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A PROPOSAL FOR THE CONSTRUCTION OF A SOLAR PILOT PLANT BASED ON HIGH TEMPERATURE (500°C) SHELL MIRROR COLLECTORS

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SUMMARY

It is proposed to manufacture a high temperature (up to 700°C) pilot plant based on paraboloidal mirror collectors. The proposed collectors are novel and their demonstration would represent a significant contribution to the field of study in solar power generation. In addition they will constitute an important research tool in their own right enabling further experimental work in several aspects of solar energy collection and utilisation.

The total cost of the pilot plant, of some one hundred square meters collection area, is $87,300. In addition 18man months of School workshop time will be required. A large fraction of this cost is for tooling and is therefore a once-only component. It is proposed that the costs be shared by the ANU and a sponsor.

The anticipated costs, if transferred to a mass production situation, correspond to the exceptionally low figure of approximately 100$/m^2. The demonstration of the pilot plant would therefore also demonstrate the immediate competitiveness of the collectors with Middle East oil.

The proposal involves the use of the large boring mill located in the 'accelerator' wing of the Cockroft Building and also the use of part of this wing during construction.

The final location of the pilot plant is to be arranged with the sponsor.

CONTENTS

1. INTRODUCTION

It is most likely that the advent of solar power will depend almost entirely on economic factors. It is therefore of paramount importance to approach the problem of cost reduction from as high an academic level as possible and indeed there is need for a completely new methodology in this area. The collector system and the manufacturing processes described in this proposal are innovative and result from a determined effort to discover a minimum cost design.

In the course of the work, an embryo methodology has evolved which seeks to standardise the comparison of candidate designs and to point the way to beneficial variations. However, all methodologies require, in the first place, a feedstock of concepts and this can only be generated by human ingenuity. It cannot therefore be claimed that the solution described in this proposal is the best. Neither is the reservoir of ingenuity exhausted nor the optimisation process, at this point, free from subjective judgement. However the largest unknown cost factors at present are likely to be related to the operation, maintenance and lifetime and are therefore unobtainable unless the step of building a pilot plant is now taken.

Accepting the estimates which appear in Section 10 of this proposal for the quantity production of mirror collectors, and provided field tests demonstrate that operation, maintenance and depreciation can be kept to a maximum of 20% of the capital value of the installation, it can be shown that the proposed solar collector system is immediately competitive with fuel oil at the present world market price. Such a finding would have enormous impact not only throughout a large part of Northern Australia but also throughout the world especially in the developing nations.

The collectors described here are capable of efficiently heating fluids to about 700°C. Their application is therefore wide-ranging. Not only will they satisfy the needs of industry for hot water, steam and for other fluid heating requirements, but they will also be able to produce superheated steam for use in conventional turbines. Thus solar derived electric power may be generated.

Moreover, the collectors are admirably suited for concentrating solar energy onto certain types of solar cells. By increasing the intensity of solar energy falling on a cell the output per dollar invested may be increased by several orders of magnitude. Thus the now prohibitive cost of solar cells may be effectively reduced.

But possibly of greatest significance is that these collectors are suitable for thermochemical methods of absorbing, transporting, storing and recovering energy. These methods show great promise of solving the problem of economic long-term, large-scale energy storage and also the economical transport of heat over long distances.

The sections which follow describe the system proposed and particularly the proposed method of manufacturing the prototype collectors and pilot plant comprising approximately ten collectors totalling 100 m^2 area. Although the cost estimates extend into the area of quantity production this has been done in order to demonstrate the potential of the collectors, for it is not of course the function of a research group to go beyond the pilot stage.

2. DESCRIPTION OF SYSTEM AND DEFINITION OF MAJOR PARTS

In the following description each major part of the system is underlined when first introduced. Solar radiation is focussed by means of paraboloidal shaped reflective surfaces onto focal devices as illustrated in Figure 1. Within each focal device the collected energy is transferred to a fluid which is then pumped to the point of usage. Each reflective surface is supported by a collector shell formed from sheet metal and these in turn are supported in pairs from a common frame. Mounted on or adjacent to the frame are four actuators for turning the two collector shells in azimuth and elevation. The actuators are powered by a single hydraulic unit coupled by steel cables to the actuators, and the motion of the actuators are dictated by a control system.

In order to receive solar energy the collectors are steered to face the sun. During inclement weather, however, it is necessary to protect the mirror surfaces from damage so the collectors of a pair are steered to face one another. In this position they resemble a closed clam. In strong winds the clam is free to swing like a weather vane and align itself in the direction of the wind.

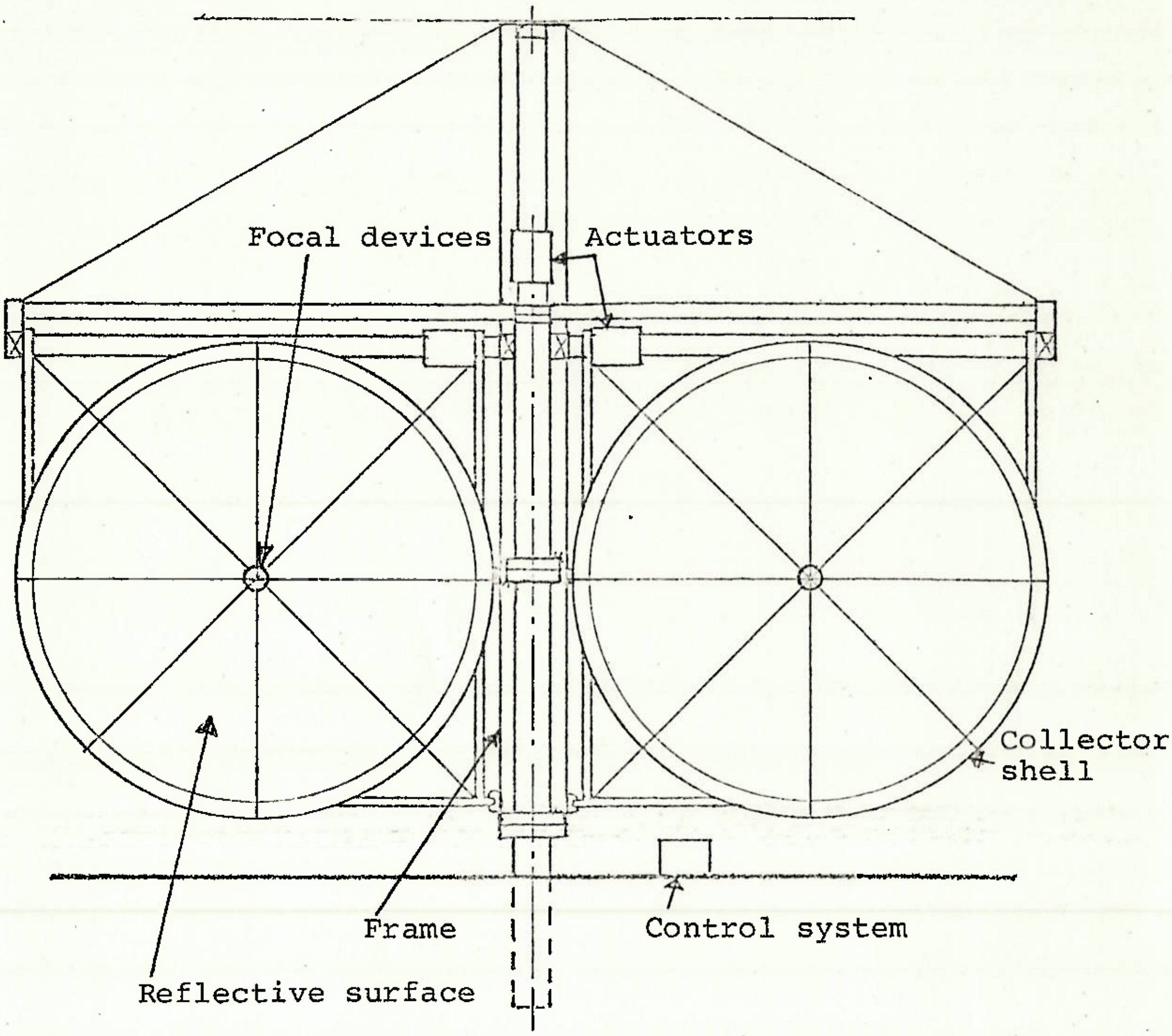


FIGURE 1: Diagram illustrating major components

3. COLLECTOR SHELLS

The paraboloidal shells, of diameter 3.66 m, are the structural substrates which support the reflective film. Because they are shells they are inherently much more rigid than the original flat metal sheet from which they were made. The preferred metal for the prototype is aluminium 1.2 mm thick but there is no reason in principle why thinner steel sheet should not be equally suitable. Aluminium is chosen for the prototype because it obviates the need to consider corrosion protection at this stage and gives us an extra option for the reflective surface viz polishing the substrate. This option will be particularly attractive if we can procure high purity aluminium or at least standard aluminium with a high purity clad layer.

The focus of the shells will be just inside the plane of the rim making the depth of the shells 0.95 m.

In the clammed position, two shells form a pressure vessel which will experience pressure differences of up to 2 kPa in cyclonic winds. This withstanding pressure difference is to be compared to the manufacturing forming pressure which must be at least ten times greater in order to provide an adequate design safety factor. However, a substantial increase beyond this factor would be uneconomical. The simple logic of the above statement must be modified in accordance with the following considerations: (a) forming pressures produce predominantly non buckling conditions whereas wind pressures may cause buckling as a result of compressive stresses; (b) stresses around support points for the shells require special attention.

