexure F).

There are many brands on the Indian market (all are manufactured abroad); we chose Hohner because it is well priced and also because we are using similar encoders from Hohner for the heliostat of Matrimandir, so we won't have to re-write this part of the software.

Gear boxes or Linear Actuators

To transmit the movement from a stepping motor to the axes of our system, we still had to choose between gear boxes, or linear actuators. At first we thought of using linear actuators rather than gear boxes. We changed our mind for the following reasons:

- The output torque of a double reduction worm gear from Shanti Gears is of 230kgfm, while a linear actuator from SKF (CARR40) would only give us a torque of 176kgfm.
  The tracking system must be able to move the swinging arm as required even on windy days (but not when the wind is too strong). Having taken into account what can be reasonably achieved and what might occur, we opted for a working torque of 230kgm.

  This means that the system is able to move the swinging arm as required, even if a force of 25kgf is applied at the extremity of the receiver (25 x 8.6 = 215kgm).

- The cost of a strong and precise linear actuator is about three times that of a gear box.

- Linear actuators wear out much faster than gear boxes.

- A force applied on the arm will not make a worm gear (and even better a double reduction worm gear) turn; but it could make a linear actuator equiped with a planetary gear move.

- With a gear box, the rotation of the stepping motor and that of the axes are (linearly) proportionate. As it is not the case with a linear actuator, the computer software is more complicated.

We acquired 2 nos double reduction (worm) gear boxes from Shanti Gears giving a reduction 3000:1 and an output torque of 230kgfm.

9. PERFORMANCES IN ORIGINAL CONFIGURATION

This entire chapter is an excerpt from the thesis submitted by Ms. G. Ezhil Malar to the Puducherry University, Puducherry, in partial fulfilment of the requirement for the award of Master of Technology in Energy Technology.

9.1 METHODOLOGY

The performance test has been conducted for the month of July, August, October and December. Due to maintenance work and unfavourable climatic condition, the test was not conducted for the month of September and November.

The mass flow rate of the fluid is changed by the frequency in the frequency variator. If we set 20 Hz in the frequency variator, it controls the pump such that it discharges 1,000 l/hr (m_l). Similarly, if we set it at 30 Hz, the pump discharges 1,500 l/hr (m_2), for 40 Hz it is 2,000 1/hr (m_3) and 50 Hz is 2,500 l/hr (m_4).

The time duration for the test conducted was 8 hours. The system is made to run continuously from 9 A.M. to 4 P.M. and the readings are recorded. Simultaneously the solar radiation is measured. With the measured radiation values, a direct solar intensity graph has been drawn for the month of July, August, October and December.

9.2 RADIATION MEASUREMENT

To calculate the efficiency of the system, the solar radiation, which is the input of the bowl, should be measured.

Since the bowl reflects only the direct solar radiation, a pyreheliometer was used for the measurement of radiation. For every one hour the radiation was measured and recorded.

The hourly radiation was calculated for all the four months from 9 A.M. to 4 P.M.

9.3 CALIBRATION OF PYREHELIOMETER

The pyreheliometer used for this experiment is a long tube thermoelectric pyreheliometer. Its meter reads in millivolts.

So the conversion factor to convert millivolt to W/m² was calculated by calibrating this Auroville meter with the Ashram pyreheliometer. The calibration constant evaluated is 141 W/m² for the Auroville's long tube pyreheliometer.

9.4 PARAMETERS MEASURED

The parameters measured during the test are:

- Inlet temperature of the receiver
- Outlet temperature of the receiver
- Temperature of the storage tank
- Frequency in the frequency variator
- Direct beam solar radiation

The above parameters are measured from 9 A.M. to 4 P.M.

9.5 CALCULATION OF OUTPUT AND EFFICIENCY OF THE BOWL

The efficiency of the solar bowl is calculated as follows.

Energy harvested Q = m h

m mass flow rate (kg/s)

h change in enthalpy (kJ/kg)

Input energy Q = I x A

I solar intensity (W/m^2)

A projected area (m^2)

Projected area = area of the bowl x cos è

Area of the bowl = $176.7 m^2$

è - Angle of incidence

Cos è for horizontal surface is given by the formula,

Cos è = sin δ sin (Ø - β) + Cos δ Cos (Ø - β) Cos ù

δ declination angle

Ø latitude of the location (12^o)

β slope (12^o)

ù hour angle

Since the bowl is tilted by 12^o to compensate for the latitude, we have

Cos ù = Cos δ x Cos ù

The declination,

$\delta = 23.45 \sin [360/365 (284+n)]$

n day of the year

Efficiency = output / input

9.6. HEAT LOSSES IN SOLAR BOWL

The heat input to the receiver cannot be used completely as it is subjected to various kinds of losses due to radiation, wind velocity, conduction etc. Now from useful heat, net heat energy is obtained by deducting all the possible losses i.e.,

$Q_{net} = Q_u - Q_{rad} - Q_{conv} - Q_{cond}$

The heat losses are calculated for the maximum surface temperature of the receiver (500°C). The concentration ratio is calculated to be 60.

Useful Heat (Qu)

The Energy Harvested in the Solar Bowl is calculated as follows

$Q_u = m C_p (\Delta T) \quad = 67.05$ kW

Where,

C_p = specific heat (J/Kg°K)

ΔT = Temperature difference (°K)

m = mass flow rate (kg/s)

Radiation loss

The loss due to radiation from the receiver is calculated as follows:

$$Q = \frac{\sigma (T_R^4 - T_S^4)}{\frac{1 - Є_1}{Є_1 A_1} + \frac{1}{A_1 F_{12}} + \frac{1 - Є_2}{Є_2 A_2}}$$

Where,

f_{12} = 1, because all radiation is reflected to the sky via the mirror

A_2 = 0 (sky)

$Є_1$ = receiver emissivity (0.981)

$Є_2$ = sky emissivity

Δ = Stefan Boltzman constant (5.562×10^{-8} W/m²k^4)

T_R = Receiver temperature (773°K)

T_S = Surrounding temperature (303°K)

Al = Receiver area 2.7 (m²)

$$Urad = \sigma Є_1 (T_R^2 + T_S^2)(T_R + Ts)$$
$$= 41.8 \text{ W/m}^2$$
$$Qloss = Urad \times A_1 (T_R - Ts)$$
$$= 52.2 \text{ kW}$$

Convective Loss

This is due to the fact that the receiver is let open to the atmosphere where wind velocity takes away percentage of heat from the receiver due to convection. Here both forced convection and free convection takes place.

