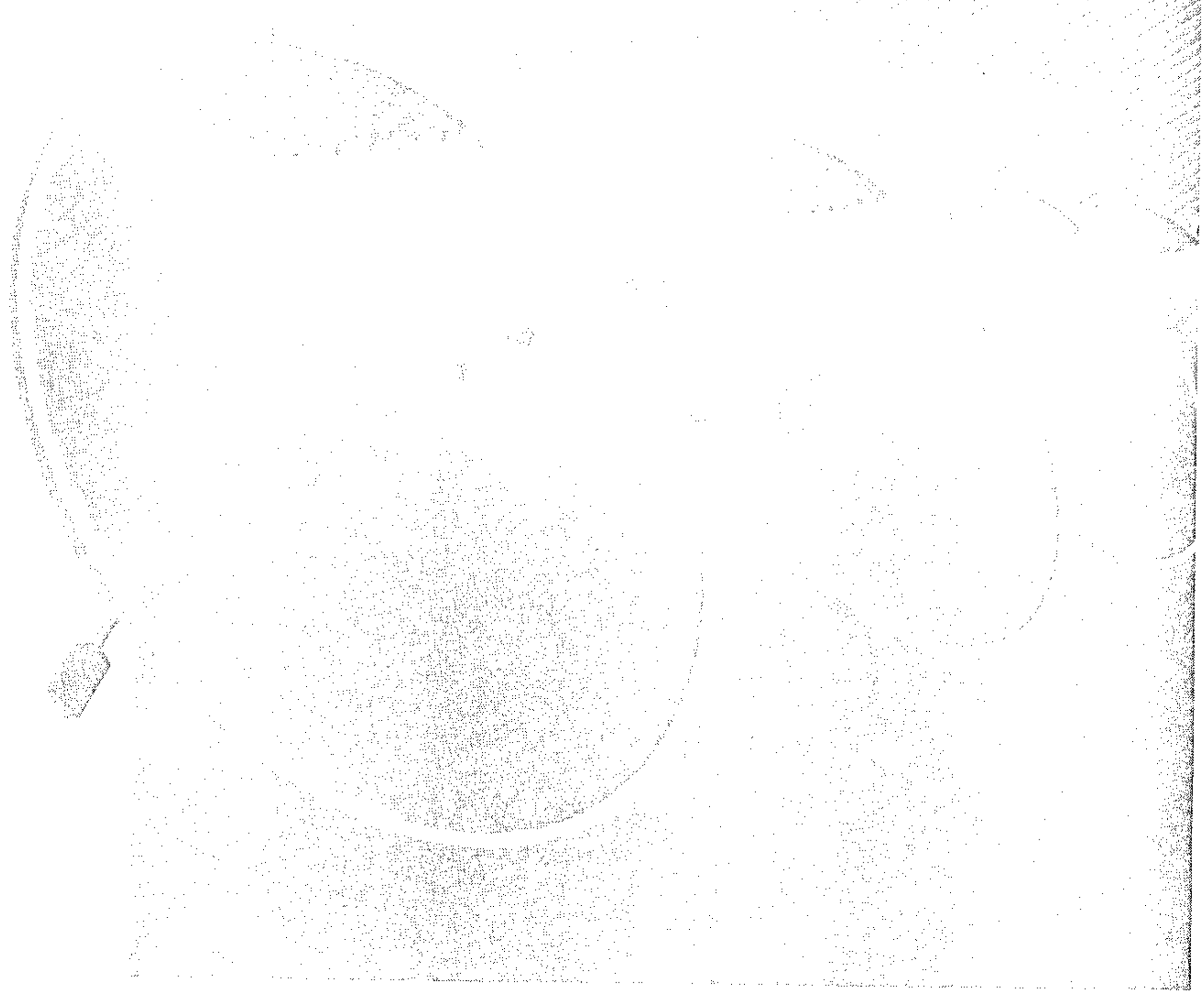
THE WHITE CLIFFS PROJECT

Overview for the period 1979-89



OFFICE OF ENERGY

THE WHITE CLIFFS PROJECT

Overview for the period 1979-89

Prepared by S. Kaneff
The Australian National University

OFFICE OF ENERGY
SYDNEY 1991

This publication resulted from a Research, Development and Demonstration Program funded by the New South Wales Government.

The views expressed are those of the author and not necessarily those of the Office of Energy.

ISBN 0 7305 6954 3
91/113

Page

CONTENTS

LIST OF TABLES

LIST OF TABLES CONTINUED

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS - CONTINUED

LIST OF ILLUSTRATIONS CONTINUED

LIST OF ILLUSTRATIONS - CONTINUED

LIST OF ILLUSTRATIONS - CONTINUED

LIST OF ILLUSTRATIONS - CONTINUED

LIST OF ILLUSTRATIONS - CONTINUED

LIST OF ILLUSTRATIONS - CONTINUED

The remoteness of the site required establishment of a field station which has turned out to be extremely useful and effective and has allowed other research, for example into wind energy, to be conducted with White Cliffs as a base; a group from the Physics Department of the University of Adelaide has been using 3 units of the solar array (at the vertices of the largest triangle possible with the existing array configuration) for gamma ray astronomy at night, replacing the usual solar receivers with special sensors.

Travel to the site involved little fuss while installation was carried out, but subsequently became a saga during check-out and commissioning, due mainly to the problems met with engine development. The writer made some 100 trips over the first 7 years, each involving a return journey of 2 200 km, often at night and driving (within 600 km of White Cliffs) in the midst of what always seemed to be an endless stream and variety of animals feeding or congregating at the roadside, where the meagre rainfall is concentrated due to run off, causing a presence of the only greenery in the area during drought years, especially 1981–83 and 1985–86. Animals run down by passing vehicles provide food for another group of animals and birds; the whole presenting a profoundly moving spectacle of what might be described as a roadside ecosystem involving not only indigenous life but also imported species such as foxes, and (stray) sheep, cattle and horses.

On 24 October 1979 (the first site visit) the writer and a colleague were astonished to see, over the final stretch of some 100 km of road in mid-morning, a succession of reptiles which must have represented nearly the full reptile repertoire of the region, with a density of one every few tens of metres, a sight not observed before or since. Volumes could be written on these episodes and generally on the spectacular sunsets, the rich natural life, the harshness of existence and the extremely interesting people in the region.

The foregoing is noted to indicate that in spite of logistic problems we were enriched by the experience of White Cliffs in a most profound manner, both mentally and physically. We had cause to reflect on our intrusion into this sensitive area. Obviously much animal and birdlife which had been eliminated from settled areas, was still flourishing here. Were we to be the cause for even these areas to be denied to them?

But this was only one facet of our complete involvement in the project, which included conception, research, development, design, construction, installation, checking out, commissioning, operation, maintenance, and updating; and subsequently the incorporation of lessons learned into the next generation units. Although we have been criticised in some quarters for such an extensive involvement, we consider that a large part of the success of the project has been due to this very factor. It is hard to envisage how otherwise the resulting experience could be assembled, preserved, organized and utilized for advancing into new generation systems.

The various *extras* built into the project, the remoteness of the site and the extension of time, involved additional costs and the original $0.8 million grant was increased to $1.3 million in order to accomplish the full programme on site.

Project Outcome

Now that a great deal of environmental, design, operational and maintenance experience has been gained from the first system, we have no cause to change the early perception of solar thermal power prospects except to reinforce this potential and to accept the original concepts as proved and successful. We consider White Cliffs has met the original

Project Evolution

It was originally envisaged that the first unit would be grid-connected at a convenient location for experimentation — the grant allocated was appropriate for this purpose and required a very tight 2-year schedule. But when White Cliffs (a small opal mining community some 300 km from the nearest grid and 1100 km to the west of our laboratory) was selected as the site for the station later in 1979, revision of the specifications became necessary. As White Cliffs had no common power supply, it was necessary to include storage and diesel backup, and to require automatic unattended operation; this necessitated extension of the 2-year contract period and the allocation of further resources.

Another factor emerged; the Australian National University then had no formal mechanism for handling projects which they perceived as applied/commercial. Although those working on the project regarded the task as a true research programme which, after due study (theoretical and experimental in the laboratory, followed by an experiment in the field) would or might lead to a commercial product eventually, this view was not accepted and the Australian National University (ANU) formed a commercial company, ANUTECH Pty Ltd, to handle the project.

ANUTECH decided to commission an outside feasibility study and to appoint parttime project managers from an industrial firm of mechanical engineers. This development was, in hindsight, to a degree intrusive and counter-productive at least in the first year when a series of research projects was carried on in order to develop and select the options to be used later in the project. The project management exercise was not without significant cost; on the other hand, useful professional engineering assistance was rendered in regard to systems and components, especially the steam system, once project directions had developed.

Other demanding aspects arose when White Cliffs was chosen as the site. While originally intended as a unit to gain the necessary knowledge, experience, understanding, design data and strategies for a range of solar stations, the White Cliffs Solar project also had the onerous task of providing power reliably and continuously on a stand alone basis (with diesel backup); that is, the project had to progress from conception to useful effective operation in one step. All these requirements were met.

The first year was spent on research and development on several concepts for collectors and other components; a final decision as to the configuration and systems to be used was made in August 1980. Construction by our workshops and some outside subcontractors was completed by May 1981; installation was completed by our staff in December 1981.

System tests were commenced on 1 January 1982; and by June 1982 the station had met output specifications. A year's operation on dummy load was carried out to check out reliability, following which connection to the town was made in November 1983[1]. Since that time, station operation has been continous[2] with a good record for consumer service, with operation and maintenance handled well by local inhabitants on an *as required* basis. Various improvements have been made from time to time as longer term problems have been revealed and lessons learned.

[1] The station was handed over to the then Energy Authority of NSW represented by Mr Peter Holligan and Mr Malcolm Williams on 30 November 1983.

[2] Diesel backup.

FOREWORD

In response to an enquiry in 1979 from the New South Wales Government, we suggested that solar thermal electricity generation might be made technologically and economically viable in inland areas of Australia, given appropriate resources for its development under realistic conditions.

This was in accord with our research objectives determined in 1971/72, directed to ascertaining the feasibility of mass utilization of solar energy and the provision of energy supply with more benign consequences than occur with the use of traditional fossil (and nuclear) sources. It also fitted in well with the State Government's desire to facilitate progress in the use of renewable energy. Because of the likelihood that success could lead to major solar thermal stations being installed in sunny areas, and eventually to much larger thermochemical stations providing not only electricity and industrial process heat, but also various energy rich products including fuels and fertilizers (as a result of another aspect of our research programme), this project was seen as potentially influential and significant.

While large systems were (and are) our major preoccupation, the approaches we had in mind could be introduced initially in very small size (albeit with less favourable economical viability) so that massive resources were not necessary to conduct the requisite research and development. Accordingly we proposed a small 25 kWe project as a starting point, our perception being that the first unit would provide initial vital information, understanding, performance and experience, to allow a family of systems to be developed and produced in sizes ranging from a few kilowatts to many megawatts (eventually matching the capacity of the largest fossil and nuclear mainline stations) to suit appropriate needs, modularity being envisaged.

Because development was perceived as being urgent, we agreed that the first unit (even) should work on a realistic basis in order to gain the experience and data which can come only from operation with an authentic load.

Our initial study indicated that the next generation units of a similar size, if produced in batches of hundreds, might cost some $40 000 (early 1979 Australian dollars) for a 25 kWe systems (ie $A1.6/watt) and that electricity generation costs would compete with those of diesel/electric plant, while larger units would tend to be more cost-effective. This perceived potential was a major reason for initiation of the project.

Allocation of funds was made in July 1979.

expectations and has provided information which is assisting the development of new generation systems. It has shown particularly that the technology can be handled by local people with no special skills beyond automotive/agricultural experience.