According to experiments with 600 mm diameter models, the buckling pressure appears to be about 1.1 kPa. A negative internal pressure of this value could be created in practice if for example there were an opening at the apex of each shell, a very good seal betweeen the rims of clammed shells and the wind velocity was 110 to 150 km/hr. If on the other hand there were no opening at the apex and a slight opening at the rim, we might expect the internal pressure to exceed the external pressure in which case buckling would not be a problem. Further investigations of this aspect and of methods for controlling the internal pressure under all conditions are intended using model tests in a wind tunnel.

High stresses around support points will be eliminated by introducing continuous rim support through the agency of a 50 mm OD x 1.5 mm tubular reinforcing ring. The deformation of this ring will be resisted by 8 radial spokes of 1.5 mm piano wire stretched across the aperture of the collector.

The parts of the frame to which the shells will be attached are essentially two arms welded to an upper horizontal tube. The latter forms a hinge as shown in Figure 3. Additional attachments to the frame will automatically occur in the clammed position by means of two hooks per shell which engage in eyes attached to the vertical member of the frame.

The shells will be press formed from a single sheet approximately 4.2 m diameter. The single sheet will be made by edge welding sheets approximately 1.5 m wide using the T.I.G. process.

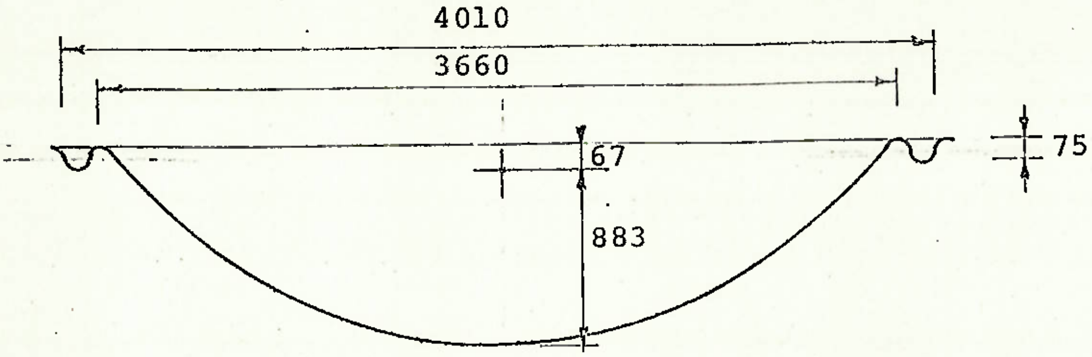
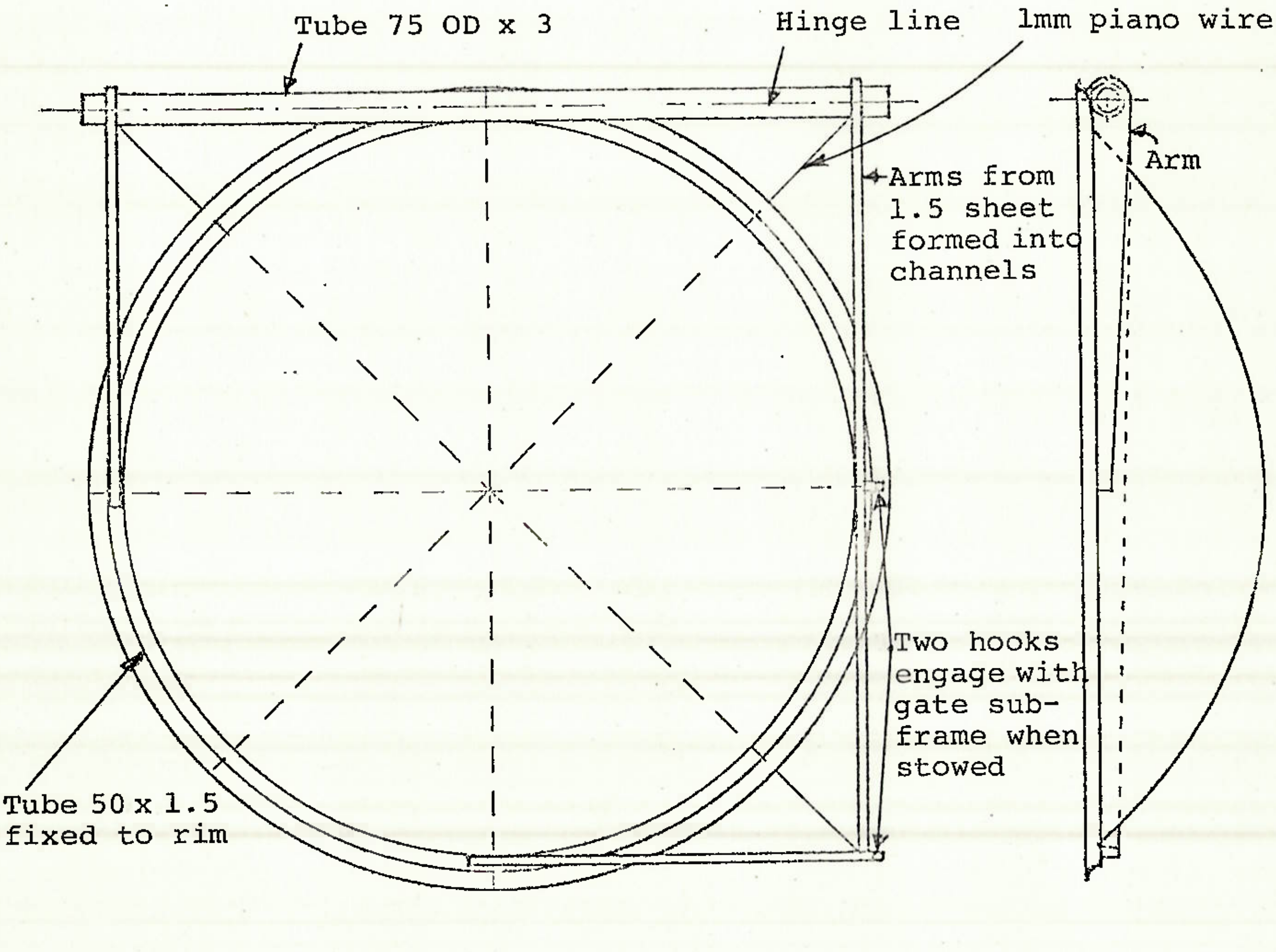


FIGURE 2: Cross section and dimensions of shell substrate

FIGURE 3: Rear view of shell with supporting shell sub-frame



Consideration of wind pressures as discussed above leads to the conclusion that a manufacturing forming pressure of 100 kPa should be adequate, ie. the pressure of 1 atmosphere, and this conclusion in turn determines the sheet thickness. The vacuum press that has been designed, and related model tests, are described in the next section.

3.1 Vacuum Press.

The vacuum press is illustrated diagramatically in Figure 4. An aluminium dish fabricated from 8 cast segments forms the principal component. This is machined internally to form the paraboloidal mould and is supported by a lower clamp ring attached to several legs. The two clamp rings and clamp ties form a system for containing the action and reaction forces of the hydraulically (oil) operated draw control ram.

In operation the mould is filled with water and a flat circle of sheet metal placed across the top and under the draw control ram. The ram is then pressurised causing the sheet to become grooved but the engagement of the ram in its matching groove is only partial at this stage. Water is then pumped from the mould space forming a partial vacuum. The vacuum seal is located against the upper side of the sheet causing the rim of the sheet to be lightly clamped and this clamping is augmented by a set of hydraulic rams. The clamping is required in order to resist buckling as the sheet is drawn radially inwards and also in order to provide a radial reaction force. The action of the draw control ram is partly to amplify, by means of the capstan effect, the resistance to inward radial movement caused by this radial

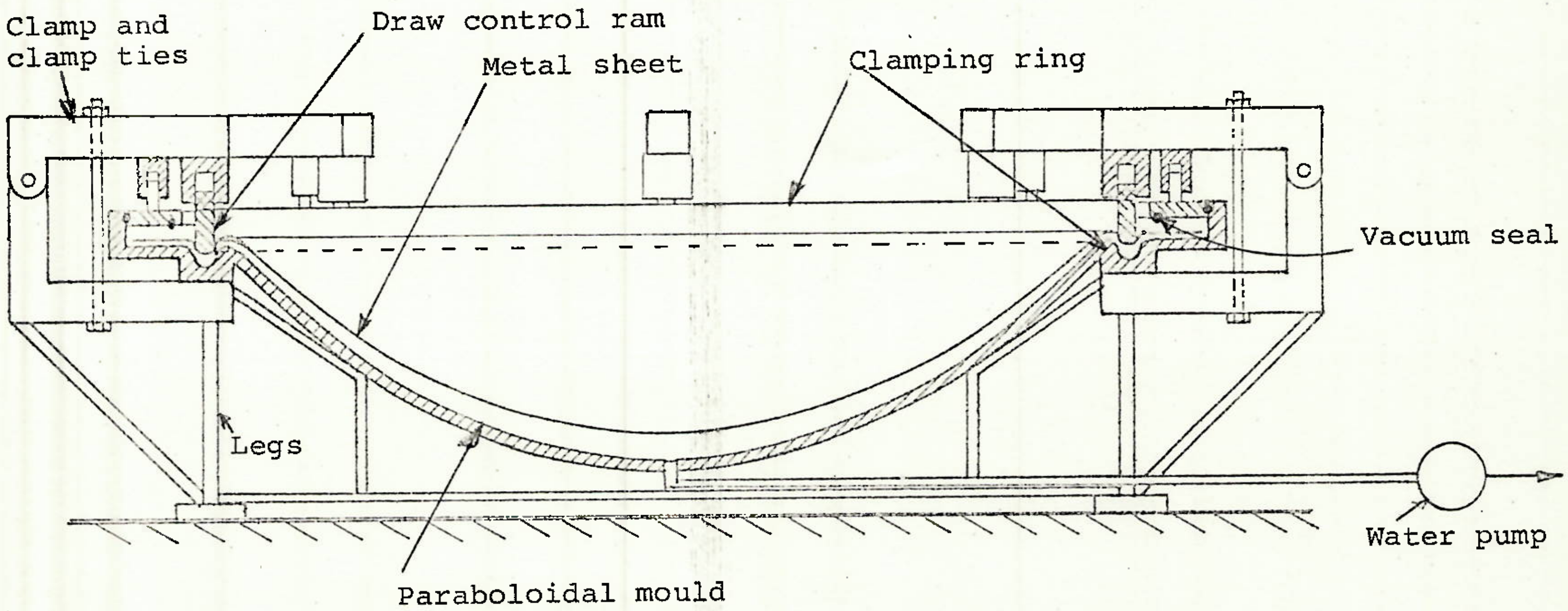


FIGURE 4: Diagram of vacuum press

reaction force. An additional component of resistance comes from the bending work expended as the sheet negotiates the groove.