Forced convection

Qconc = $h_1 A_1 (T_R - T_A)$

h_1 = Forced Convective heat transfer co-efficient (W/m²K)

T_R = Receiver temperature (K)

T_A = Surrounding temperature (K)

A_1 = Receiver area (m²)

H_1 = Nu x K/D

Nu = Nusselt number

$$Nu = 0.3 + \frac{0.62 (Re)^{½} (Pr)^{1/3}}{[1 + (0.4)^{2/3}]^{1/4}} \times \left[1 + \left(\frac{Re}{282000}\right)^{½}\right]$$

Pr

Nu = 86.6

Pr = 0.677

Re = $\frac{VD}{\upsilon}$

= 2 x 104

D = =Diameter of the receiver (23cm)

Qconv = 20.6 kW

Free convection

Qconv = $h_2 A_1 (T_R - T_A)$

h_2 = Convective heat transfer co-efficient (W/m²K)

T_R = Receiver temperature (K)

T_A = Ambient temperature (K)

A_1 = Receiver area (m²)

Qconv = 7.35 KW

Conduction

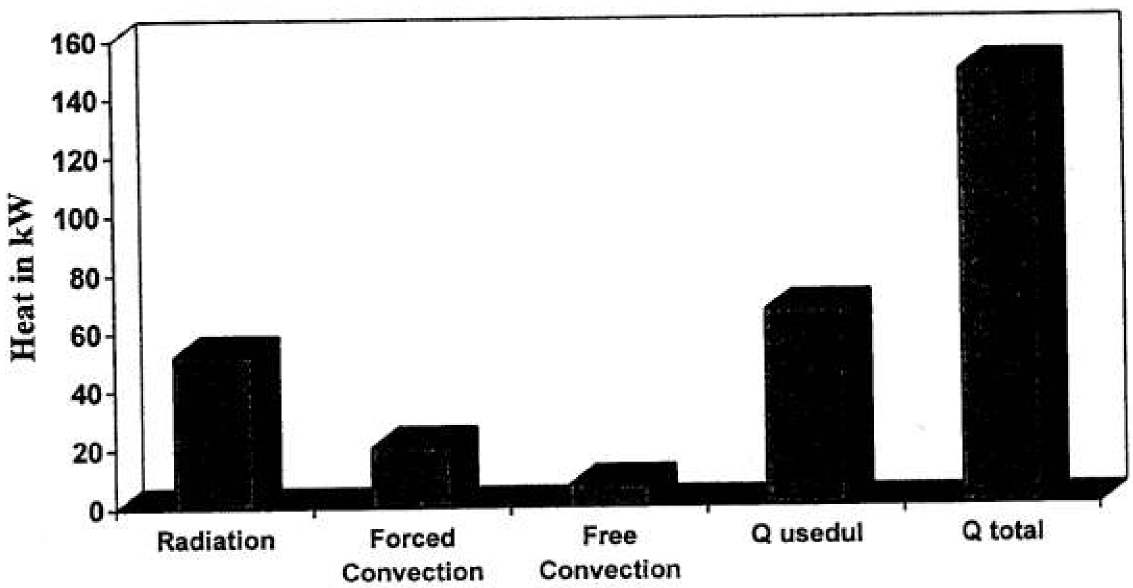
The loss due to conduction between walls in neglected since it is not very significant.

Unaccounted Loss = $= Q_{net} - Q_u - Q_{rad} - Q_{forced} - Q_{fre}$

= 148.42 - 67.05 -52.2 - 20.6 - 7.35

= 1.228 kW

Heat Balance Chart



9.7. RESULTS & DISCUSSION

The performance test was carried out by varying the mass flow rate of the working fluid Therminol 66. By varying the mass flow rate, the variation in output i.e the energy harvested by the bowl is evaluated.

The performance test was conducted for the months of July, August, October and December and the output as well as the efficiency for all the four months is given in the tabular column. The experiments were carried out daily for different time of the day from 9.00 AM to 4.00 PM. For every hour the reading are recorded and the direct solar radiation intensity which is the input to the system is measured by means of a pyreheliometer.

Taking the mass flow rate, the inlet and outlet temperature of the collector into account the energy harvested by the bowl is calculated for the different solar intensity graphs are drawn for each month and the variations in output as well as the efficiency for different mass flow rate are shown in the graph.

Also the heat losses due to convection, conduction and radiation at maximum collected temperature is calculated and a heat balance chart has been made.

Direct solar intensity for the month of July, August, October and December is also given in the graph.

DISCUSSION

From the calculation made and from the graph it is evident that, the bowl harvest's more energy only when the mass flow rate is 1000 l/hr. There is a considerable variation for the other mass flow rates of the working fluid. According to the steam requirement the flow rates can be fixed.

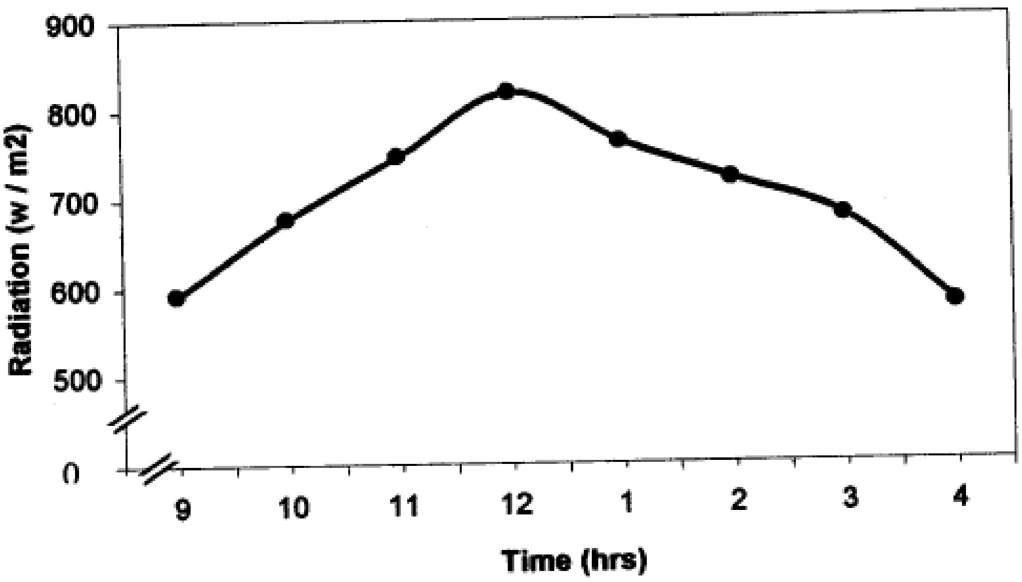
SOLAR INTENSITY FOR DIRECT RADIATION

Time (hrs)	Solar intensity (W/m^2)
9	592
10	677
11	747
12	818
1	762
2	719
3	677
4	578