Current studies show that the next generation units would cost (with due configurational changes in the light of experience), some \$100 000 for a 50 kWe[3] system of \$2.0/watt (1986/87 dollars), for a system without storage or backup. This may be compared with the original potential promise of \$1.6/watt (these numbers are consistent with USA projections for much larger systems). When installed cost, the likely operation and maintenance (O&M) costs and annual collection efficiency of these units are considered, they will, we believe, compete more than favourably with diesel/electric sets in inland and remote areas in Australia and will also be attractive on-grid where avoided cost is relatively high.

A number of substantial *spinoffs* have followed: the development of a cost-effective collector technology suitable for industrial process heat; an engine technology which can be used for other applications and purposes — biomass fuelled operation and waste heat utilization, cogeneration; a number of significant design advances, including a quantification of the economy of size; various component advances, including rotary joints; contributions which facilitate the development of thermochemical systems; the accumulation and organization of much environmental data not previously available; scientific and technological information useful to the realisation of next generation systems (White Cliffs II is currently being developed), and others. A valuable bonus arising from White Cliffs has been our success jointly with a USA organisation in gaining a competitive development grant from the US Department of Energy for an innovative solar thermal power station project in USA. Please see Appendix I.

Success of White Cliffs has caused not only commencement of the next generation systems. Projects have also been initiated to involve Australian industry in the further development and manufacture of advanced dish and engine technology for electricity generation and the provision of industrial process heat; to employ engines for biomass and waste heat-fuelled power supplies and generally for cogeneration; the engine technology has been licensed and other negotiations for licensing are being conducted[4]; a series of basic studies is ongoing, with the objectives of placing all aspects on firm theoretical foundations and allowing system and component optimization as well as advancing the *state of the art* in each area of study (for example ceramic engine valve and piston components are expected to lead to useful efficiency increase and cost reduction; new dish concepts allow very much larger dishes to be realised at lower cost/m^2; new receiver concepts promise to increase life and reduce O&M costs; heat storage in high temperature phase change materials is a promising approach to the problems of operation in intermittent cloud and the provision of overnight heat storage).

The original station, having been checked out and made robust and reliable, now plays and can play a continuing part, at relatively little extra cost, as a testbed for new ideas; for revealing relatively long term (lifetime) problems (eg. for mirrors, collectors, absorbers, engines); ascertaining the effect of adding auxiliary-fuelled superheat to enable more of the collected solar energy to be made *available* and utilized; the life testing of new concepts (currently the least well developed long-term performance involves receivers); and

[3]See, for example, "Report on the Third Generation Dish/Engine Project" by S. Kaneff, submitted to Department of Minerals and Energy August 1990; subsequent cost reductions have improved prospects further.

[4]Power Kinetics Inc Troy NY hold exclusive licences for North and South America; non-exclusive elsewhere. Work proceeding on a cogeneration system with University of Sydney; process heat for India and sawmill waste burning in Australia could lead to other licences.

permitting side-by-side comparison with new generation and other technology under the same conditions — and White Cliffs can continue to enjoy solar power.

In relation to other solar power developments, we have noted with interest that our early 1970s perceptions that paraboloidal dish systems appear to have significant advantages over alternative solar technologies, are being confirmed and reinforced qualitatively and quantitatively by latest experimental and theoretical findings and the results of forward projections by colleagues overseas.

Some Misconceptions

As with many new developments which may appear to some to be unattainable, or at least unlikely to be viable for a long time to come, solar thermal power carries its own detractors and its own set of misconceptions. Among these must be included the assumed unlikelihood of attaining cost-effectiveness. The past decade has seen this aspect and many others, clarified in favour of solar thermal power.

But two specific aspects of the White Cliffs system which have been raised as problems may be mentioned. The first relates to the 25 kW designed output. This has been taken as if it were a basic limitation on the technology rather than simply a chosen value for the system which was selected before a site was identified.

The second misunderstanding is more plausible and relates to energy flows in the system which involves the solar system, ac/dc machine set, the storage battery and the back-up diesel. This matter is addresed in Section 5.5.5, Tables XV(A-D). Apparently the power supplied to the town load is less than one half that generated and in some cases it appears that the solar section consumes more energy than it generates. This comes about as a result of a combination of factors, including the battery system losses, the fact that the ac/dc set rotates continuously and other aspects; reconnection of the station and adjusting its operating strategy can nearly double its useful output. thereby overcoming its apparentluy poor performance.

S. Kaneff
March 1991

ACKNOWLEDGEMENTS

A project which has moved through many different phases necessarily involves many contributors for varying periods. Special thanks are due to R.E. Whelan who has participated in a substantial way throughout; to E.K. Inall who entered at the checking out and commissioning stage and has continued to contribute ever since, particularly in relation to the steam/water/engine systems; to H.P. Cantor for contributions to collector development, collector tracking and control systems, to battery systems and to field installation; to K. Thomas for substantial design and development assistance up to the commissioning stage; to P.O. Carden for contributions in the early stages of the project; to G.J. Vagg for providing the conceptual design of the steam engine and supplying an early prototype unit; and to K.G. Fulton for general planning and related assistance, including contributions to the steam system.

Dedicated support during the construction and installation phases was provided by Technical Staff of the Department of Engineering Physics and by Workshop Staff of the Research School of Physical Sciences; this support was essential to the success of the project and is gratefully acknowledged.

We acknowledge early consulting advice from Mertz and McLellan of Sydney and Davy Pacific of Melbourne, especially on steam systems. Environ Mechanical Services of Sydney provided assistance, to the end of the installation phase, with planning, costing and scheduling.

We are pleased to acknowledge the assistance provided by Peter Thompson of White Cliffs, on site, from the commissioning stage onwards, as Station Operations Manager, and by many White Cliffs citizens, especially G.J. Wellings, during the construction stage and later.

A substantial grant from the New South Wales Government established and has maintained the project; this is specially acknowledged, together with the always helpful cooperation of the Energy Authority of New South Wales who have administered the operations, and provided various services.

Finally we thank the Australian National University for the provision of support for the project through ANUTECH (formed as a result of this project) and the staff, resources and facilities of the Research School of Physical Sciences.

PROJECT COSTS

Expenditure on the project was as follows:

Station sitework, power reticulation to White Cliffs, etc	$337 000
ANU Research and Development	
Initial grant	800 000
Supplementary grant (Aug 1982)	248 000
O&M agreement with further grant (Dec 1983 to Dec 1985)	200 000

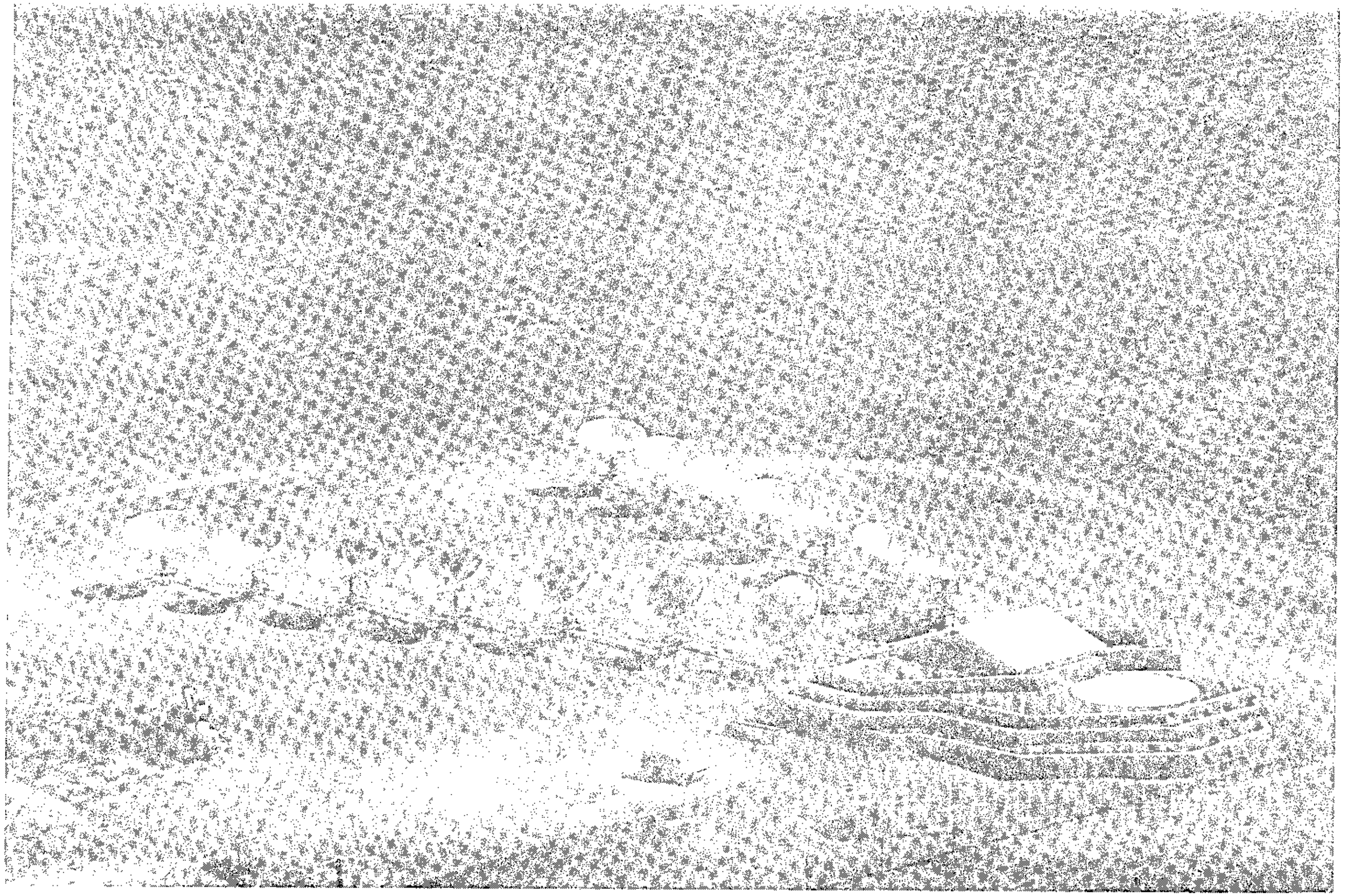


Figure 1. Aerial view of the White Cliffs Solar Power Station in early 1982 during system check out.

1 INTRODUCTION

Some 40% of our primary energy is used as industrial process heat and a further 20% as electricity. Replacement of traditional fossil sources by the application of solar energy for these purposes has great appeal; early efforts are proceeding to develop suitable effective technologies. These activities are still in a search phase, with many options yet to be revealed, let alone studied and developed. Nevertheless, sufficient hard evidence is now available to provide reasons to expect very substantial developments in the next decade, in spite of the relatively low energy density (rarely more than 1000 W/m^2) and intermittent nature of our solar resources, in marked contrast to the concentrated energy in fossil (and nuclear) fuels which can also be readily stored — factors which promote economic viability. (In the longer term, the remaining 40% of primary energy, used as energy rich products, especially as fuels for transport, may well, with the assistance of thermochemical and related approaches, also be provided from our solar resources.)

One approach to the conversion of the relatively diffuse insolation to usable high quality heat, involves concentration by sun-tracking optical systems employing concave mirrors, with collection of the concentrated energy by a focal absorber for conversion (for example to electricity)or use at that point, or for transmission by some heat absorbing medium (thermal or thermochemical) to the point of utilization. In any event this approach, to be implemented with requisite conversion efficiency, requires two-axis tracking concentrating collectors, a fact which has been often wrongly assumed in the past to result necessarily in uneconomic systems. So development of such systems has been a comparatively late starter in relation to other solar technologies which superficially may have appeared more economically tractable.

While the general state of knowledge of most solar technologies is still inadequate (and therefore permits controversy on the many issues involved), there is mounting hard evidence in relation to concentrating two axis systems, as a result of field experience and in-depth studies, to point to potential economic viability of such systems, so long as proper attention is paid to a wide variety of design factors, for example as outlined in Kaneff [1983, 1984, 1985, 1986 and 1987].