Thus as the vacuum is increased the sheet is drawn deeper into the mould and radially inwards under the draw control ram. The engagement of the ram is gradually increased to provide the required reaction force and to control buckling of the formed sheet.

Except for the aluminium mould, the vacuum press is constructed of steel sections and plate. The pattern for the cast aluminium segments will most probably be constructed from reinforced fine grained concrete using parabolic templates. All large diameter machining can be accommodated by the boring mill located in the Research School of Physical Sciences and indeed it was the capacity of this mill which determined the maximum diameter of the shells.

Two model presses have been built and with them several 150 mm diameter and 600 mm diameter shells have been formed. Experiments with these models have demonstrated the feasibility of the vacuum press and have verified the scaling laws.

3.2 Accuracy, Mould Machining.

The accuracy of the formed dishes will be almost entirely dependent on the accuracy of the paraboloidal mould. The effects of spring-back when the forming vacuum is released and variations in sheet thickness are expected to be negligible and in any case can in principle be corrected by slight modification to the mould.

The mould will be formed by machining the aluminium dish to an accurate paraboloidal shape on the boring mill. A special machining rig will be constructed, designed to generate paraboloids with vertical axes of symmetry. The principle of generation is shown in Figure 5 while in Figure 6 is shown diagramatically the major assemblies of the machining rig. The semi angle α shown in Figure 5 is maintained by means of the alpha bar shown in Figure 6 which rotates the cutting head support assembly about the contact point through appropriate gearing.

4. REFLECTIVE SURFACE

There are several options for reflective surfaces ranging from treatment of the shell substrate itself to application of films and coatings. The full range of options is presented here in order to demonstrate the great difference that exists between methods suitable for small production runs and methods suitable for mass production. In this area more than any other there appears to be great scope for future reductions in cost.

4.1 Blow Moulded Acrylic Sheet Back Silvered.

With this option a thin sheet of acrylic material, approximately 1 mm in thickness, is placed over the rim of a paraboloidal mould and pressed or sucked inwards while being heated. The moulded sheet may then be back silvered by conventional chemical means and fixed into the sheet metal shell with an adhesive.

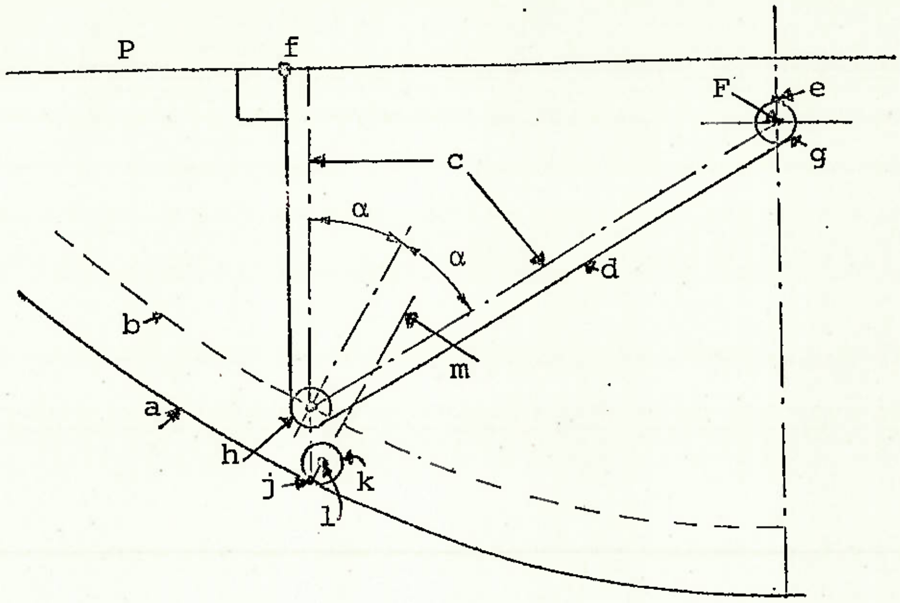


FIGURE 5: Principle of generation of paraboloid

a Paraboloid surface being generated

b Parallel parabola

c Parabola generating lines. The combined length of the two sections of (c) must be constant. (c) begins at the focus F and ends perpendicular to generating plane P. The parabola (b) is generated by moving point (f) along P.

d Constant length chain wrapped around stationary wheel g, fixed at (e), wrapped around wheel h and fixed at f.

j Contact point for cutting wheel (k) whose centre (l) must lie as shown on a line through j and at semi angle α to both sections of (c).

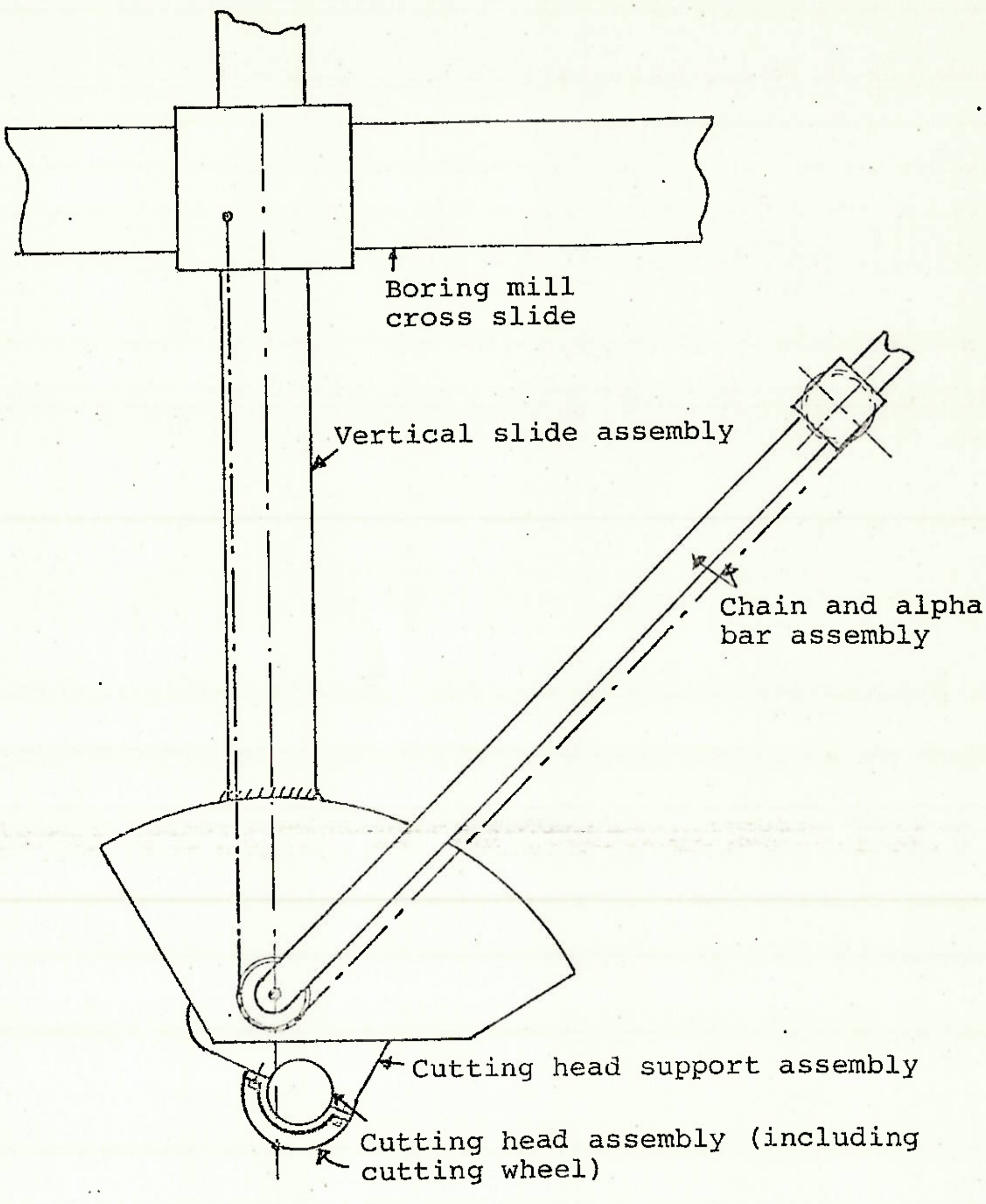


FIGURE 6: Paraboloid machining rig

Acrylic sheet 2.4 m x 1.2 m x 1.5 mm is normally available in Australia at a price of approximately 13\$/m^2 in small quantities. Although this material cost is high in comparison with other options, the capital equipment required for forming and mirror coating is relatively inexpensive. It is highly probable that the shell forming vacuum press will be suitable for the blow moulding process with the addition of an array of heaters for softening the acrylic. A cheaper alternative to any array of heaters may be a single heater located at the focus of a shell reflector placed over the acrylic sheet. Equipment for preparatory edge welding of the sheets, and equipment for mirror film application would have to be manufactured or purchased. In the long term this option is appealing since thinner and less expensive sheets may be employed as they become available.