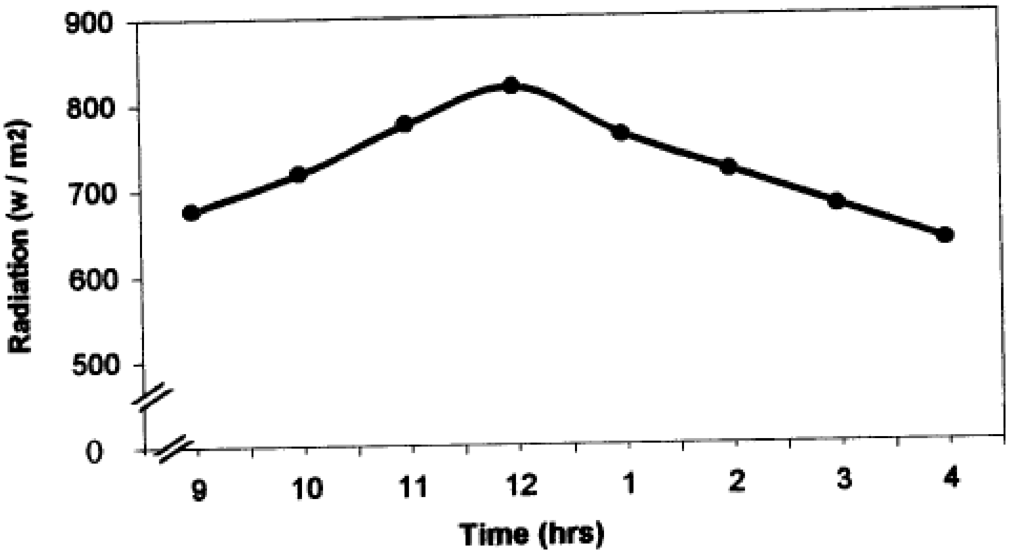
Table 1: Average direct solar radiation intensity w.r.t time for the month of July

Time (hrs)	Solar intensity (W/m^2)
9	677
10	719
11	776
12	818
1	761
2	719
3	677
4	635

Table 2: Average direct solar radiation intensity w.r.t time for the month of August



Solar Intensity graph for direct Radiation w.r.t time for the month of July



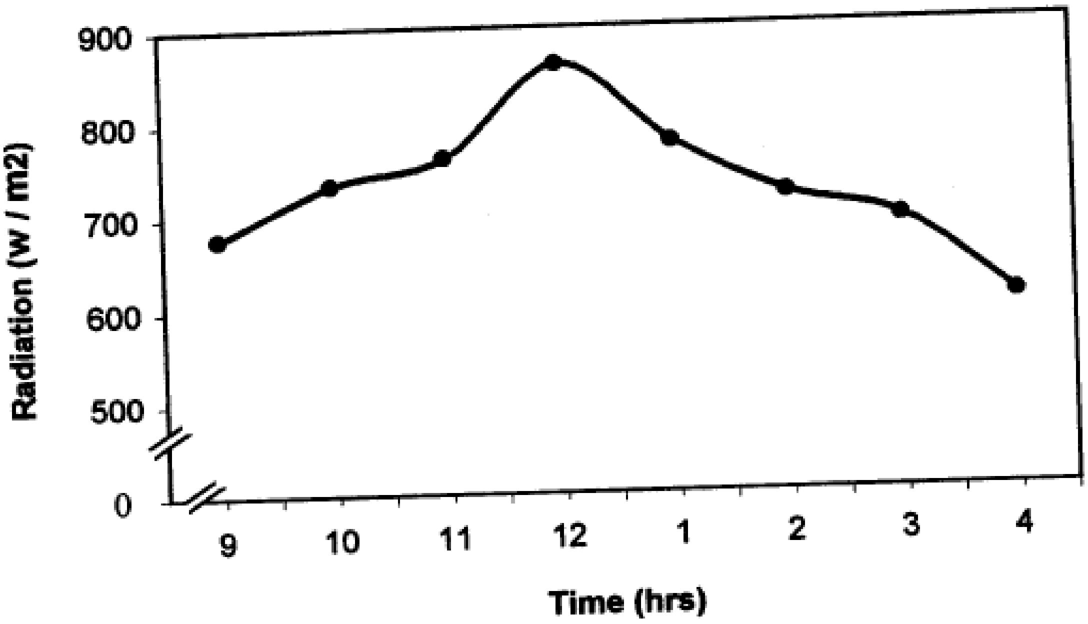
Solar Intensity graph for direct Radiation w.r.t time for the month of August

Time (hrs)	Solar intensity (W/m²)-
9	677
10	733
11	761
12	860
1	776
2	719
3	691
4	606