Impressed with the need to provide electricity to many areas in inland Australia without existing grid-connected power systems, the New South Wales Government commissioned the Australian National University in July 1979 to develop and build an experimental solar thermal power station to supply a small community with electricity on a continuous, stand alone basis, employing a paraboloidal array of 14 collectors to produce some 25 kWe and 140 kW thermal (low quality heat) to be used at a later stage for water desalination, a need just as pressing in many areas of Australia as that for electric power.

Size of the system was chosen to be sufficiently large to be convincing and nontrivial, to encompass the necessary parameters and to reveal all the problems associated with systems of a wide range of sizes, but small enough to ensure that development, hardware, installation and running costs were not excessive. The site (chosen some months after project commencement) of White Cliffs, a small opal mining community of 40–50 people[5] (plus a transient mining population of over 100 others), 1100 km west of Sydney, was selected because it satisfied the definition of being inland and remote, having no existing

[5]This was a 1979 estimate; the 1986 ABS Census indicated 207 in the White Cliffs area.

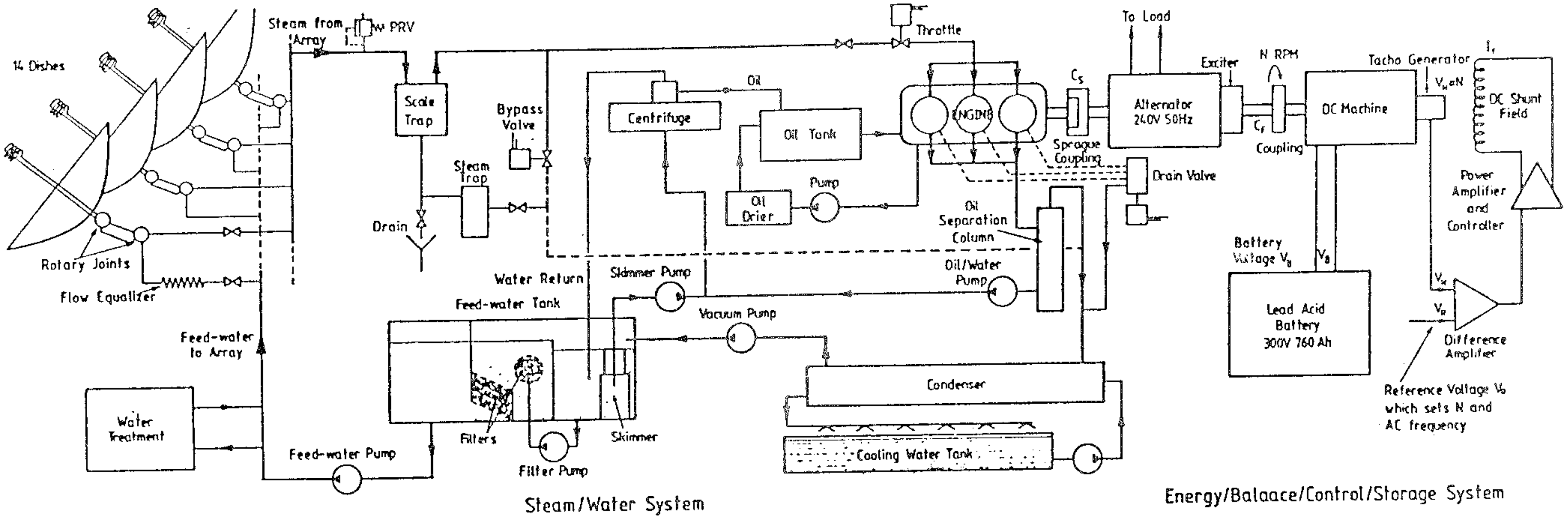


Figure 2. Functional diagram for the White Cliffs Solar Thermal Power Station.

Array, Engine, Oil/Water, Feedwater, Condensate, Cooling, Generation, Storage and Control Systems.

power supply (with the nearest grid being nearly 300 km distant), having an extreme and hostile climate and, in short, being typical of areas over much of inland Australia.

Performance of the array at White Cliffs was also seen as providing valuable information on possible industrial process heat applications in many country towns 400–700 km to the east, where insolation conditions are only slightly inferior but environmental and resource problems are not as demanding.

1.1 System Description

Figure 1 provides an aerial view of the station as it was in early 1982 during checking out and commissioning; the general drought conditions applying at that time are evident. Following completion of the check out phase in June 1982, system configuration was finalized and needed little change subsequently (more recent improvements are reported in Sections 5.9 and 6).

Figure 2 portrays the station functional diagram from June 1982 onwards. (Changes in later years are recorded in Section 5.9.) Operation may be viewed as follows:

Feedwater at pressures up to 7 MPa (70 atmospheres) is pumped in parallel through the absorbers of the 14 paraboloidal dish collectors, tracking in azimuth and elevation, through 2 rotary joints in each collector, then conveyed in insulated stainless steel tubes to the engine room via a pressure relief valve and scale trap. When steam temperature has exceeded 180°C, a bypass valve (previously diverting the steam to a condenser cooled by water circulated from a cooling tank), closes, causing pressure to build up; when this reaches 2.7 MPa, a throttle valve opens automatically, and the engine starts; its drain valve then closes (an electric starter motor ensures that rotation commences in the required direction). Engine speed increases as the unit warms up. When 1500 rpm is attained (synchronous speed for 50 Hz), any further speed increase causes torque to be applied to an AC/DC rotating machine set (which runs continuously) through a *free wheel* coupling.

The AC machine is connected to the town load while the DC machine connects to a 300 V 760 Ah heavy-duty lead acid storage battery (which can store some 250 kWh, approximately a full day's solar generated electricity). A torque balance control system ensures that the 3-machine set rotates at 1500 rpm$\pm$1% at all times. Excess energy beyond that required to supply the town, is stored in the battery. If there is an energy deficit, the DC machine is controlled to work as a motor assisting the heat engine to drive the alternator. At night, or in cloudy periods, the DC machine draws energy from the battery to drive the alternator, the heat engine being stationary. To ensure that only steam, not water, enters the engine, a thermodynamic steam trap is employed to bypass water. The steam exhausts through a vacuum assisted condenser system, condensate being collected in a vented feedwater tank to be recirculated, via a water treatment unit, to the array. Oil is removed from the condensate by filter and centrifuge systems operating on the feedwater tank and by a vortex chamber following the engine exhaust (more recently, this system has been simplified to reduce components, cost and power demands; Sections 5.9 and 6).

The system operates automatically; solar start is initiated by clock at preset times each day, the collectors track all day and are parked automatically by clock signal in the late afternoon. In the event of inadequate sunshine causing the battery to be discharged to a preset voltage (representing nominal 80% energy discharged), the diesel backup unit takes over until sunshine is re-established to a level adequate to keep the system operating.

A particularly demanding aspect of the development of the system has been the need to remove engine lubricating oil from the exhaust steam and condensate prior to recirculation through the array. In order to achieve a high practically attainable efficiency of heat-to-mechanical work conversion as well as simplicity of maintenance in remote areas permitting local inhabitants to operate and maintain the system, the heat engine has been realised as a conversion of a 3-cylinder diesel engine to steam operation. This allows most of the engine parts to be readily available diesel components (there are thousands of such diesels throughout the country with good spare parts backup). As it happens, this option was by far the most efficient and economical available to us — the only real alternative being to use a small turbine whose efficiency was lower and whose cost was higher. (Only if and when the new generation Stirling and Brayton cycle engines, Organic Rankine Cycle Systems and alkali metal thermoelectric converters, all currently under development, become available as reliable, cost-effective units, would there be a serious competitor to the diesel conversion we have employed for systems of the sizes involved in the intended applications.)

In order to attain the high performance from the steam engine (up to 23% heat-to-mechanical work efficiency), steam quality can reach up to 500°C and 7 MPa pressure in the engine room. Oil must be injected into the cylinders to assist lubrication under these conditions; other oil is gathered by the steam from the sump. To prevent oil dissociating in the absorbers, attention is required to remove this from the feedwater.

By far the major part of the project time, effort and other resources was required to establish the steam engine (especially its simple valve mechanism) and water/oil treatment systems as robust, reliable working units. The solar array, collectors, electrical and electronic control and energy generation and storage systems posed relatively few problems in design, development, checking out and establishing continuous reliable operation.

1.2 System Configuration and Philosophy

The White Cliffs system configuration used is only one of a vast number of alternatives which can be identified as potentially suitable candidates for the production of high quality solar-derived heat and its conversion to work and electricity, with a wide range of alternative components differing in form and function, being suggested. But we know even now (July 1987) of only five working paraboloidal dish arrays, each employing different approaches, for which there is any accumulated operating experience so far — the White Cliffs station generating electricity; the MBB–Kuwait station for electricity generation/water pumping and water desalination [Zewen and Co-Workers 1983, Moustafa and Co-Workers 1983]; the Shenandoah, Georgia, system for electricity generation and the provision of industrial heat [Ney and King 1984]; the La Jet 5 MW electricity generation plant [Schefter 1985, McGlaun 1987] at Warner Springs, California; and the Power Kinetics Inc 18-dish array in Saudi Arabia for water desalination (Krepchin and Co-Workers, 1987). Several developments are at different stages of completion/commissioning/design, and involve single dish/engine units, notably the Advanco Dish/Stirling system at Indian Wells, California; the McDonnell Douglas Dish/Stirling modules (Colemand and Raetz, 1986) and others.

While common features in existing and proposed paraboloidal dish systems may be identified, it would be inappropriate to claim that anything like common principles and philosophies with respect to design have emerged, let alone standardized key hardware components. Each system has been a special study designed to reveal the characteristics and viability of a particular approach, selected from many alternatives. There seems as yet no *conventional* dish array to serve as a guide to further developments; and it may take some time for such to emerge. Suffice to remark that a great deal of research and development on dishes, engines and systems is currently ongoing.

If the situation even now is unresolved, it was the more so in July 1979 when the White Cliffs project commenced, with no direction being available from past experience, beyond the results of tests and operational experience with single dishes of various kinds. In many respects it was not known even what environmental loads would apply since records were not available; consequently the designs had to be constrained to be conservative, and assumptions had to be made without firm information. A start had to be made on the best available evidence using whatever experience could be assembled; once a system was working, iterations towards ideal performance could be carried out. In the event, our first system definition has proved suitable — it has turned out to be extremely viable, with much potential for further improvement.

1.3 Design Objectives

The main reason for establishing the White Cliffs Solar Power Station was to ascertain the feasibility and potential (both technological and economic) for providing electric power in conditions which exist over much of inland, remote area and off-grid Australia. The station was seen as a first step in a long line of development of families of systems of different capacity and form. Economic considerations were recognized as of overriding importance from the start. To be successful, the initial experimental system would need to reveal that later developments can be economically competitive with other forms of energy (including diesel and wind based) and to point to what has to be accomplished to make them so. In other applications (of industrial process heat), solar arrays would need to be potentially competitive with oil in the nearer term and the possibilities for competing later with coal and natural gas would also be of interest — the White Cliffs Station was expected to throw some light on all these issues.

From the start, overall project objectives demanded very careful attention to all aspects of configuration, design, construction, installation, operation and maintenance strategies — suggesting consideration of particular approaches, including the following:

1. Design to allow all available solar energy to be collected and used, as this would tend to make the most of whatever hardware is provided: system control philosophies and strategies should be directed to this purpose.

Cogeneration would assist in these objectives — for example the use of heat rejected from the steam engine during operation, along with heat energy gathered during early morning and late afternoon and generally whenever insolation is inadequate to maintain engine operation at above breakeven output (ie to supply the required auxiliary power plus some useful load). Such heat may be employed for water desalination, provision of hot water or space heating (possibly in conjection with latent heat storage or other means), or for aquaculture, to name only a few possibilities.