4.2 Polyester Sheet with Adhesive.

Plastic sheet less than 0.1 mm is available comprising a sandwich of two mylar films with an aluminium film between. One side of the composite sheet is coated with an adhesive and all materials are comparatively insensitive to ultra violet radiation. The material is used commercially as an insulating covering for window glass and as such has been designed to partially reflect incident solar radiation with a reflectance of 56%. This low value of reflectance is barely admissible in our application. However there seems to be no technical problem in increasing the aluminium content in order to achieve the known maximum reflectance of almost 80%. It remains only to induce a manufacturer to make the appropriate modifications to his process.

Experiments are planned to establish whether this sheet may be applied to the metal sheet prior to forming the shell.

The presently available material is approximately 8$/m^2 imported from USA in small quantities. It is 1.5 m wide.

4.3 Polyester Sheet Vacuum Fixed.

Aluminised mylar sheet approximately 0.1 mm or thinner is available having a high reflectance and made from suitably ultra violet insensitive material. It should be possible to fabricate an approximately paraboloidal shape from this film which, under slight suction will lie contiguous with the shell over its entire concave surface. Much of our experimental work so far has been related to this option and several problems have been exposed: dew drops covering minute holes in the sheet are sucked under it and eventually cause the aluminium deposit to migrate from the mylar; dust particles which remain between sheet and shell cause the reflective layer to be rough in texture and thus adverse to specular reflection.

A mylar laminate is also available similar to that described in Section 4.2 but without the adhesive backing. It is 0.1 mm thick and 1.25 m wide and is reported to have a reflectance of 87%. It is manufactured in the USA where the price is approximately 3.5$/m^2.

In order to implement this option, using for example the above laminate, it will be necessary to develop a technique for segmenting sheet and for edge bonding the segments together to form the required shape. The technique must avoid the over-use of labour. Additional work is required to develop a satisfactory seal to the shell and to reduce the problem of dust.

The same technique using suction may be applied to thicker sheets. There is available an aluminised acrylic sheet 3 mm thick costing approximately 30 $\$/m^2$. The substrate could be covered with approximately 30 tiles shaped from this sheet and sealed with silicone rubber. Reduction in the number of tiles is limited by the maximum allowable suction that can be applied before the substrate buckles.

4.4 Adhesive Tape.

A range of reflective adhesive tapes is manufactured by the company 3M. A shell surface could be covered by placing side by side in the radial direction suitably shaped lengths of this tape. The system for accomplishing this would need to be highly mechanised to be practical and economical. The tape is manufactured to widths up to 72 mm and a thickness of .02 mm. The cost is approximately 5$\$/m^2$ but the reflectance is poor.

4.5 Buffing Substrate.

It is possible that a mechanised system for buffing the finished aluminium shell can be developed which will give a sufficiently specularly reflective surface. Several preliminary tests have revealed that it is difficult to remove normal surface scratches and to achieve high reflectances.

4.6 Lacquer, Vapour Deposition.

In contrast to buffing which aims to remove material until the original depressions disappear a lacquer may be used to fill the depressions. Ideally such a lacquer should have a high surface tension so that its air-lacquer interface is pulled into a smooth surface. It should be able to set bubble-free and this may necessitate it being solvent-free. Alternatively the lacquer, might be buffed into a suitable surface. Once rendered smooth the surface would then be metalised by a vapour deposition technique similar to that employed in metalising astronomical mirrors and for bright finishing parts in the automobile industry.

However, the metallising equipment is expensive and unless we can borrow or rent an existing facility this option is not presently available.

In the long-term one can envisage equipment for handling batches of a hundred or so and costing approximately $500,000. The preferred type of equipment requires a high vacuum and employs an electron beam for vaporization. This type of equipment is able to vaporise high melting point materials such as silicon monoxide which is a candidate protective coating for aluminium vapour depositions. Pumping a high vacuum is generally a time-consuming task and hence the virtue of batch processing. The equipment envisaged would require a vacuum vessel approximately 6 m diameter fitted internally with handling equipment and with a moveable vapour source. The cost may be estimated assuming an output of 100 shells per day and assuming a total running cost (including interest on capital) of 350$/day. The resulting figure of 35 cents per m^2 is quite inexpensive. By adding an allowance for lacquering and buffing the final cost of this reflective surface is estimated at 2$/m^2.

4.7 Electro Brightening Substrate.

Aluminium may be electro polished and electro brightened by processes which are essentially the reverse of electro plating ie. material is removed from the surface being treated. The process depends on the fact that under the action of electric fields high points are selectively eroded. Excellent results are achievable with high purity aluminium (99.99%) and sheets of this purity are available from the UK 1.2 mm thick at a cost of 15.55$/m^2. It may also be possible to obtain standard grade sheets having a thin high purity overlay. Thus the substrates themselves could be made from this material. On the other hand, it may be possible to apply a high purity thin sheet to the substrate. High purity film is regularly imported for manufacturing electronic capacitors.

Equipment used for electro polishing and electro brightening may also be employed to deposit protective anodic oxide films (anodising).

Electro polishing is carried out at high current densities, 1000 to 3000A/m^2, and electro brightening at low current densities, 300-500A/m^2. The work must be subjected to a series of immersions and washes in addition to immersion in the electrolyte, and timing must be fairly precise. The process is therefore more suitable for continuous strip rather than single large items like our shells. Nevertheless, a process could be devised.

4.8 Electro Brightened Segments.

Pre brightened high purity thin aluminium sheet is available which may be cut into segments and applied to the substrate. One such sheet is 0.3 mm thick and costs 6.1$/m^2. The sheet would be cut into approximately 300 radial segments each of which could be fitted by clipping between a circular lip located around the apex of the substrate and a lip located at the rim. On the basis of one man pressing the segments at one per 30 seconds on a press tool and hand fitting at 1 per minute the additional costs are estimated to be 10$/m^2. Thus allowing 4$/m^2 for the lips the total cost is estimated at 20$/m^2.

4.9 Electro Brightened Tiles.

As an alternative to 4.8, pre brightened high purity thin aluminium may be formed into slightly dished tiles, approximately 25 being required for each substrate. The boundaries of the tiles would be formed by the rim and two circles concentric with the apex together with appropriately spaced radial lines. Each tile would be of the order of 1 meter across in either direction. Each tile has two principle curvatures which, except for the central tile, are different from one another. It should be possible to reproduce these two curvatures by clamping a flat sheet across an elliptical opening of a pressure vessel operating at a fraction of an atmosphere. After creation of the curvatures each sheet is clamped in a jig and the edges cut to the shape of the tile. The finished tiles would be glued into place. Allowing 2 man hours per tile for cutting forming and glueing, the cost additional to the cost of material is approximately 5$/m^2. Material waste would be higher than for 4.8 so the total cost is estimated at approximtely 15$/m^2.

The tile technique is also applicable to adhesive backed mylar film or blow moulding.

4.10 Summary of Options.

The nine options above are categorised in Table I in terms of labour and capital equipment required for their implementation and in terms of reflectance and prime cost of reflective material. Option 4.6 is considered inappropriate for a prototype.

Selection of the best option is difficult. Probably the most important factor to consider is reflectance and durability of the surface since it is generally cheaper to provide the best reflectance and durability than to provide, for example, double the number of collectors having half the reflectance or durability. The prime cost of the reflective surface is probably of least significance but the cost of labour and capital is of practical significance in manufacture of the prototype. With these considerations the options appear to be narrowed to 4.1, 4.3, 4.7 and 4.9. Of these 4.1 is presently favoured but further information is required before a final selection can be made.

TABLE I

O	D	LI	CI	R	C	C+S
4.1	Blow mould	l	m	h	13	20.5
4.2	Polyester-adhesive	h	h	l	8	15.5
4.3	Polyester-vacuum	m	m	h	3.5	11
4.4	Adhesive tape	h	h	l	5	12.5
4.5	Buff substrate	l	m	l	7.5	
4.6	Lacquer-vapour	-	-	-	-	-
4.7	Brighten substrate	l	h	h	15.6	15.6
4.8	Bright segments	h	h	h	6.1	13.6
4.9	Bright tiles	m	h	h	6.1	17.5*

* prime cost increased to 10 to allow for wastage

LEGEND:

O = Option (Subsection number)
D = Description
LI = Labour intensity rating
CI = Capital intensity rating
R = Reflectance
C = Prime cost $\$/m^2$
C+S = Prime cost plus substrate cost at $7.5\$/m^2$

h = high
m = medium
l = low

5. FOCAL DEVICES

The immediate object of the focal device is to heat a liquid, such as Gilotherm OMD or pressurised water, to approximately 300°C. The focal device will be constructed from stainless steel tubing of approximately 4 mm OD coiled into a cylinder of pitch diameter approximately 5 cm as illustrated in Figure 7(a). There may be a smaller concentric cylindrical coil internal to and hydraulically coupled in series with the former. The coils will be capped with a disc of insulation and mounted on struts off the shell.

Our research indicates that the absorptivity of such a coil when oxidised is approximately 0.95 and that when placed at the focus of a paraboloid proportioned as described above, will suffer only small losses of the order of 2% for reradiation and 2% due to convection in a 16 km/h wind.