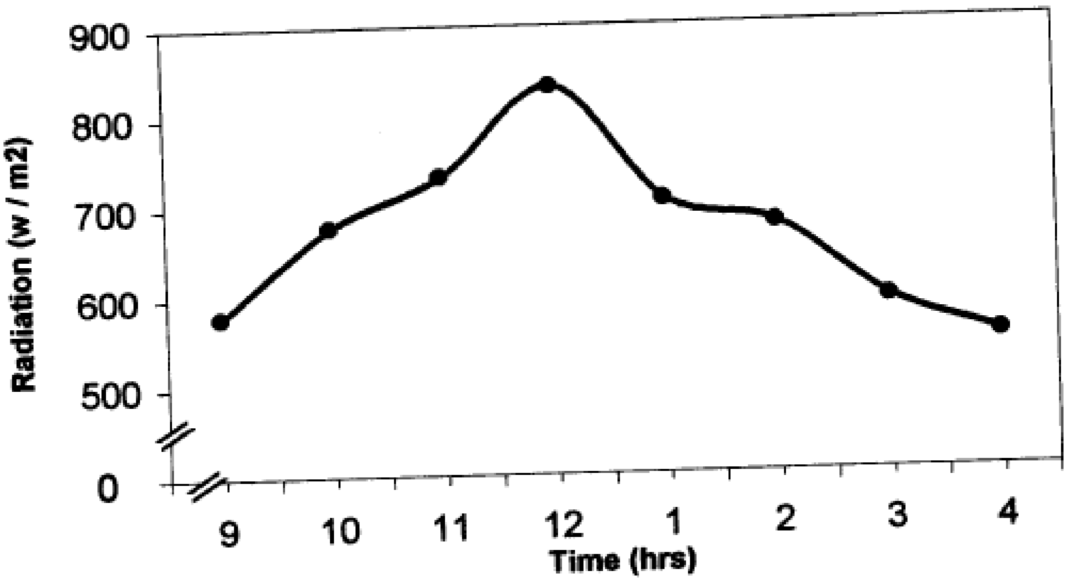
Table 3: Average direct solar radiation intensity w.r.t time for the month of October

Time (hrs)	Solar intensity (W/m²)
9	578
10	677
11	733
12	832
1	705
2	677
3	592
4	550

Table 4: Average direct solar radiation intensity w.r.t time for the month of December



Solar Intensity graph for direct Radiation w.r.t time
for the Month of October



Solar Intensity graph for direct Radiation w.r.t time
for themonth of December

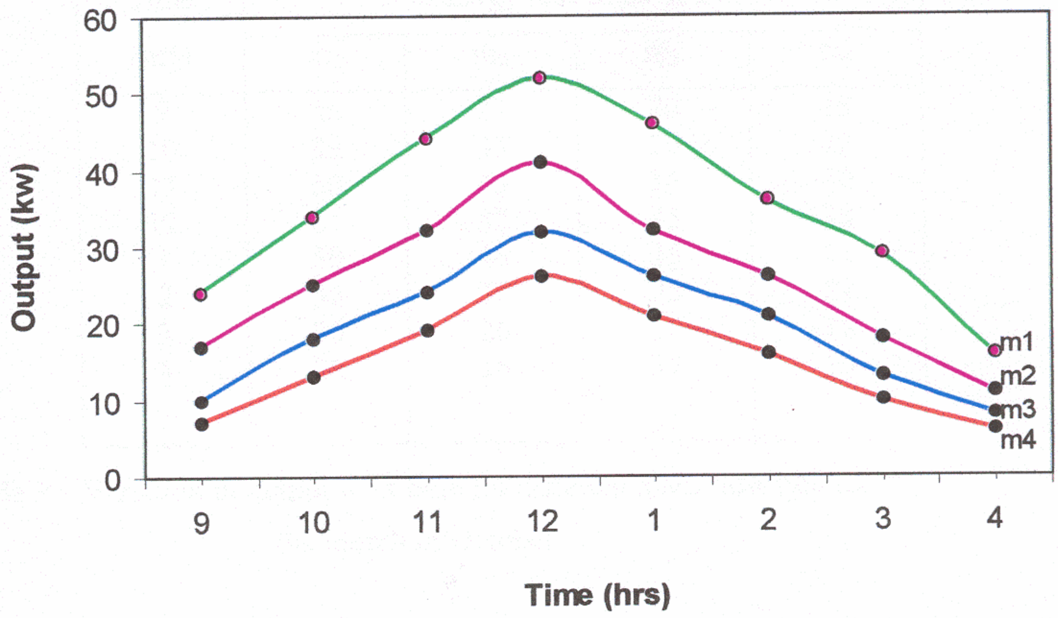
Tabular column for output

Time (hrs)	Energy harvested in kW			
	m_1	m_2	m_3	m_4
9	24	17	10	7
10	34	25	18	13
11	44	32	24	19
12	52	41	32	26
1	46	32	26	21
2	36	26	21	16
3	29	18	13	10
4	16	11	8	6

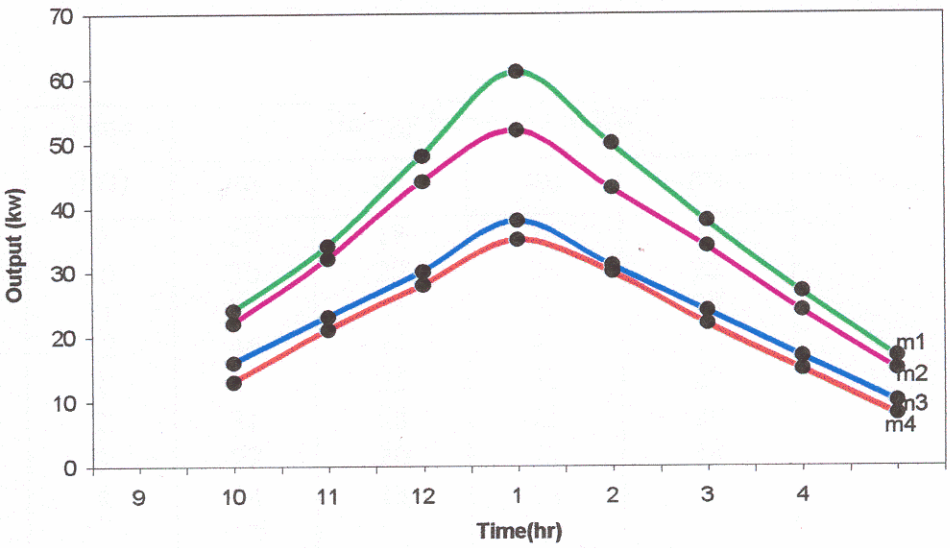
Table 1: Variation in output w.r.t time for different mass flow rate for the month of July

Time (hrs)	Energy harvested in kW			
	m_1	m_2	m_3	m_4
9	22	24	16	13
10	33	33	23	21
11	48	44	30	28
12	60	52	38	35
1	50	43	31	30
2	38	34	24	22
3	26	25	16	15
4	16	15	10	8

Table 2: Variation in output w.r.t time for different mass flow rate for the month of August.