2. Every attempt should be made to design all components for maximum transmission and minimum loss consistent with costs — for example, a 5% increase in collector output for whatever reason, means the use of one less collector in twenty and pays off if the added cost of achieving the extra output is less than the cost of a collector plus the extra maintenance and operating costs of this collector.

3. Simplicity should be a prime philosophy, assisting not only in reducing costs directly, but also indirectly as a result of improved reliability and reduced operating and maintenance demands.

4. Use readily available standard components, unless good grounds exist for not doing so — for example, inadequate performance or high cost relative to what might be readily developed. (This strategy had to be compromised occasionally to permit the not substantial avilable resources — and the limited time — to be committed to the most important developmental tasks, leaving the lesser aspects to be refined later.)

   Consistent with this policy, we were able to purchase:

   - steam system components such as manually operated valves, non-return valves, tubing and fittings; heat insulating materials; AC and DC machines, contactors, control and protection gear; electromechanical and electronic relays; mechanical couplings including free wheel unit; storage battery; condenser and cooling plant; pumps and drive motors, controllers; steam trap; water treatment plant; bearings; O-rings; filter elements; gearboxes and electric drive motors; engine block, crankshaft, connecting rods, oil pump, governor gear, starter, pistons.

   We needed to design and build inhouse or by subcontractors:

   - Almost all components for the 14 dishes, including absorbers and specially developed rotary steam/water joints (excluding some bearings, azimuth and elevation gearboxes and drive motors); engine conversion parts; oil/water treatment components; feedwater tank, skimmer, oil separation column; throttle and drain valves; centrifuge; steam safety valves; electronic control units for the dishes, central station control system, torque balance, automatic protection system. (Some of these components can now be purchased commercially.)

5. System components to allow ready transportation over long distances. Generally, all practicable construction and assembly should be carried out in the factory, minimizing onsite work, installation time and field expertise required.

6. All aspects of the system to be compatible with the environment, requiring:

   - Careful selection of materials which are low cost, robust and as maintenance free as practicable, readily manageable — steel, glass and concrete were seen to be key ingredients.

- All components to be either environment tolerant or environment proof. This applies to purchased as well as specially manufactured items, and particularly to units such as motors, gearboxes, contactors and relays. Dust is one of the major environmental hazards to be faced.
- Structures able to withstand all likely extremes of wind, rain, temperatures and other stresses. Particular care and attention needed to be given to dish size/strength, as wind is the major load factor.
- That the array be able to track and gather energy during all sunny periods, provision being made for automatic parking in a safe orientation if wind velocities exceed normal working values.

7. Remoteness and consequent cost of bringing in expert technical staff in the event of problems, set a requirement for high standards of robustness and reliability and a design philosophy which produces equipment able to be operated and maintained by local inhabitants. This required a particular level of sophistication similar to that of agricultural/automotive practices which has turned out to be cost effective and of a desirable simplicity. Provision of spare parts, particularly those connected with the specially designed components, needed to be well supported.

8. Because the system, although small, was intended to provide as rich as possible a source of information regarding much larger installations, its configuration, design, installation, control, operation and maintenance had to be consistent with this aspect. In other words, although small, the system had to include all the appropriate features of a very large system.

9. Virtue was seen in the array being structured as a group of modular semi-autonomous collector units so that faults in any part of the array or even in some aspects of the overall station control, were less likely to disable the whole system; individual dish units should be able to take care of themselves if contact is lost with the control plant; inexperienced personnel can then isolate apparently faulty units; and manufacture on a volume basis should be facilitated. The concept of modular organization was also considered important and advantageous in the configuration of all electronic and electric power units, for similar reasons.

10. The system was required to operate automatically unattended, with routine checks once per day and on-demand maintenance provided as required. This was a taxing feature to be provided for a new technology which was the first of its kind.

11. The system had to supply, on a continuous stand alone basis, a real township load of unknown characteristics in environmental conditions which, apart from manual recording of temperature, barometric pressure, rainfall and descriptive accounts of sunshine, were undocumented and unknown.

1.4 Design Considerations and Criteria

Fluid Conditions in the system are dependent profoundly on the heat engine parameters — particularly steam expansion ratio, mass and quality of steam injected per stroke, vacuum conditions, engine efficiency, as well as on feedwater flow, insolation, dish reflectivity, cooling water temperature and others. All these factors need to be taken account of in design.

- Array Fluid Flow Paths

  Since it is generally not possible or practicable to have all collectors equidistant from the point of use of the heat energy, the hot fluid from some will traverse longer paths and be subject to greater losses than that from others. Designing for distant absorbers to run at lower temperatures than for those near the load, presents one means for optimization of the array output and reducing overall array losses. But such an arrangement brings with it a complexity of more than one absorber design as well as the need for series-parallel flow paths. Consequently it was not thought desirable to introduce this added complexity in the first system built, but to consider employing the option later. For this reason, all absorbers were specified as working in parallel.

- Rated Steam/Feedwater Conditions

  To achieve maximum heat-to-mechanical-work conversion efficiencies, steam conditions were set to near the permissible operating limits for readily available (and reasonably economical) stainless steel in the form of pipes, valves, fittings and other units.

  Design parameters: absorber steam temperature 550°C maximum; pressure 7 MPa; engine room temperature 500°C maximum; to be attained at an insolation level of 1000 W/m^2, and for a feedwater flow rate of 50 ml/s.

  Equal feedwater flow is necessary in each absorber to maintain uniform steam generation temperatures.

- Insulation, Losses and Superheat

  Any loss of superheat is a relatively serious loss, since in the conversion of heat-to-mechanical work the superheat contributes the major part of the useful power, yet represents only a fraction of the total heat collected. For example, at 500°C and 7 MPa, 19% of the added heat energy is in the form of superheat; at 360°C and 6 MPa, 9% of the heat energy represents superheat and at lower temperatures, typical of conditions when available insolation is less than maximum, superheat percentages can be much less. Adequate heat insulation is therefore necessary, and pays off, to reduce losses in transmission to a practical economic minimum. The advantages of employing vacuum assisted engine exhaust/condensation are also very apparent.

- Dish Design Criteria and Parameters

  In the absence of wind records (and in the face of local lore telling of motor cars being stripped of their paint during dust storms in the past), it was deemed prudent to limit the dish diameters. Transportation limits also set a maximum diameter of 5.18 metres due to the width of a bridge (allowing 1.5 cm clearance only). Larger diameters would have required onsite construction or manufacture and/or transportation in segments — both alternatives appeared to carry time and cost penalties.

  - Coping with wind

    The dishes were required to operate effectively and gather useful energy in usually present winds (often very strong), so long as velocity does not exceed 80 kmph (50 mph), beyond which an automatic signal would cause parking in the *storm* (vertically facing) position, with aerodynamic lift being in the downward direction and a lesser drag force sideways. In the *storm* parked position, the dishes were expected to withstand winds of over 180 kmph (112 mph).

– Reflective Surfaces

Our early experiments with reflective surfaces indicated that excellent optical properties could be attained using thin plastic aluminized film which readily can conform to paraboloidal contours. But environmental conditions at White Cliffs were considered too demanding, particularly with respect to the perceived need to clean dishes regularly, with consequent probable damage to the reflective surface. (Our studies suggested that unless dishes were cleaned at appropriate intervals — depending on weather — energy lost could amount to 20% or more which, due to the need to operate on super heat, would require reducing mass flow and represents an even greater loss in system output. The strategy of coping with this by increasing the number of collectors and dispensing with cleaning, did not appear attractive, technologically or economically.)

A reflecting surface of back-silvered glass was accordingly specified.

For simplicity and economy, plane glass tiles were selected, following experiments in producing accurate glazed surfaces by this means, results of which indicated long life and relatively low costs. There was the additional advantage of producing a focal region where energy density, while adequate, permitted relatively low thermal stresses in the absorbers, fitting in with the general philosophy of low cost and long life.

Experiments also indicated that the additional spread of energy in the focal region due to imperfect laying of tiles could in practice be held to acceptable limits.

Back-silvered plane glass tiles 2.5 mm thick and 105 mm maximum side, were assessed as being suitable. Using these tiles and ideal optical realization, the minimum *neck* diameter at the focal region would then be 242 mm. We had reason to expect to be able to hold this *neck* (as a result of controlling, in the manufacturing processes, the dish imperfections and tile laying inaccuracies), to less than 400 m diameter in practice. (Subsequent measurements indicated an achieved 350 mm diameter for all 14 dishes.) This dimension determines the nature and configuration of the absorber and general design approach to be employed.

- Storage; Coping with Daily Sunshine Variations and Intermittent Cloud

Two aspects regarding intermittent operation may be identified:

1. Night and Day: Unless grid connected, a solar station effectively requires storage to cope with daily sunshine cycles, if it is to provide power continuously. Winter/Summer variations provide an added problem in this respect, with the amount of energy collected varying as much as 3:1 between the seasonal extremes. Periods of cloudy weather extending for several days also pose problems. Storage is clearly necessary if a backup system is not to be called on whenever the sun is not shining. The question of how much storage, is central to cost effectiveness. As a preliminary decision, we opted for overnight storage only, in the form of electrical storage in batteries.

2. Intermittent Cloud: To obviate frequent stopping and starting of a system in the presence of intermittent cloud, some form of storage of energy between collectors and engine is necessary. To avoid the need to design yet another component at the early stages of the project, it was decided not to include such intermediate storage, relying only on the heat capacity of all components in the steam lines up to the engine to allow running on for several minutes

after the onset of cloud. (At the time of writing this report, it was abundantly clear that an intermediate heat store of some 30 minutes' heat supply at full temperature and output would be a substantial advantage and that a phase change material (latent heat) store would be preferable to a sensible heat store. Such a unit could form part of each absorber or be a separate component.)

- Heat-to-Mechanical Work Conversion

  We would have preferred to use latest heat engine technology which promises higher heat-to-mechanical work conversion efficiencies. For example a suitable Stirling Cycle engine might be expected to have more than twice the conversion efficiency of a high performance Rankine engine of the kind eventually developed for White Cliffs. But in 1979 reliable cost-effective Stirling engines suitable for solar application seemed removed from near term availability; in 1987/88 this still seems fair comment.

  Small Rankine cycle steam turbines were and are still of relatively low efficiency and high relative cost; and the various expanders working on fluids other than water (for example toluene) have not yet reached commercial viability.

  We were consequently led to select a reciprocating expander based on the high performance features achieved over the years by steam car enthusiasts. Such an expander was specified for the additional reason that it potentially could be maintained by those with motor vehicle engine experience, so fitting in with our general philosophy of relative simplicity and maintainability by local people without special skills.

  This approach has worked out well and we now believe, all things considered, that such an approach might well continue to have advantages over more exotic systems, particularly now that we can visualize significant further improvements in our engine and dish technology.

- The Problem of Cooling Water

  Because of the advantages of water-cooled condensing systems, including the ready availability of suitable components, it was decided to specify this form of condensing.

  Availability of water, however, has not unexpectedly proved a problem.

  Although geologically classified as an area devoid of underground water, there was some expectation of such water being found in White Cliffs in view of the fact that good quality bores were running on station properties as close as 15–20 km away. But a NSW Water Resources Survey bore put down at the solar site in 1980 found only a trace of water (less than 500 l/day) at a depth of some 130 m, with a salinity of some 10 000 ppm; this was deemed inadequate for the power station needs. Two deeper bores for community use were sunk in the area in later years with no better result.

  An earth tank of some 800 m^3 capacity was constructed in the station enclosure in 1983 to accept runoff water and has filled several times since then but, because of poor natural water retention of the soil, has not become properly sealed, holding water for only a few weeks.

  Reliance up to 1986 had to be placed on collected rainwater, on the town water supply, partly on the enclosure earth tank and a similar tank nearby, on water trapped in an old mine, and on some carting of water from Wilcannia in really dry times. In 1986 a very large earth tank (100 000 m^3) was established several kilometres to the northeast of White Cliffs in an area with much runoff from a series of creeks; this is expected to solve all water problems from 1987 onwards, with reticulation to the station being made[6].