The shells are designed so that, when they are laced together in the clam configuration as shown in Figure 7(b), the caps of the focal devices do not interfere.

6. FRAME

The frame supporting the shells and enabling them to point in any desired direction will be constructed principally from welded mild steel. The frame for a pair of shells comprises four planar sections hinged together and the layout and names of these sections or sub-frames are shown in Figure 8.

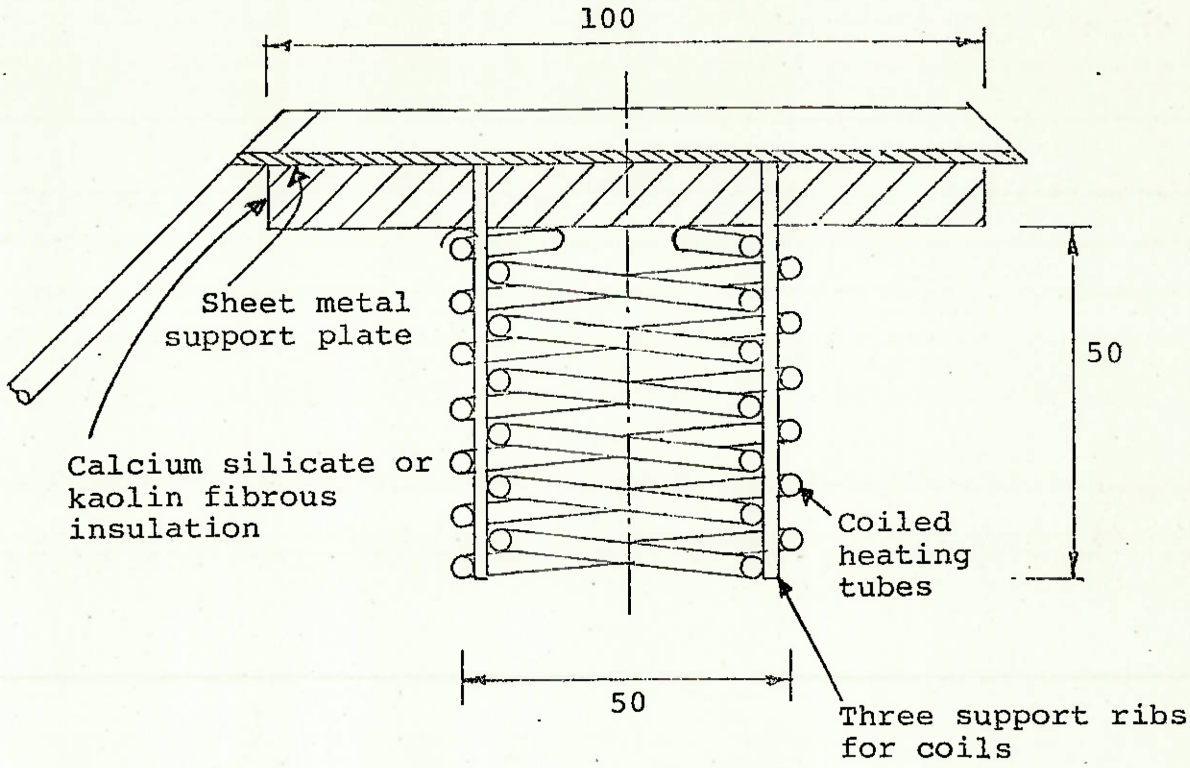
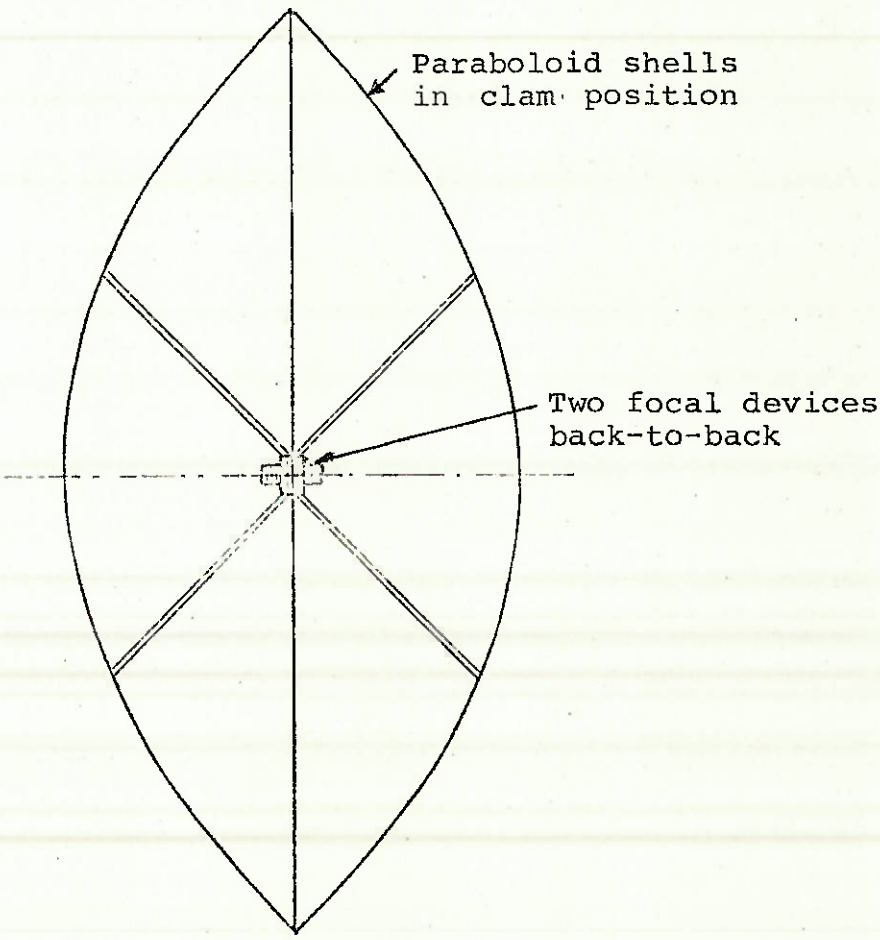


FIGURE 7(a): Schematic of focal device.

FIGURE 7(b): Illustrating position of focal devices in clam configuration



Each shell sub-frame is basically a square frame having an upper tubular member about which the shell rotates in elevation. This member is 100 mm diam x 1.5 mm and welded to it are two arms constructed from cold formed sheet steel. Fixed to the arms and the 100 mm tube is a wire braced ring formed from 50 mm diam x 1.5 mm tube. This ring is attached at multiple points to the rim of the shell. In the clammed position, provision will be made to link together the wire braced rings of adjacent shells if ever the wind strength threatens to force open the clam.

The upper member of each shell sub-frame is hinged to the horizontal member of a gate sub-frame of triangular form. The rigidity of the structure in azimuth will be largely due to the rigidity of this horizontal member acting as a cantilever and resisting deflection in the horizontal direction. Consequently it will be made from two 75 mm OD x 1.5 mm tubes. The vertical member of each gate sub-frame is a 100 mm diam x 3 mm tube and extends from just above ground level to approximately 3 m above the elevation rotational axis. This vertical member is attached to the central column by bearing rings at the three points shown. The upper end supports the horizontal member of the gate sub-frame by means of a 6 mm tie rod. In addition the upper ends of the vertical members of both gate sub-frames are hinged together and provision is made here for attachment of stay wires if required.

When a shell sub frame is at zero elevation, two hooks engage in eyes on the vertical member of the gate sub-frame. This facility enables the horizontal wind forces on the closed clam to be transmitted directly to the column.