Variation in output w.r.t time for varying mass flow rate for the month of July



Variation in output w.r.t time for varying mass flow rate for the month of August

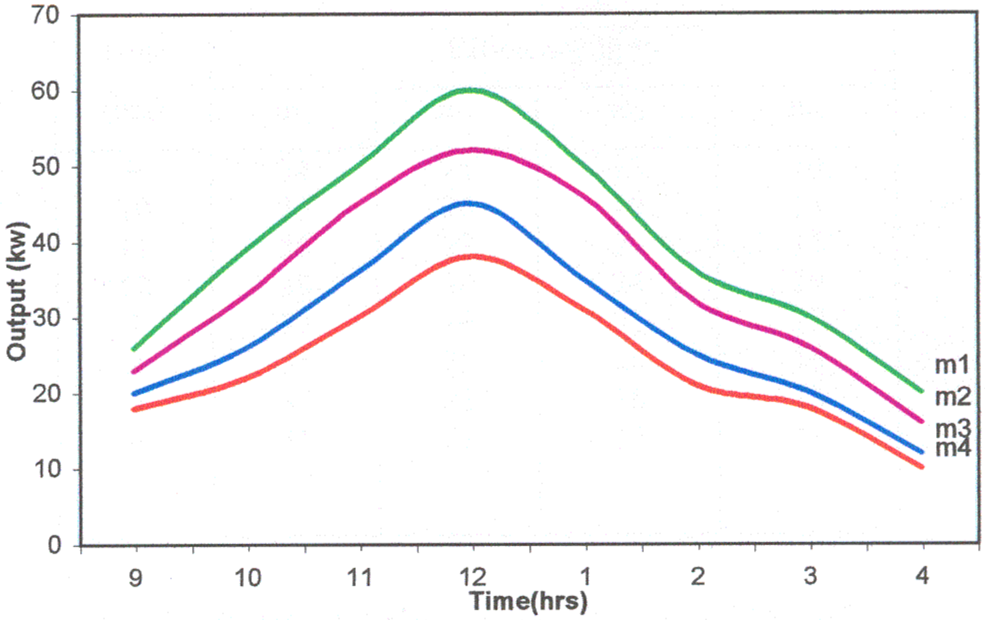
Time (hrs)	Energy harvested in kW			
	m_1	m_2	m_3	m_4

9	26	23	20	18
10	39	33	26	22
11	50	45	36	30
12	61	52	45	38
1	50	46	35	31
2	36	32	25	21
3	30	26	20	18
4	20	16	12	10

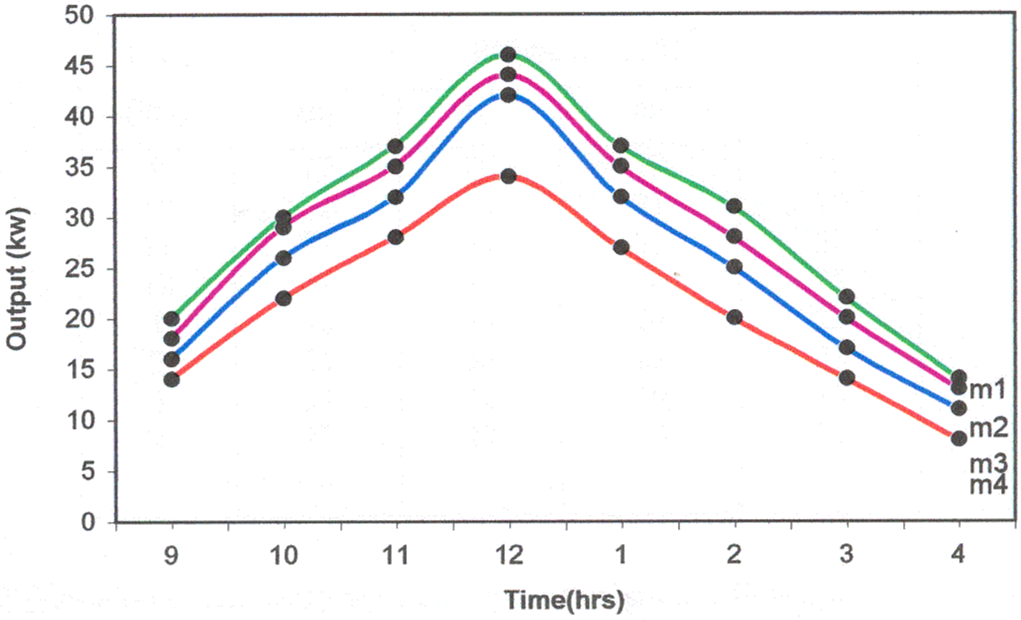
Table 3: Variation in output w.r.t time for different mass flow rate for the month of October

Time (hrs)	Energy harvested in k W			
	m_1	m_2	m_3	m_4
9	20	18	16	14
10	30	29	26	22
11	37	35	32	28
12	46	44	42	34
1	37	35	32	27
2	31	28	25	20
3	22	20	17	14
4	14	13	11	8

Table 4: Variation in output w.r.t time for different mass flow rate for the month of December.



Variation in output w.r.t time for varying mass flow rate for the month of October



Variation in output w.r.t time for varying mass flow rate for the month of December