Curiously, almost anywhere in the region — except the White Cliffs area itself — underground water of adequate quality is available. Nevertheless it seems advantageous to pursue development of cost-effective aircooled systems for use in the inland.

In summary, site and environmental conditions at White Cliffs are quite demanding on design; considerable ingenuity is necessary to produce systems which are environment tolerant and cost effective at the same time.

In spite of the many options possible, it was essential to select rapidly a set which was potentially the most suitable for the purpose, in view of time and resource constraints. This led to the concept outlined in Figure 2, the details of which are considered in Section 3. It has turned out that essentially the only major changes which might have been made at the time (had this been appreciated and practicable) would have been those relating to dish size and the provision of short term ($\frac{1}{2}$/hour) intermediate heat storage between absorber and engine.

[6]Over the years it has proved quite satisfactory to use rainwater collected from the roof of the station building for feedwater (this water has less chlorine than commercially obtained distilled water). Feedwater and cooling water use are recorded in Table XVC.

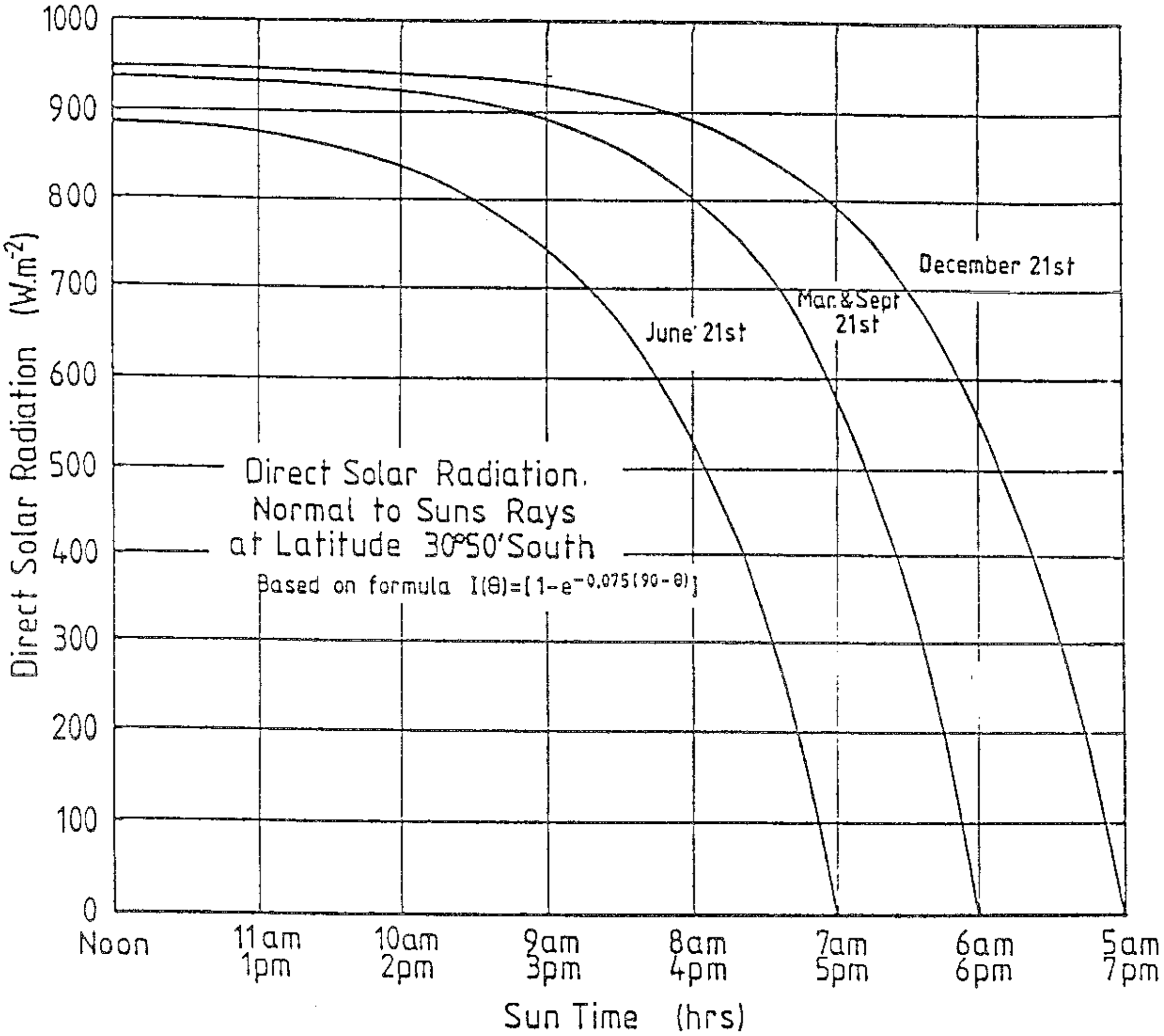


Figure 3. Hourly and seasonal variations in direct insolation for White Cliffs according to textbook formula.

2 SITE AND ENVIRONMENT

White Cliffs is located at latitude 30°51' south and longitude 143°05' east. Until December 1979, when we set up automatic measuring and recording equipment at the solar station site to measure direct axis insolation, wind velocity and direction, such information had previously not been available (although wet and dry bulb temperatures, rainfall and descriptions of sunshine (based on a "scale of 8") had existed for many years in post office records compiled manually).

White Cliffs' climate is typical of much of that of inland Australia, with an irregular rainfall whose average is well below 25cm (10 inches) per annum. A substantial amount of this precipitation appears as thunderstorms which cause flooding at times. During good years (1983/84 for example), the whole countryside is carpeted with greenery; animal and bird life abound and insolation is more uncertain than normal due to variable and above average amounts of water vapour and cloud in the atmosphere. At other times (most of the time) conditions become extremely dry and dusty, with excellent sunshine occasionally tempered by dust haze.

2.1 Insolation and Cloud

Figure 3 depicts the hourly and seasonal variations in direct insolation for White Cliffs according to a textbook formula. But our records over the past 7 years have frequently recorded higher values than these, especially following rain (suggesting that atmospheric dust plays an important part in the process). It is not uncommon during the period October to March for peak direct beam insolation to exceed 1kW/m^2 (even reaching 1.08 kW/m^2 on rare occasions).

Meteorological records for the White Cliffs region show approximately 3000 hours of sunshine per year and a total incident energy of around 2100 kWh/m^2 per annum. Our records for 1979–87 show some 2380 kWh/m^2 per annum average, a figure which should be compared with the values of Table I which shows an ideal situation for mean energy/day/m^2 and mean peak insolation for each month on the basis of 100% sunny days — total annual incident energy would then be 3390 kWh/m^2.

But the above figures for incident energy per year disguise the form and content of the available useful insolation. While, as may be expected for areas which are reputedly very sunny, many days during the year are completely sunny and very few are completely cloudy, a surprisingly large number of days are only partly sunny: these may be considered in three categories, days in which:

1. A continuous band of sunshine is followed by a continuous band of cloud or vice versa (such as occurs when a cloud front arrives or existing continuous cloud clears).
2. Intermittent cloud is present — a surprisingly frequent phenomenon which can occur at any time of year but particularly in summer. What is often involved is the local formation of a matrix of very slow-moving clouds in the early afternoon lasting until late afternoon. Mechanisms involved appear to be the formation of 'chimneys' of hot air rising from the ground in a relatively stable pattern, accompanied by the

TABLE I — MEAN ENERGY PER DAY AND PEAK INSOLATION LEVEL AT WHITE CLIFFS FOR IDEAL CONDITIONS

Month	Mean Energy $kWh/day/m^2$	Mean Peak Insolation W/m^2
January	11.10	947
February	10.50	944
March	8.25	920
April	8.25	920
May	7.25	890
June	7.00	885
July	7.20	890
August	8.95	920
September	9.41	938
October	10.45	944
November	11.10	947
December	11.25	948
Total/Annum	3390	

TABLE IIa — CLIMATIC CHARACTERISTICS — WHITE CLIFFS*

Averaged over the period December 1979 to March 1987

Quantity	December	June	Annual
Sunshine Hours	283	155	2 920
Peak Axis Direct Insolation W/m^2	1 060	940	1 080
Average Direct Axis Insolation kWh/m^2	256.3	127.6	2 380
Average Direct Axis Insolation MJ/m^2	923	459	8 568
Maximum Temperature °C	46	26	47
Minimum Temperature °C	12	0	0
Wind Velocity Peak m/s^+	14	12	23
Wind Velocity Average m/s^+	4.5	3.5	4·0

+ At a height of the top of the solar array ($\approx$ 7m). At a height of a further 20 metres, average wind velocity = 6.8 m/s.

* White Cliffs has good insolation, but not substantially better than for areas to the east, but still west of the Great Dividing Range. The best insolation in Australia occurs over a wide band starting NW of White Cliffs and stretching NW to the West Australian coast. In this zone an annual direct beam component of about 2900–3000 kWh/m^2 may be expected.

TABLE IIb — INSOLATION AT WHITE CLIFFS

Direct Beam Radiation, kWh/m^2.
Averaged over the period December 1979 to March 1987.

Month	Average Monthly Insolation kWh/m^2	Variation on the Average %
January	251.3	+4 −14
February	224.5	+16 −23
March	225.5	+3 −5
April	157.5	+17 −16
May	148.5	+15 −8
June	127.6	+34 −31
July	120.0	+25 −29
August	180.9	+11 −20
September	226.5	+13 −20
October	229.6	+10 −20
November	231.7	+9 −15
December	256.3	+5 −9
Total Annual	2 379.9	+1 −6

formation of a corresponding stable pattern of cloud which moves but slowly, causing insolation at any given point to vary from full sunshine to shade. The periods of sun and shade vary typically in the range of a few minutes to 20–30 minutes — sometimes the clear periods are the longer, sometimes they are the shorter.

3. Haze due to sparse cloud, water vapour and/or high level dust is present, lowering the mean insolation level usually with a characteristic 'spikey' profile, with the insolation varying by a significant amount in relation to the total insolation — the spikes are frequent (every minute or so, sometimes less frequent).

Figures 4–10 are records portraying different insolation characteristics.

Table II and Figure 11 record actual insolation and other characteristics of the White Cliffs climate over the period December 1979 to March 1987. Figures 11(b) and 11(c) present the insolation in integrated kWh/m^2 as a function of daily peak insolation, taking different bands of insolation level.

2.2 Wind

White Cliffs is located in a slight depression surrounded by occasional low hills some tens of metres high on a generally flat terrain. Available meteorological information is sparse and does not provide an adequate or true picture of wind conditions. The area is obviously very windy and local observers report harrowing tales of past storms. Our records over the past 7 years at the solar site (anemometers at 7m and 30m above ground) and on nearby Turley's hill (25m higher than the site) show that whereas the wind normally dies down at night at the 7m level, at 30m above ground and on the hill the wind almost never stops, with an average velocity of nearly 7 m/s (compared with about 4.5 m/s at 7m above ground)[7]. The area is clearly excellent for wind turbines but, curiously and for currently unknown detailed reasons, this potential is only local (even though the terrain in the whole region of tens of thousands of square kilometres appears uniform), extending probably over several hundred square kilometres, for our wind recording stations at Tibbuburra, Wilcannia, Menindee and Cobar all show inferior average wind velocities.

The wind can be described as being usually very strong and gusty during the day and strongly buffetting. Figures 4–10 provide typical wind records at the 7m level above the site. However, peak velocities have not much exceeded 80 km/h since December 1979. Wind effects in the winter are quite unpleasant for people's comfort.

Wind influences which have to be considered in design of systems include:

1. The possibility of really strong winds and the common sudden appearance of very steep velocity fronts which need to be accommodated; the strong buffetting effects on tracking performance have to be coped with.