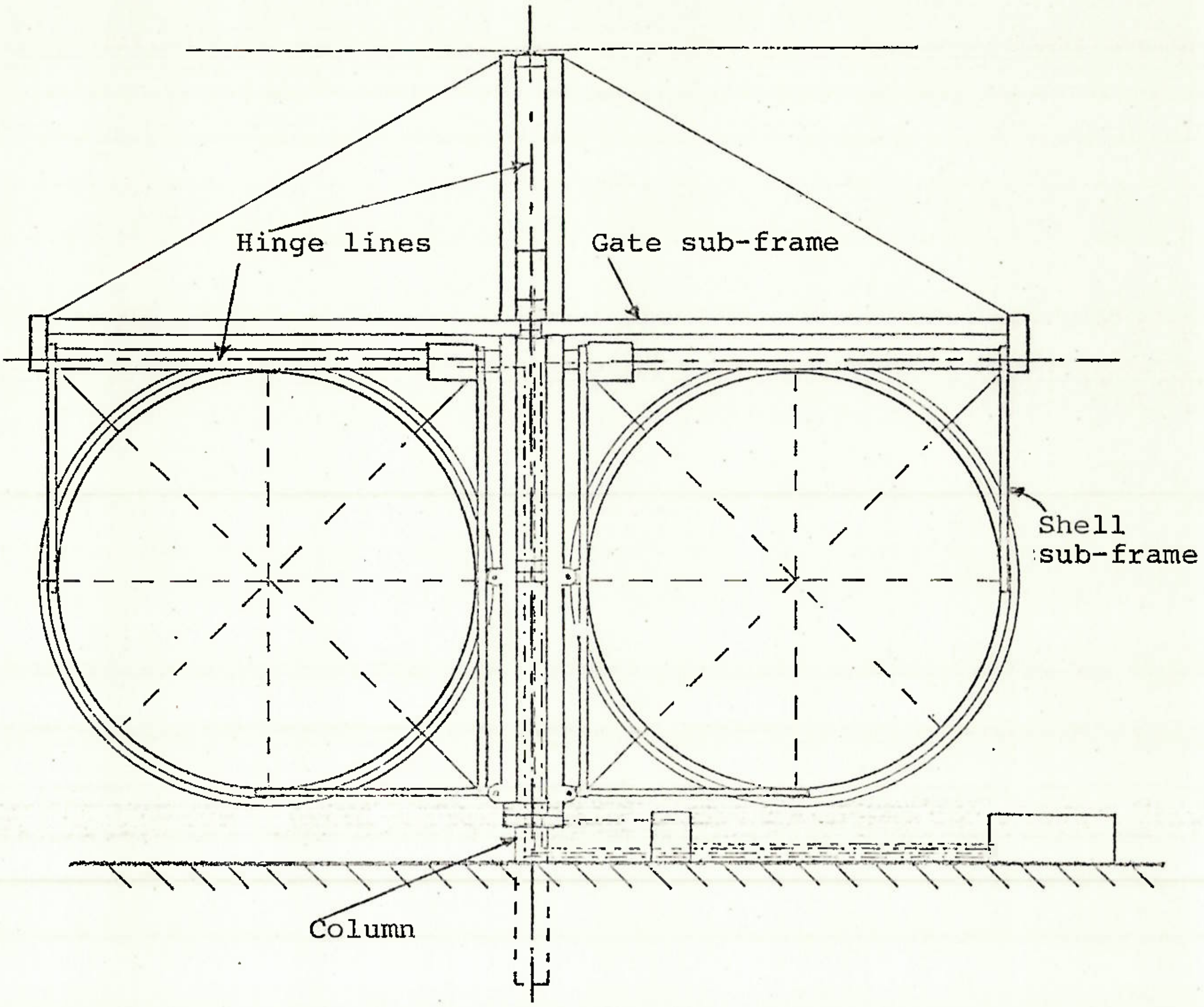


FIGURE 8: Principle of structure of frame sections

Both gate sub-frames are supported by and turn about the column which is a steel tube approximately 300 mm diameter with wall thickness 1.5 mm suitably strengthened at load points and protected from corrosion below ground level. It is planned to set the column directly in the ground provided the ground is found to be sufficiently firm. The size of the column has been selected on the basis of withstanding the maximum wind force on a pair of shells in closed clam configuration and oriented so as to present minimum area to the wind (similar to a wind vane). The effect of a sudden 90° change in wind direction has also been taken into account. The maximum wind force has been estimated on the basis of a wind speed of 185 km/hr and a drag coefficient of 0.5. The chance that gusts may exceed this speed in a 30 year period for the locality of interest is estimated to be 0.1.

7. ACTUATORS

For each pair of shells there are four actuators designated: elevation 1, elevation 2, azimuth and clam. The two elevation actuators are located on the hinge between each shell sub-frame and gate sub-frame and control individual elevations. The azimuth actuator is located on the ground and operates on one of the gate sub-frames controlling its orientation. The clam actuator operates between the two gate sub-frames controlling the angle between them. Thus the azimuth of each shell may be independently determined by appropriate rotations of the azimuth and clam actuators.

Hydraulics has been chosen for the motive mechanism for the following two reasons:

(a) in a solar power system based on high pressure thermochemical energy transfer and storage, it would be highly advantageous if the thermochemical fluid transport system could also double for the actuator power transport system. For a large solar power station, a separate system for the actuators would most probably require an overhead high tension electric network together with numerous transformer substations. The elimination of the need for such a system would clearly result in considerable savings,

(b) a hydraulic system is capable of rapid velocities in emergencies as a result of the inherent storage capacity within it. In addition an hydraulic system matches the low-speed high-torque requirements of a solar array without resort to expensive gears.

The system we have developed so far comprises: a single oil hydraulic ram for each pair of shells which is located on the ground beside the column; a system of pulleys and wire cables which divide and transfer the ram force to four separate actuators three of which are located on the frame and one (azimuth) on the ground; at each actuator, a pulley arrangement for producing two counter directed forces; and finally a bidirectional torque amplifier, powered by the two counter directed forces and amplifying by some one thousand times the torque of a small position controlling electric motor. The wire cables connecting the ram and three of the actuators pass along the axis of the central column and are thus immune from the effect of rotation of the gate sub-frames.

In operation any rotation of an actuator in either direction results in a proportional unidirectional displacement of the ram. The stroke of the ram is chosen to be of adequate length for one day's operation of all the actuators. At the end of the day, the ram is returned to the starting position by reducing hydraulic pressure to zero and by the action of return springs and ratchets located at each actuator.

7.1 Torque Amplifier.

The maximum torque required of any actuator is calculated to be 5000 Nm on the basis of closing the clam against a wind of velocity 80 km/hr. A torque amplifier capable of amplifying torques of the order of 5 Nm to the above 5000 Nm may be constructed by winding approximately ten turns of chain on a powered drum of approximately 300 mm diameter. The smaller input torque is applied to one end of the chain as a force acting about the drum axis and a similarly acting amplified torque is available at the other end of the chain. This mechanism, the capstan, is unidirectional in the sense that it requires the drum to be rotated in the same direction that the smaller torque is applied to the chain. However, the displacement of the input end of the chain may be in either direction. The velocity of the input end of the chain may also be in either direction provided it does not exceed the velocity of the drum. Bidirectional torques therefore require for amplification a device fitted with two counter rotating drums. The torque amplifier we have developed is based on this principle.

7.2 Description.

The major parts of the torque amplifier are illustrated in Figure 9. The required angular position is set by the position controller, a small motor (such as a stepping motor) connected by light gearing to the position signal shaft located concentrically within the driven output shaft. Rising from this signal shaft and passing through slots in the output shaft are two arms viewed end-on in Figure 9. To the end of these arms are attached the capstan chains wrapped in opposite directions around the two capstan drums. The other ends of the chains are attached to the torque transfer drums keyed to the driven output shaft. The capstan drums are driven by sprockets and chains from a lay shaft, one of the chains being crossed so that the two capstan drums rotate equally in opposite directions. The lay shaft is rotated in one direction only by means of the drive cable and ratchet and the lay shaft assembly is fitted with a return spring whose duty is to wind back the drive cable when the ram is returned to its starting position.

In operation, with the position controller stationary, the chains are pretensioned at the signal input end with a small force sufficient to lock both chains to their capstan drums. Under these conditions the chains act oppositely on the output shaft which thus remains stationary as does the lay shaft and capstan drums. Rotation of the signal shaft will result in an increase and a decrease respectively in the input tension of the two capstan chains which in turn will result in one chain locking more firmly to its capstan drum while the other slips on its drum. Thus the output shaft will be driven by the former drum and chain

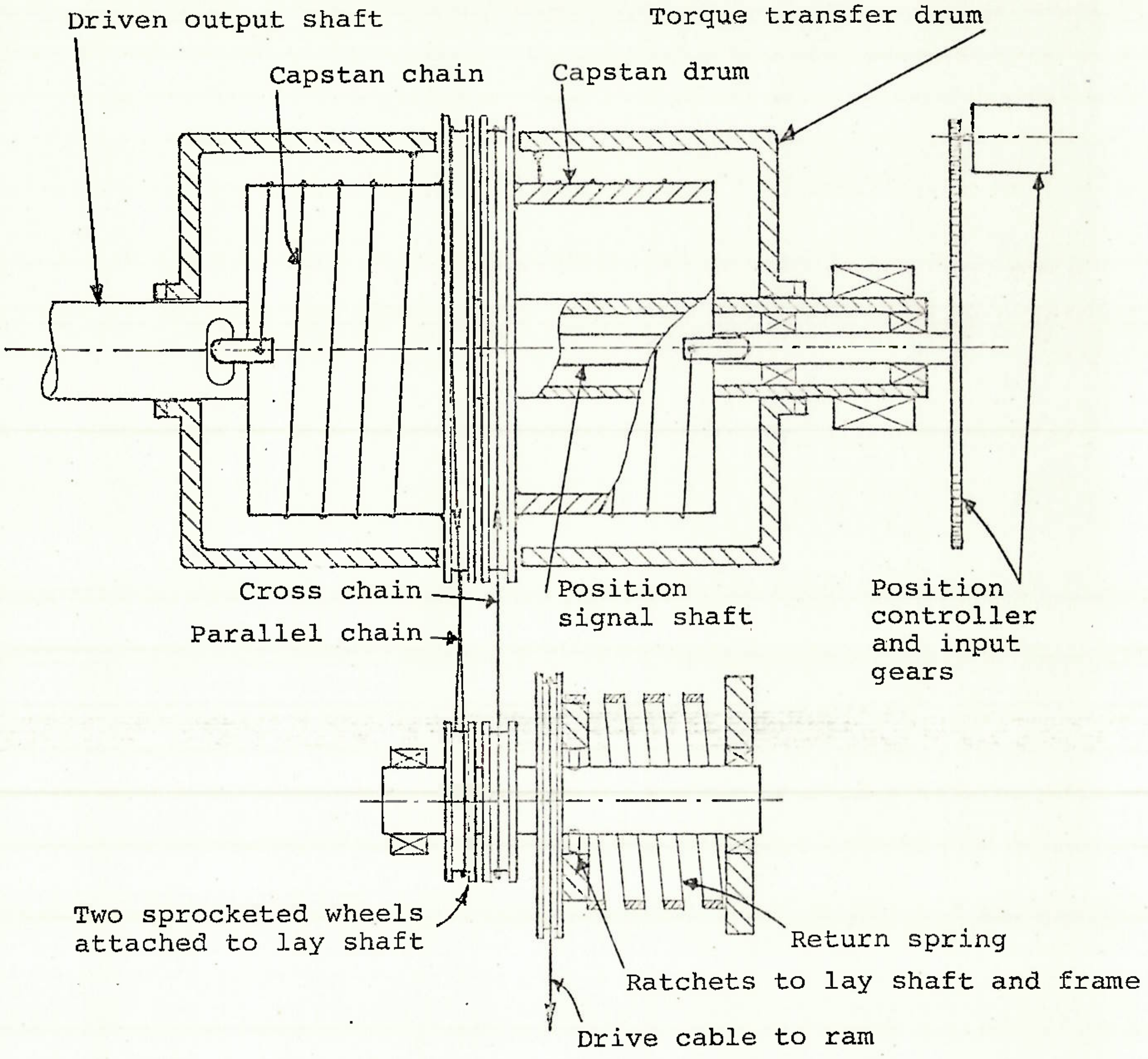


FIGURE 9: Principle of torque amplifier

and will rotate against large load torques until its angular position again corresponds to that of the signal shaft.