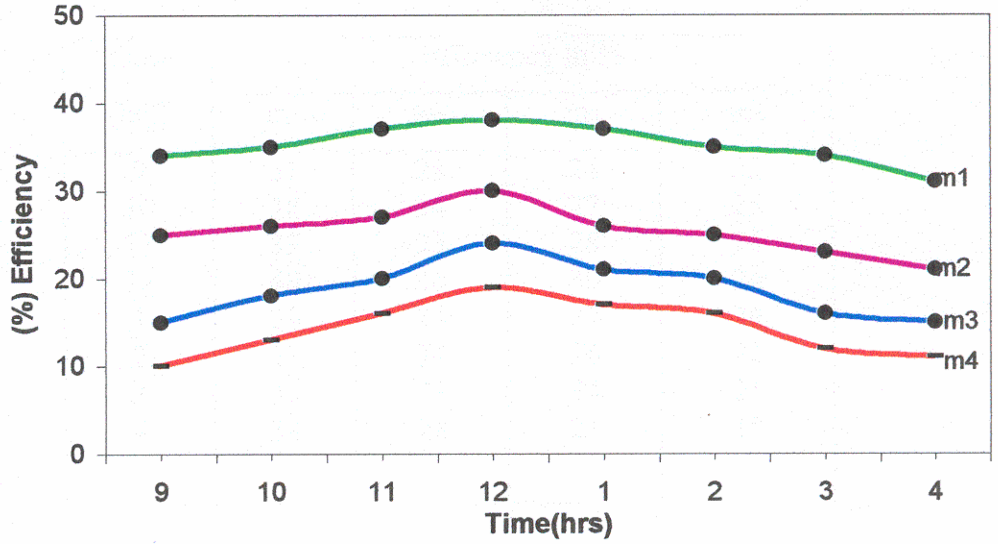
Tabular column for Efficiency

Time (hrs)	Efficiency in %			
	m_1	m_2	m_3	m_4
9	34	25	15	10
10	35	26	19	13
11	36	27	20	16
12	38	30	24	19
1	37	26	21	17
2	35	25	20	16
3	34	23	16	13
4	31	21	15	11

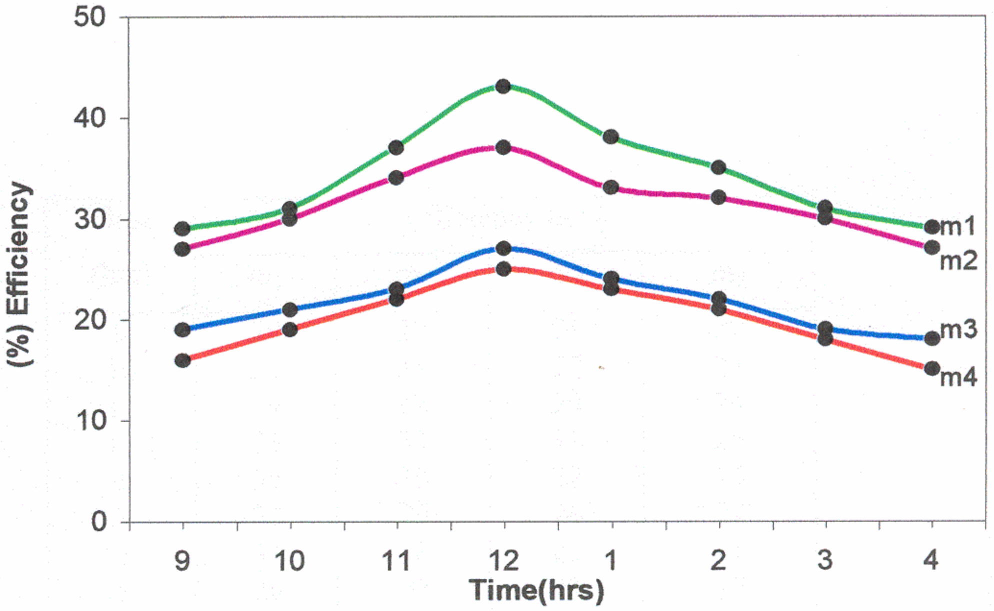
Table 1: Variation in efficiency w.r.t time for different mass flow rates for the month of July.

Time (hrs)	Efficiency in %			
	m_1	m_2	m_3	m_4
9	27	26	19	16
10	31	30	21	19
11	37	34	23	22
12	43	37	27'	25
1	38	33	24	23
2	35	32	22	21
3	31	30	19	18
4	29	27	18	15

Table 2 Variation in efficiency w.r.t time for different mass flow rates for the month of August.



Efficiency for varying mass flow rate w.r.t time
for the month of july



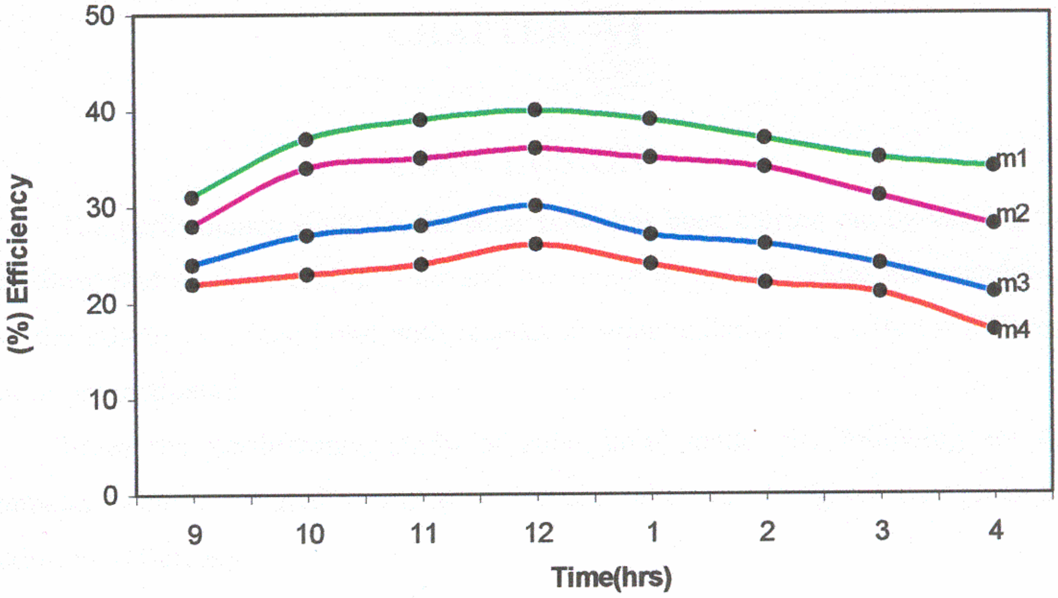
Efficiency for varying mass flow rate w.r.t time
for the month of August

Time (hrs)	Efficiency in %			
	m_l	m_2	m_3	m_4
9	31	28	24	22
10	38	34	27	23
11	39	35	28	24
12	40	36	30	26
1	39	35	27	24
2	37	34	26	22
3	35	31	34	21
4	34	28	21	17