2. The raising of dust clouds and the blowing and depositing of dust onto the collectors and into equipment both external and in the plant rooms.

3. The convecting away of heat from the solar abosrbers.

[7]That is, 2.7 times the energy output from the higher level.

4. Sudden mechanical shocks on all components.

2.3 Precipitation

The effect of rain can be only slight as it is so infrequent. Most clouds moving over White Cliffs, although reducing insolation, seem reluctant to part with their moisture. Rain would be expected to clean dishes but only superficially, as consolidated dust is not removed. Dew, frequent in spring and autumn, can result in much moisture deposition on mirrors, but its effect is to consolidate rather than remove dust.

2.4 Dust

Both coarse low level dust blown up by strong winds and high level fine dust occur in abundance in the inland. The former is not a problem since it rarely deposits on the mirrors or, if it does, is soon blown away. The latter can reduce insolation directly before it reaches the mirrors and also reduces reflectivity substantially if allowed to build up; it also appears as a fine layer on all equipment and must be coped with.

Dust of one kind or another has to be accepted as a fact of life and equipment designed accordingly to be either dust proof or dust tolerant. There is no doubt that dishes have to be cleaned in accordance with their dust deposition to achieve reasonable output — this cleaning is most desirably achieved automatically.

Fortunately, little grime is evident in the White Cliffs area; this alleviates the problem of cleaning.

2.5 Extremes of Temperature

Temperatures from just below 0°C in winter to 47°C in summer are a feature of the White Cliffs climate. Humidity in summer can also be a problem. It is not difficult to make equipment tolerant to these conditions and no antifreeze protection is used in the steam system even though water and steam lines always contain some water when the system is not running.

2.6 Water

Surface waters in the region follow the maxim — "all or nothing at all". Occasionally, heavy rains ensure the (over) flowing of normally dry creeks and the flooding of large areas of land every 10 years or so. White Cliffs can be cut off by road for weeks at a time. More usually, the township may be isolated for a few days due to flooding across access roads. In intervening periods conditions vary from moderately dry with a relatively lush

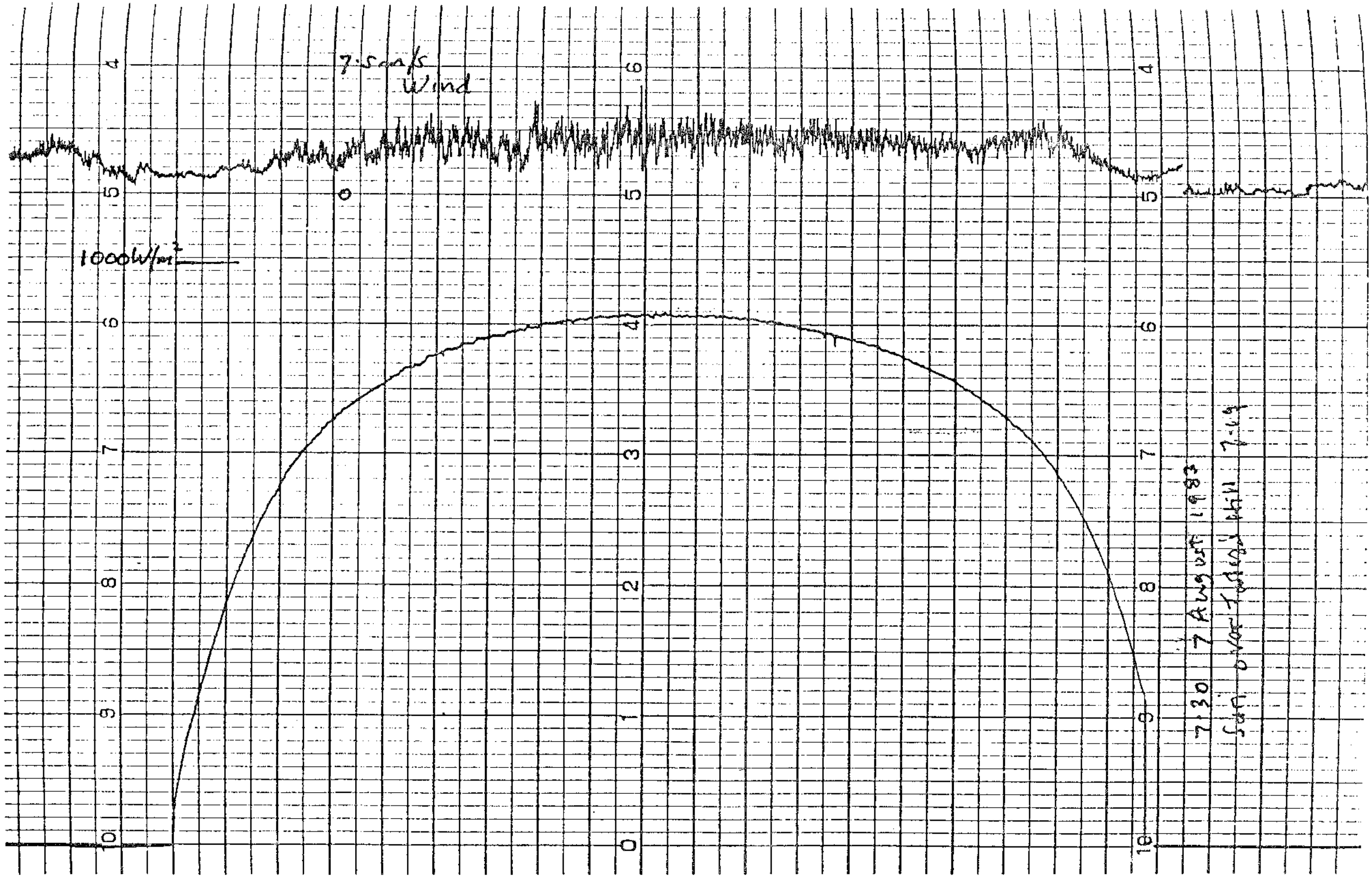


Figure 4. Clear sunny day (August, 1983)

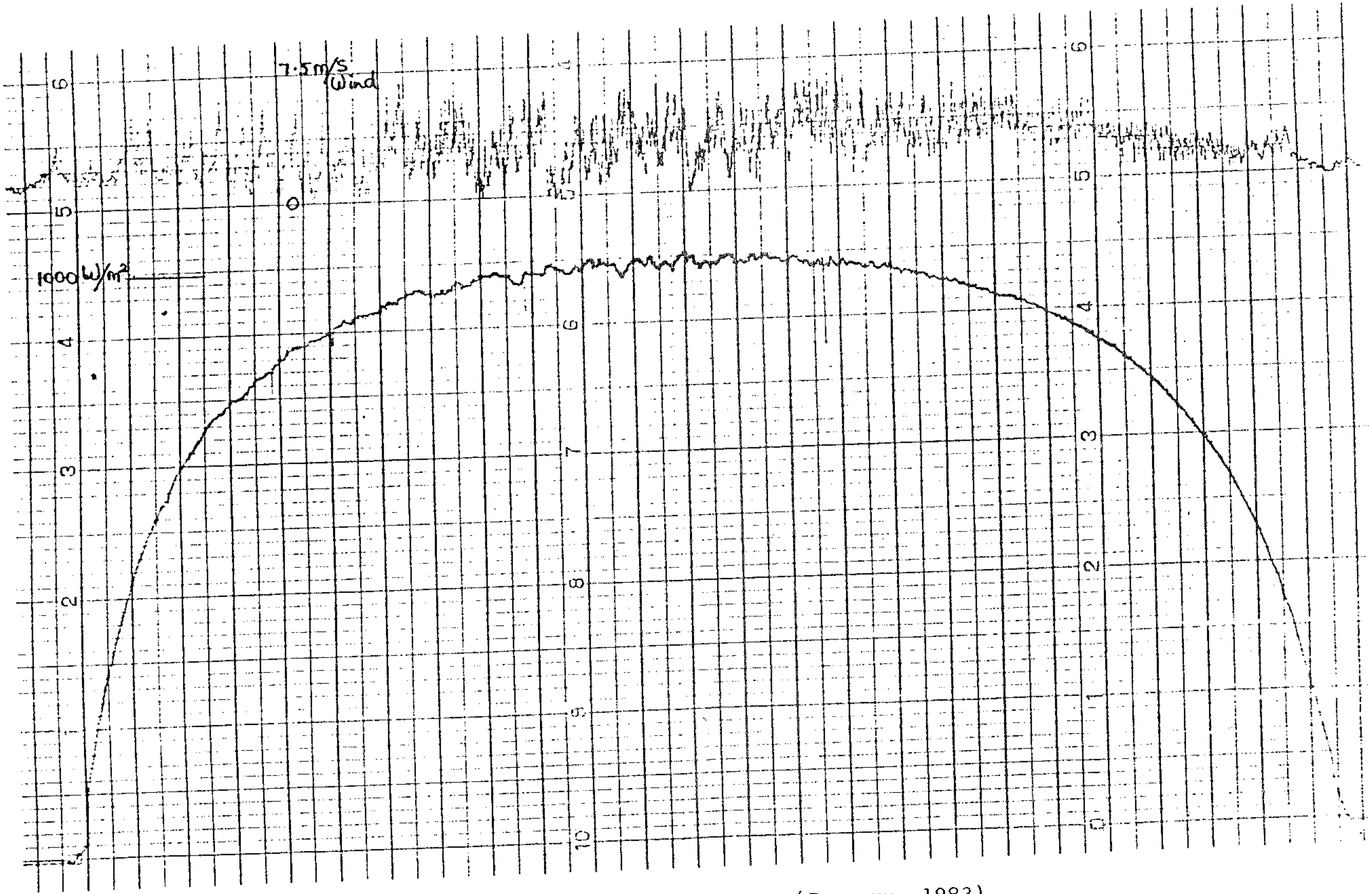


Figure 5. Clear sunny day (January, 1983)