The torque amplifiers are all identical and each is symmetrical. Thus savings in cost will result from quantity production of a few components. The drums will be cast and machined, the capstan chains will be of roller design and graded in size along the length to correspond with the chain force. The gears associated with the position controllers will be similar in construction to Meccano gears the larger wheels being made from sheet metal stamped or machined in stacks.

8. CONTROL SYSTEM

Mirror collectors are mounted in pairs with common fixed vertical axis and individual swinging horizontal axes.

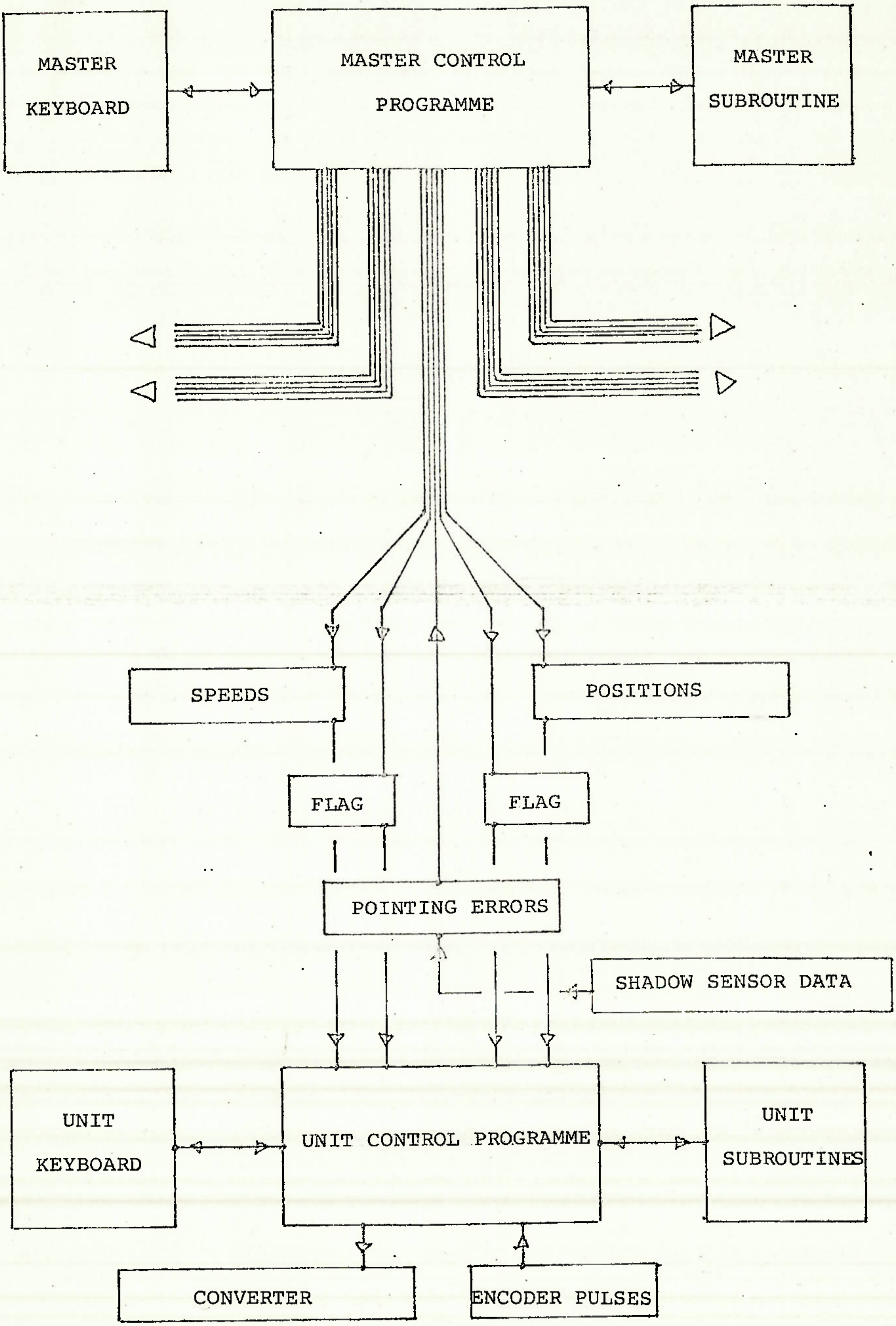
The parameters describing the pointing position of a pair of collectors are: two individual 'elevations', 'azimuth' and 'clam' which is the difference between individual azimuths. The clam is said to be shut when elevations are zero and the collectors face each other with individual azimuths in opposite directions. Thus clam = 180° when shut, 0° when open.

The collectors point according to computed instructions eg. (a) point at sun or (b) close clam and point to minimise wind force. For (a), shadow sensing pointing error sensors are used to monitor accuracy of computations and also to provide a trimming correction.

Motion about the axes is effected by actuators each comprising a torque amplifier and a small electric motor (the position controller) whose angular position represents that required of the collector. An encoder pulse is generated whenever a collector turns through a specific small angle. These encoder pulses are counted so as to record the pointing direction of the collector. They are also used for monitoring the speed of the actuator.

The hardware of the control system is microprocessor based and comprises a single master system located in a building adjacent to the collector field and individual unit systems located at the collector pairs. Interconnection is by means of multicore telephone cable. Located with the master control unit will be a keyboard and read-out facility. These will provide access to both master and unit systems.

The software comprises a master control programme, a set of master subroutines, individual unit control programmes and unit subroutines. The interface between master and units will be a set of registers into which the master programme writes calculated speeds and positions, and a set of flags for signalling specific times such as the time to stow the collectors at the end of each day. Additional interface registers will accommodate shadow sensor data which will be read by the master programme as required. The digital output of each unit control programme will, after suitable conversion and amplification, directly control the power to the small electric motors of one pair of collectors.


MASTER KEYBOARD
MASTER CONTROL PROGRAMME
MASTER SUBROUTINE
SPEEDS
POSITIONS
FLAG
FLAG
POINTING ERRORS
SHADOW SENSOR DATA
UNIT KEYBOARD
UNIT CONTROL PROGRAMME
UNIT SUBROUTINES
CONVERTER
ENCODER PULSES

A primary function of the master controller is the computation of the effective position of the sun which involves the use of trigonometrical functions. The results of these computations will be modified according to the shadow sensor data when available and also the requirements of energy balance as explained below.

The mirror collectors will be used to heat fluids to temperatures up to 500°C by pumping the fluid through tubular focal absorbers. Fluid flow will be regulated according to solar energy input so as to limit the temperature range of the focal absorber and exit fluid. As back-up protection against overheating should the pump fail, it is thought desirable to provide an off-steering facility within the control system ie. a facility to quickly steer the mirrors away from directly pointing towards the sun. This manoeuvre will cause the focussed solar energy to move away from those absorbers in peril of overheating. It is planned that this facility should reside with each unit control system and be based on the principle of adding a constant to the required elevation speed for a set period of time.

9. INSTALLATION

9.1 Layout.

The optimum layout is different for each location because of the need to balance the additional costs incurred when the collectors are spread out, against the gain in the amount of collected energy due to the reduction in shading of each collector by its neighbours. Figure 10 depicts a typical layout for a subtropical location.

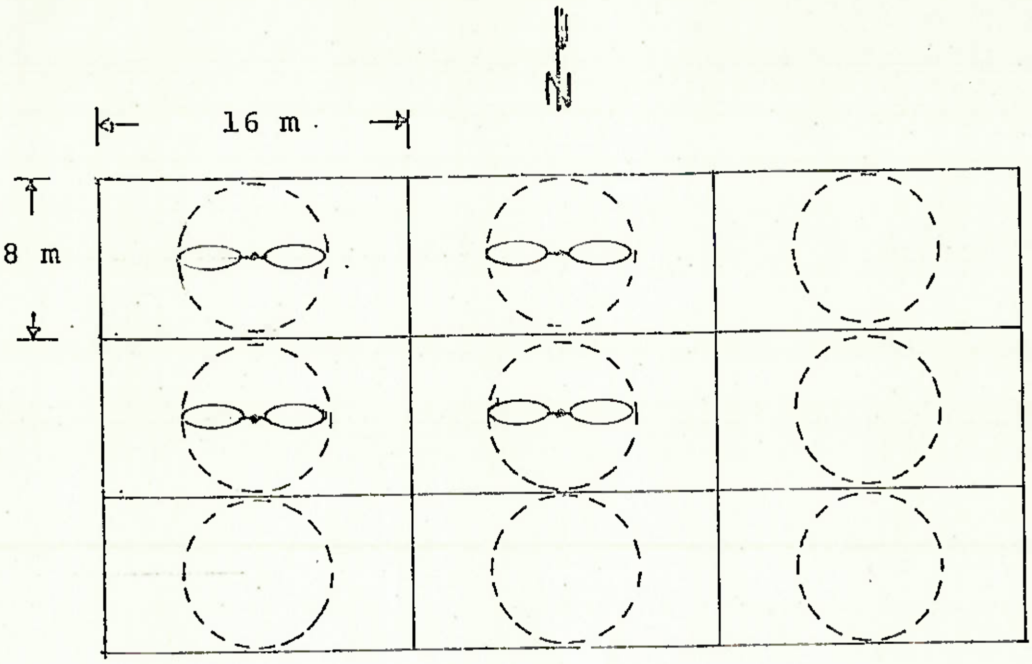


FIGURE 10: Typical layout for 10 square meter collectors.
Latitude approximately 35 S.