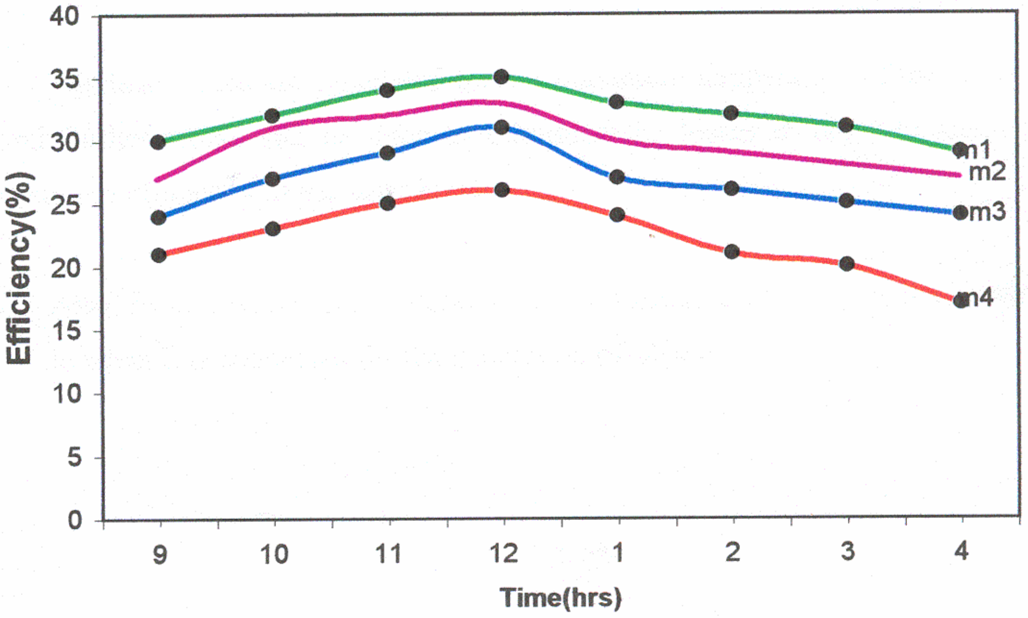
Table 3: Variation in efficiency w.r.t time for different mass flow rates for the month of October.

Time (hrs)	Efficiency in %			
	m_l	m_2	m_3	m_4
9	30	27	24	22
10	32	31	27	23
11	34	32	29	24
12	35	33	31	26
1	33	30	27	24
2	32	29	26	22
3	31	28	25	21
4	29	27	24	17

Table 3: Variation in efficiency w.r.t time for different mass flow rates for the month of December.



Efficiency for varying mass flow rate w.r.t time
for the month of October



Efficiency for varying mass flow rate w.r.t time
for the month of December

9.8. CONCLUSION

The performance study on the solar bowl has been carried out by varying the mass flow rate of the working fluid and the range of output values are calculated. Also the efficiency of the bowl with respect to solar radiation intensity for different months are evaluated.

From the performance study of solar bowl made, the following are the parameter being confirmed at which the system when run for given day gives the maximum efficiency.

(i) For the given day's solar radiation of the year, it was found that the optimum mass flow rate of the working fluid is 1,000 l/hr at which the calculated maximum efficiency of the system is 43 %.

(ii) On an average, efficiency of the bowl when it is operated under a flow rate of 1,000 l/hr is 39.1 % for the peak hours.

The heat losses are calculated for the maximum temperature of the collector and further works can be done to minimize the losses in order to attain the optimum efficiency of the solar bowl.

Also, further works can be done on the performance of the system as a whole i.e. when it is connected for the generation of steam.

* * *

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10. GOING FOR DIRECT STEAM GENERATION

10.1. TESTING OF THE SYSTEM IN THE DESIGN MODE

During 2001-2002 the system was tested using heat transfer fluid in the receiver to ascertain its performance.

Tests with a heat transfer fluid flow rate of 1,000 liters/hr produced a peak energy collection of 61 KW (thermal) at noon and a peak efficiency of 43 %.

During this test period however three main factors emerged which led us subsequently to abandon the use of the heat transfer fluid in favor of a direct water injection –steam generation approach. These were:

1) The fact that leaking of the valves and joints of the hot oil piping system were proving very hard to eliminate. When the oil was circulating at over 200ºC any leaking drops would vaporize and give off a very noxious smell which was not at all welcome in the kitchen environment.
2) The fact that the heat storage tank was found to be too large, with too much thermal inertia, thus taking about two hours to heat up to suitable operating temperatures sufficient to generate steam. As our kitchen has the requirement that all the main cooking be done by 11:30 am, this was not acceptable.
3) The fact that the fluid itself was very costly, thus placing it out of reach for future project developments. It was also not found to be environmentally friendly (it will be hard to dispose of when its use life is over).

Taken by themselves any of these three problems could have been perhaps overcome (and perhaps still can be) but at the time we decided to make the change to a direct steam generation system.

10.2. CHANGING THE SYSTEM TO DIRECT STEAM GENERATION MODE

The switch to a “water only” system was easily accomplished and has proved in fact to be very easy to run ever since.

The large heat storage tank was simply removed from the circuit and a simple water pump was installed to pump softened water, from the same supply as that used by the conventional diesel boilers in the kitchen, into the pipe leading to the receiver in the solar collector.