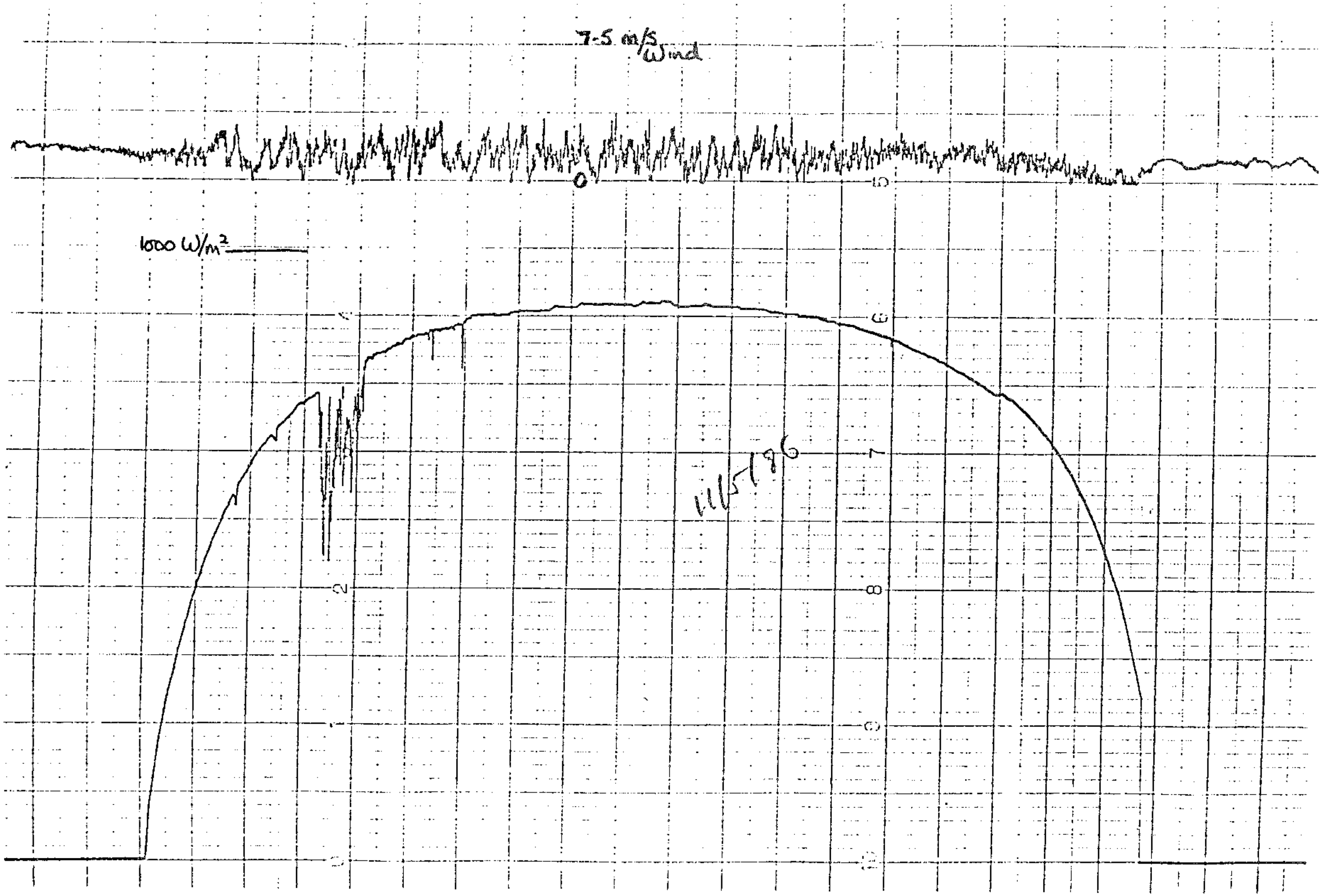


Figure 6. Slight cloud (May, 1986)

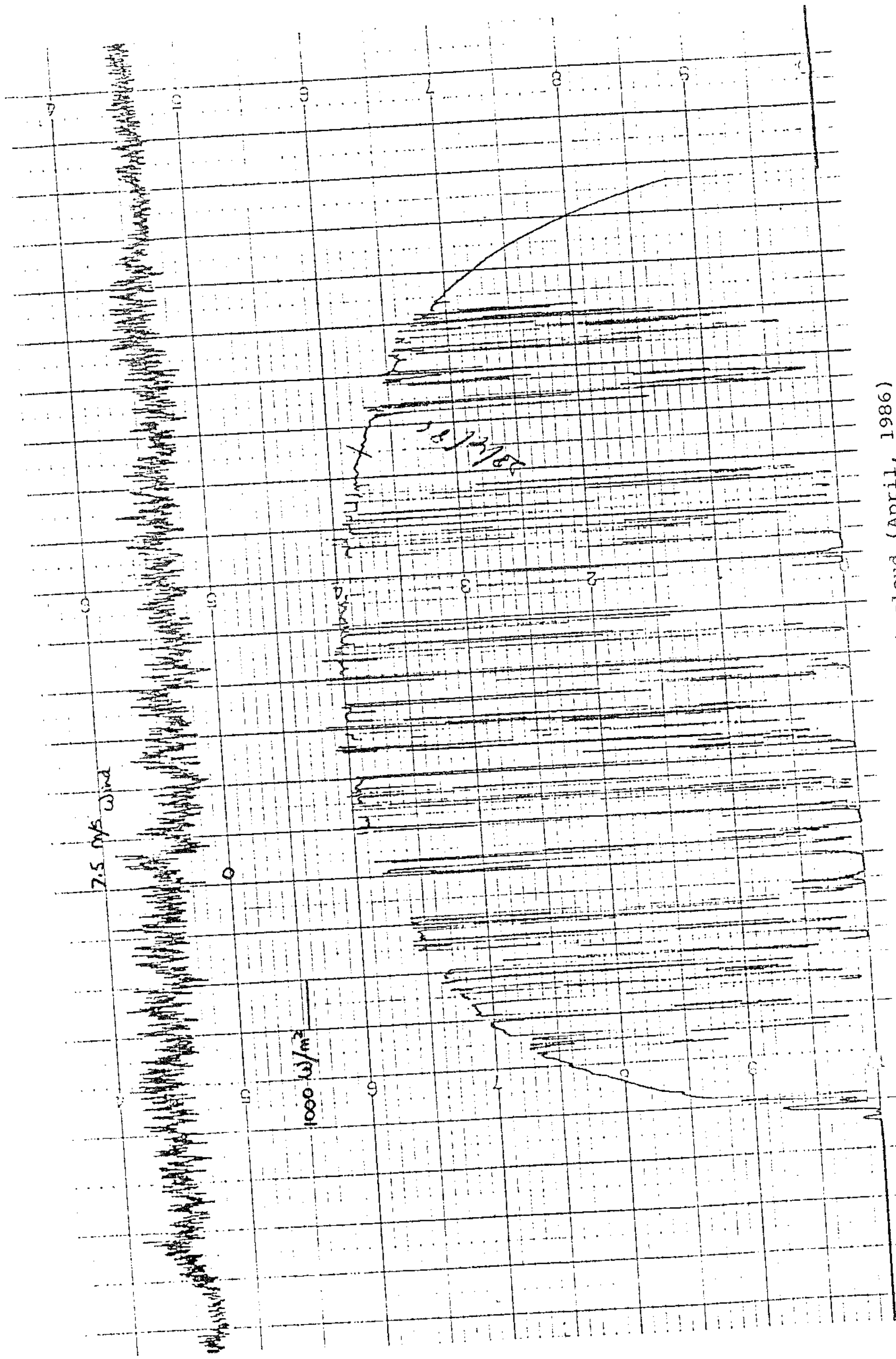


Figure 7. Heavy intermittent cloud (April, 1986)

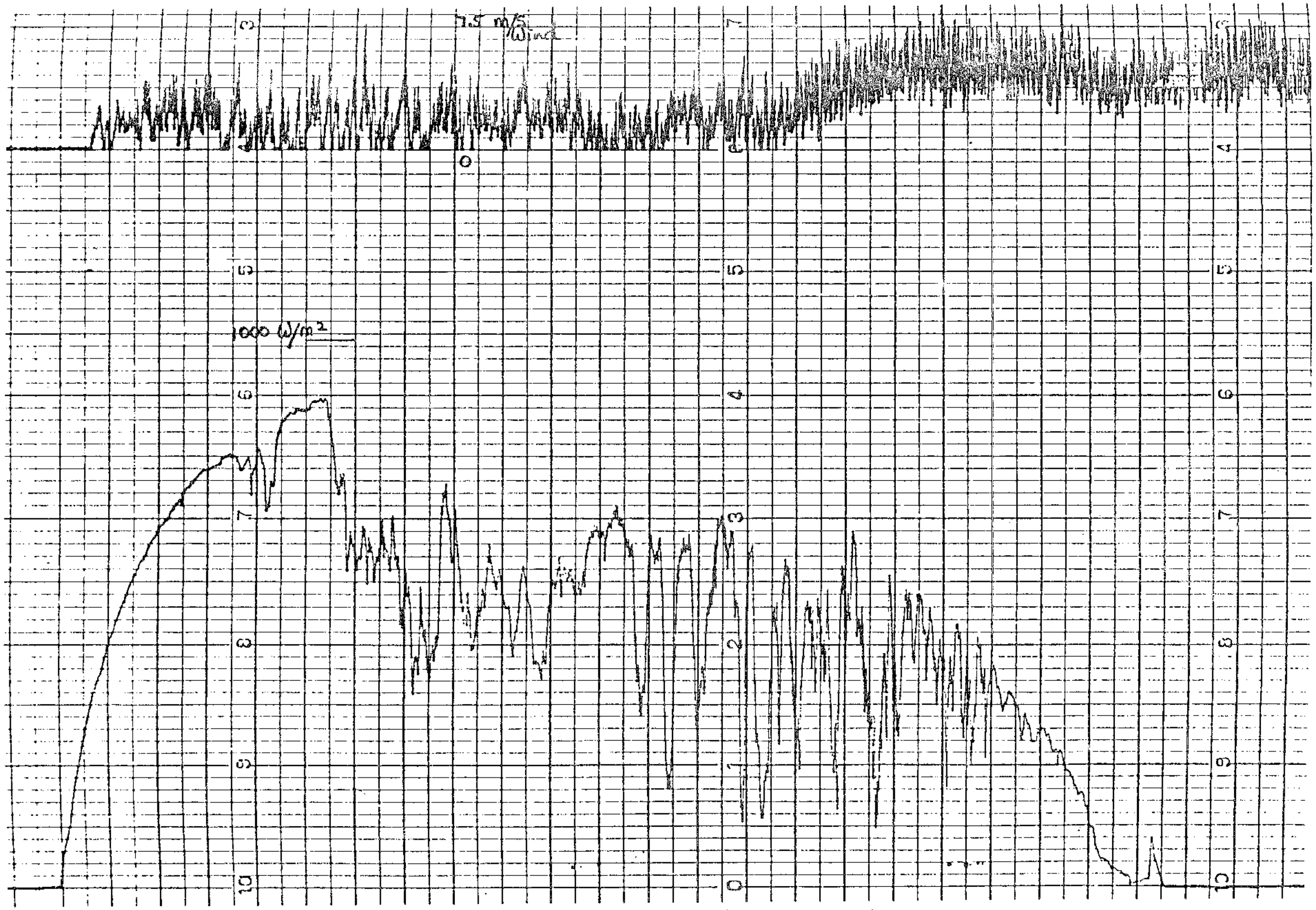


Figure 8a. Heavy haze (March, 1980)

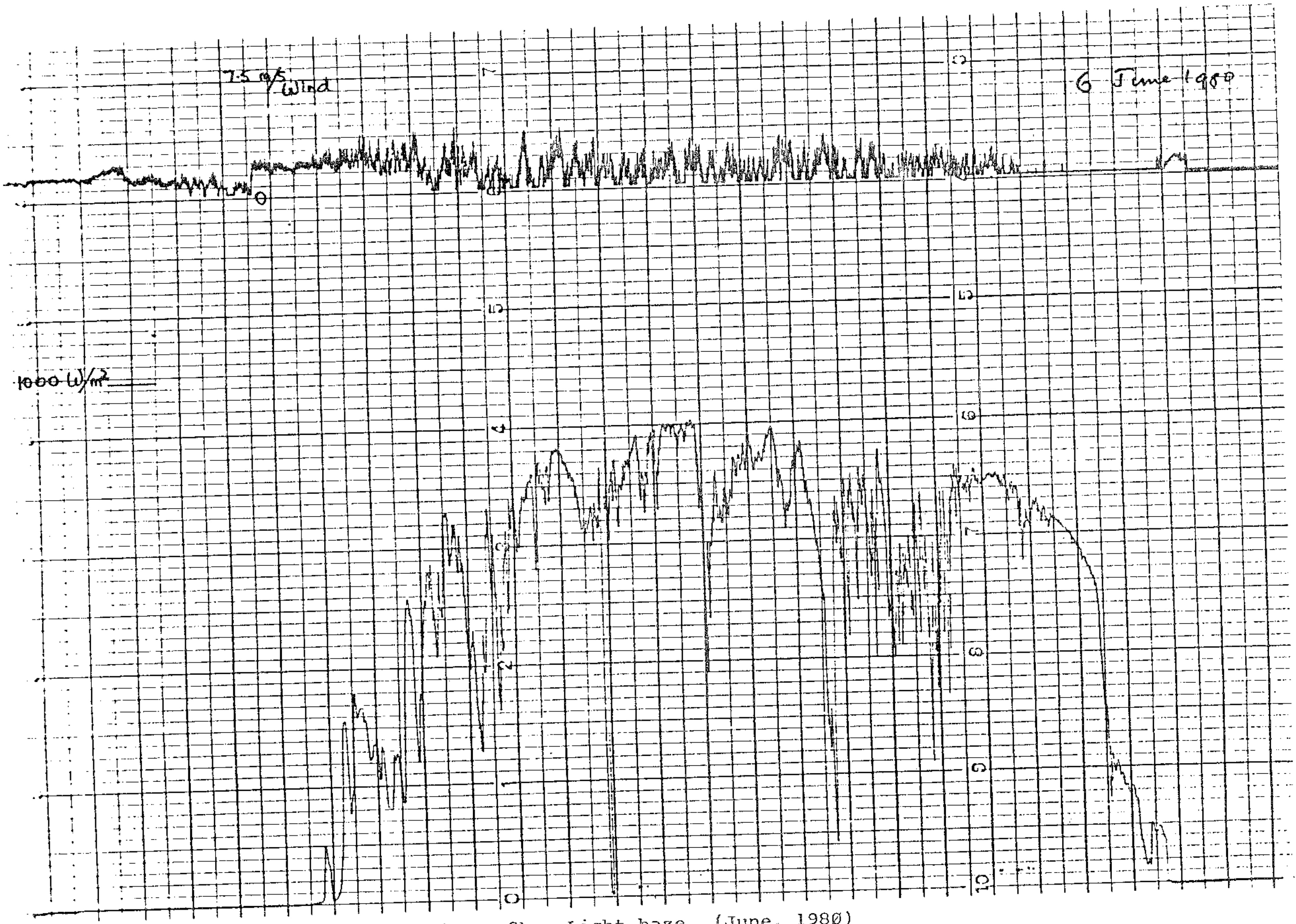


Figure 8b. Light haze (June, 1980)