9.2 Site selection and preparation.

The site should be fairly flat and preferably grassy. In order to afford a measure of protection from strong winds it is advantageous to select a site bordered with trees or buildings but they should not be so close or so high as to cause significant shading, particularly in winter.

Telephone cables and pipes should be laid first preferably in shallow trenches. A post-hole digger is then required to dig the hole for the central column of each collector pair. The tops of these columns may be interconnected by wires in which case substantially anchored stay wires are required around the outskirts of the field of collectors. These anchors require additional post holes which may need to be deeper than the others and back-filled with concrete.

If stay wires are employed a back filling of well tamped earth should be sufficient for each central column.

A small building should be provided to the north of the field to house the control and hydraulic equipment. It will also provide an observation point from which the behaviour of the collectors may be visually monitored.

10. COSTS

For any particular system the total cost may be divided into unit costs attributable to each collector pair, and a single 'master' cost attributable to the co-ordination of the system as a whole. Generally the larger the system the less significant is the latter component.

The unit costs in turn may be divided into three parts: (1) manufacturing costs of individual components assuming the availability of special tools, (2) assembly and installation costs again assuming availability of special tools, (3) the cost of special tools. Given the number of collectors to be manufactured, there is always an optimum balance of these components especially with regard to (3). It is therefore expected that unit costs will follow common experience and fall substantially with increased production. Figure 11 depicts the range of commonly experienced relationships between cost and production.

In the following tables of estimates the above effects are taken into account by giving two figures: a prototype cost and a quantity production cost.

Except for the reflective surface item under part (1) (Table II quantity production means of the order of one thousand collectors per year (seven peak thermal megawatts) and at this rate the interest and amortization on part (3) is negligible. For the reflective surface ultimately envisaged (evaporative deposition), quantity production means of the order of ten thousand collectors per year and again the interest and amortization of the additional tooling for this reflective surface is negligible at this rate of production.

Further substantial reduction in costs will be effected eventually by an upward change in scale of the collectors probably to twenty or thirty square meters each.

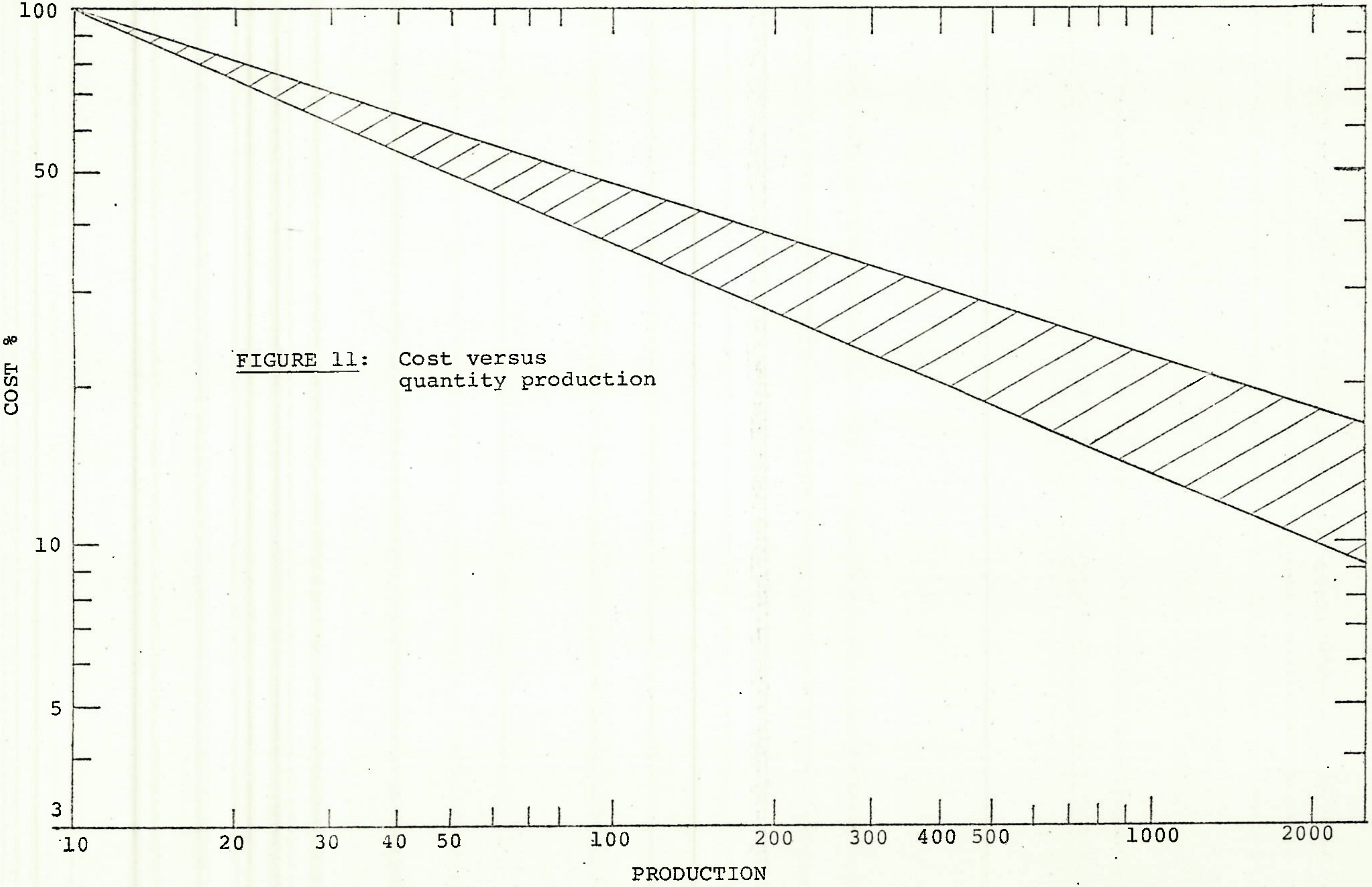


FIGURE 11: Cost versus quantity production

In the following subsections, estimates for the prototype are given in dollars and man-hours (m.h.). The dollar costs are for materials or for items destined to be manufactured by contract whereas the man hour costs relate to skilled fitters, machinists, welders and carpenters.

For quantity production, material and labour costs are summed to give a single dollar cost per item.

10.1 Part (1): manufacturing costs of individual components.

The estimates are set out in Table II.

TABLE II

Estimates for one pair of collectors (21 m^2)

Item	Prototype $	Prototype mh	Comment	Quantity Production $
2 shell substrates	300	32	(a)	) 150
2 reflective surfaces	600	100	(b)	)
2 shell sub-frames	60	16		90
2 gate sub-frames	120			160
1 central column	70	15	(c)	50
2 focal absorbers	20	20		25
4 torque amplifiers	1000	100		400
1 hydraulic ram	200	50		100
wire ropes, pulleys	620	50		400
4 position controllers and gearing	200	5	(d)	60
1 unit control system	250	3	(e)	140
	3440	421		1575

COMMENTS:

(a) Change from aluminium to steel for quantity production.

(b) Change from blow moulded acrylic, back-silvered to evaporative deposition of aluminium and silicon monoxide.

(c) Introduce concrete rigidised sheet metal.

(d) Introduce press tool for manufacturing from sheet metal.

(e) Anticipated rapid decline in microprocessor costs.

10.2 Part (2): assembly and installation costs per unit.

Assuming the availability of suitable cranes and other relevant standard industrial equipment the estimate is $250 per unit. This should reduce with larger collector fields and also with quantity production through the introduction of special handling equipment and techniques.

10.3 Part (3): special tools.

The major special tool, required for the prototype as well as quantity production, is the vacuum press. It is intended that the press will be located under an existing crane in an existing building. A machining rig is required to be attached to the ANU boring mill in order to generate the paraboloidal mould.

The auxiliaries required for the press are a water tank, water pump, vacuum pump, oil hydraulic system and associated piping. Much of this equipment may be borrowed from within the Research School.

Other tools include a table for laying out sheet metal and acrylic prior to joining, and an attachment to the vacuum press for blow moulding. The estimates for these tools are given in Table III.

TABLE III

Item	$	mh
Vacuum press	16,000	1,350
Auxiliary equipment	200	50
Machining rig	1,200	250
Other tools	1,700	150

10.4 Master cost attributable to the co-ordination of the system as a whole.

The factors under this heading are: master control unit, cabling, piping, hydraulic pump and accumulator. The figures given in Table IV are appropriate for up to one hundred collector pairs.

TABLE IV

Master Costs (including Testing)

Item	Prototype	Quantity Production
Master control unit	$4000	$2000
Cables	$2000	$2000
Lagged tubes	$12000	$10000
Hydraulics	$3000	$3000

10.5 Once only intangible costs.

The intangible costs relate to research, development, engineering design and supervision of prototype construction. Most of these intangibles will be borne by the Energy Conversion Group. However, it will be necessary to augment the efforts of the Group in some instances through the engagement of external professional people. An example of this is the engagement of a designer of computer systems to help with the control system.

The estimate of intangible costs associated with the prototype is $30,000.