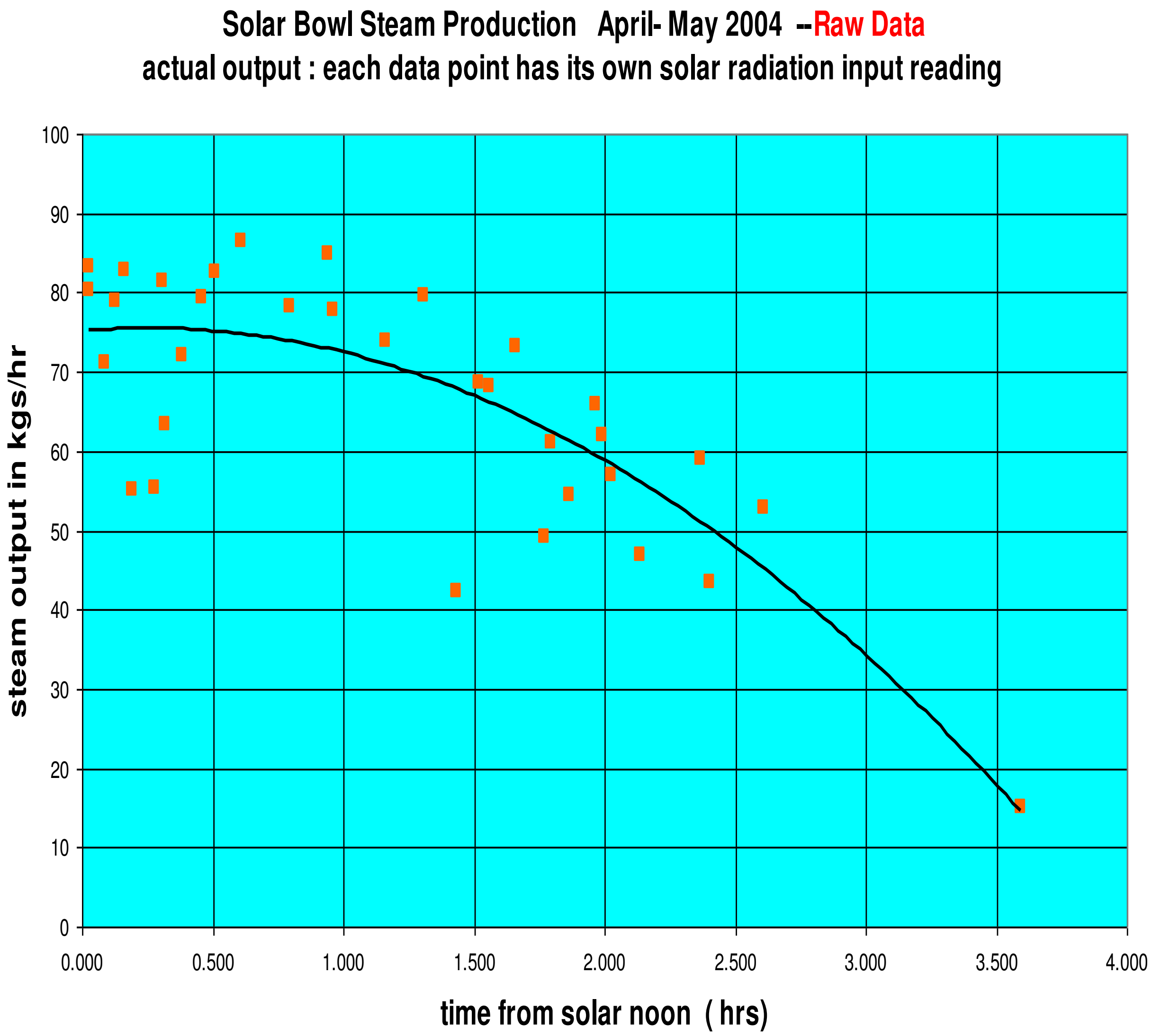
The pump was driven by a variable speed motor which was controlled by a four set point controller fed by the signal from a temperature sensor placed at the top end of the receiver coil. When the receiver heats up past a certain limit the pump will in turn pump more quickly to supply more water for steam generation to the receiver coil.

- Note that a long meticulous process, lasting several months, of cleaning the fluid lines of all traces of the heat transfer fluid had to be undertaken to ensure the cleanliness of the water steam mixture now being delivered by the solar collector in this new mode.

11. PERFORMANCES IN THE MODIFIED CONFIGURATION

11. 1. TESTING THE SYSTEM IN THE DIRECT WATER INJECTION MODE

During April of 2004 a detailed testing of the system in this new mode was carried out. During these timed tests steam production was measured and simultaneous measurements of the direct beam solar radiation were taken using a long tube pyreheliometer so that calculations of system performance could be made. The basic data for steam production is shown below.



The basic data shown above lead to the following observations:

1) peak steam generation observed was 86 kgs/hr
2) full day peak steam output is 450 kgs
3) peak thermal energy output was 63 KW
4) energy conversion efficiency (direct beam sun energy to steam heat) was 43% at noon, 41% at 11am, 36% at 10 am, approx 30% at 9 am

11.2 REALIZATION OF PROJECT OBJECTIVES

Bowl efficiency:	originally estimated	-----	= 43%
	Presently measured	peak at noon	= 43%
	“ “	average (9 am to 3 pm)	= 38 %
Daily steam production:	Original estimate	578 kgs	
	Presently measured	450 kgs	

11.3. OPERATING THE SYSTEM DURING 2005 – 2006

For the past year, the system has been operated daily in this mode of direct steam generation.
The experience has been largely trouble free and quite rewarding in its simplicity.
The system is always operated in tandem with one of the kitchen’s diesel-fired boiler because of the demand that the cooking be over as soon as possible.
On good sunny days experience has shown that the diesel-fired boiler can be shut off up to an hour early and the cooking on those days is completed between 11 am and 12 noon by the solar system itself.
The system also supplies all hot water needed by the kitchen for clean up after cooking each day.
Diesel savings of 20 % are being achieved with this system during sunny periods.

11.4. CONCLUDING REMARKS

The technique of integrating the structure of a solar bowl into the roof of a building has been demonstrated successfully.
This ferrocement structure, having been now in place for 8 years, is in excellent condition.
The reflective surface composed of laminated glass mirrors is also shown to be in excellent condition after 8 years.
A lifetime of at least 5 more years for the reflective surface and much longer for the structure as a whole is confidently expected.
Only the receiver, at it hottest end, is showing signs of serious corrosion and will evidently need replacement before long.
The system as a whole, after studies to simplify the tracking system, may be replicated to function as a source of industrial process steam.

11.5 SUGGESTED FUTURE WORK

1) Full recording and documentation of the temperatures being reached along the receiver and along the steam loop.
2) Simplification of the tracking system to eliminate the present computer (see note 2 below)
3) Building of a new receiver (cost approximately = Rs. 40,000) (see Note 1 below)

<u>Note 1:</u> A new receiver was built using copper coils of 19 mm OD and 0.6 mm wall thickness, on a dip galvanized central frame (same dimensions as the old receiver) and was commissioned in March 2007.

<u>Note 2:</u> During May 2008 a new tracking hardware was designed and installed to replace the computer. This incorporates a photo sensor mounted on the receiver arm and a simple microprocessor for generating a pulse for the stepper motor drivers. Testing is underway.