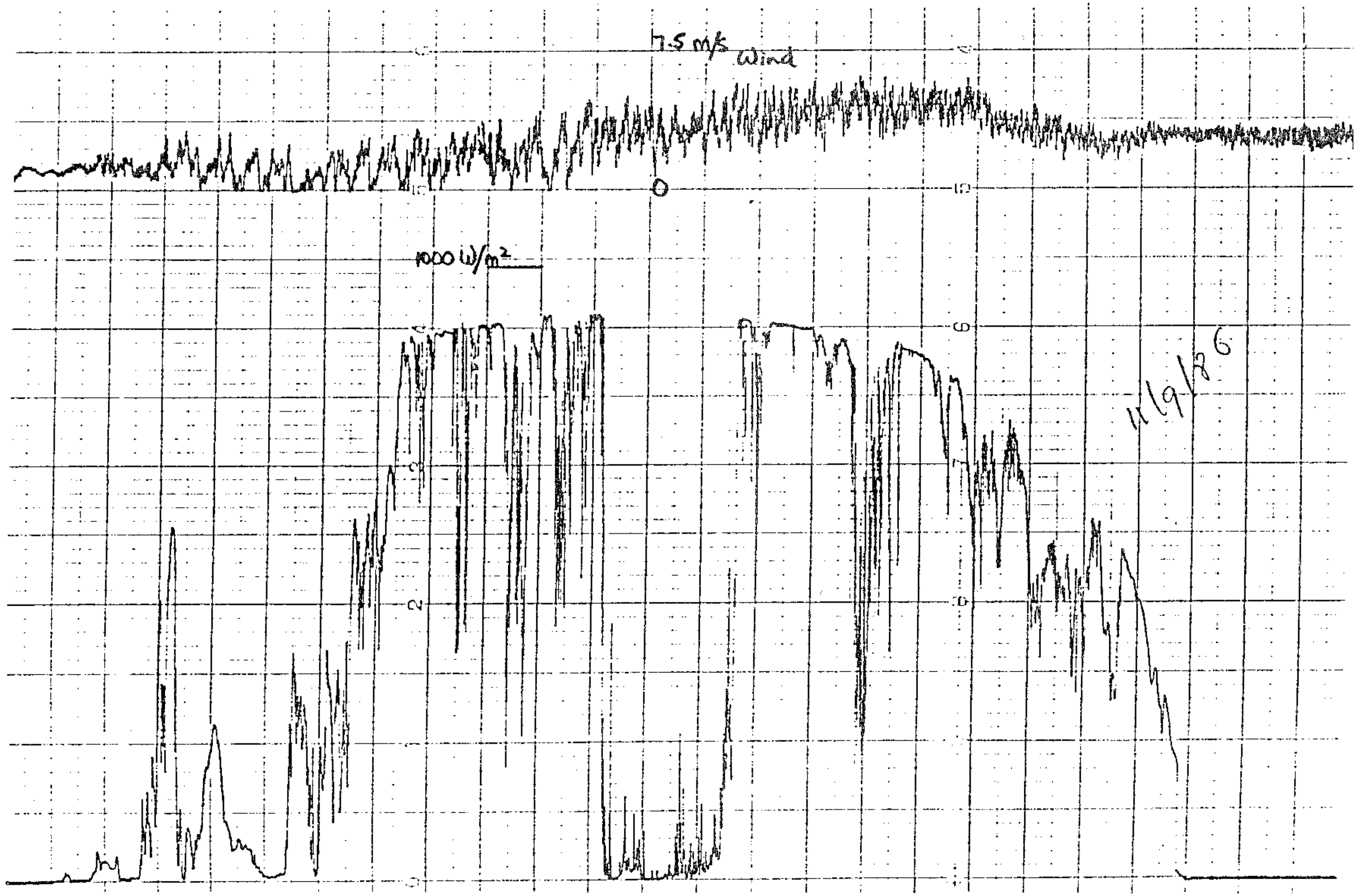


Figure 9. Haze and cloud (June, 1980)

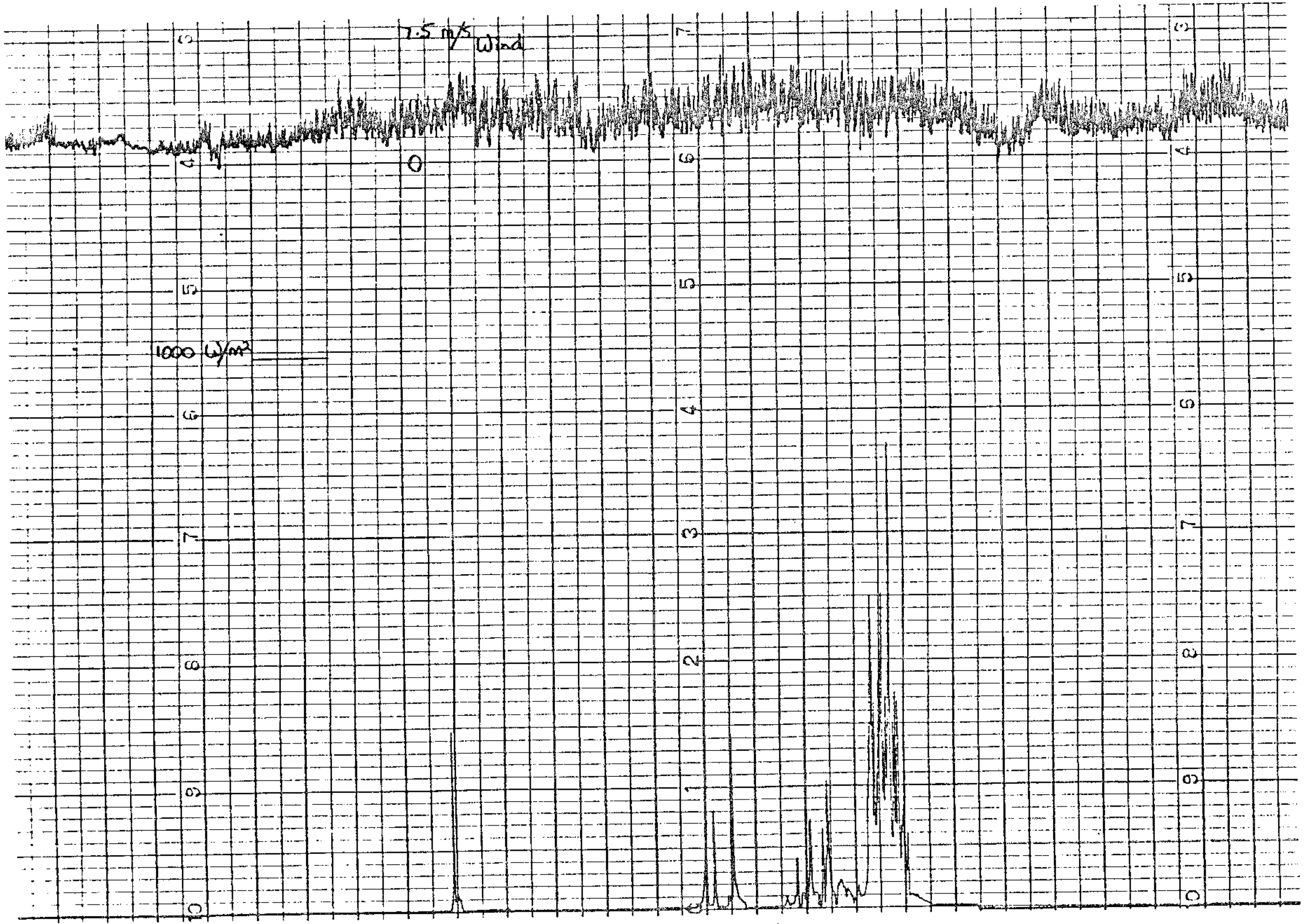


Figure 10. Heavy cloud (March, 1980)

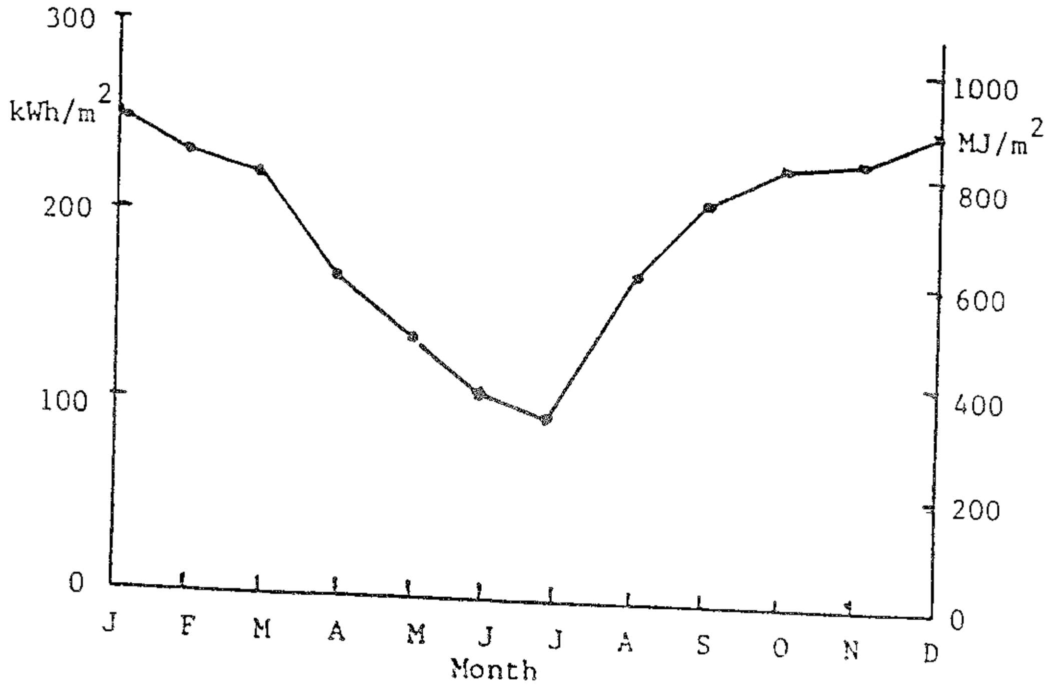


Figure 11a. Monthly direct axis average insolation for White Cliffs over the period December, 1979 - March, 1987.

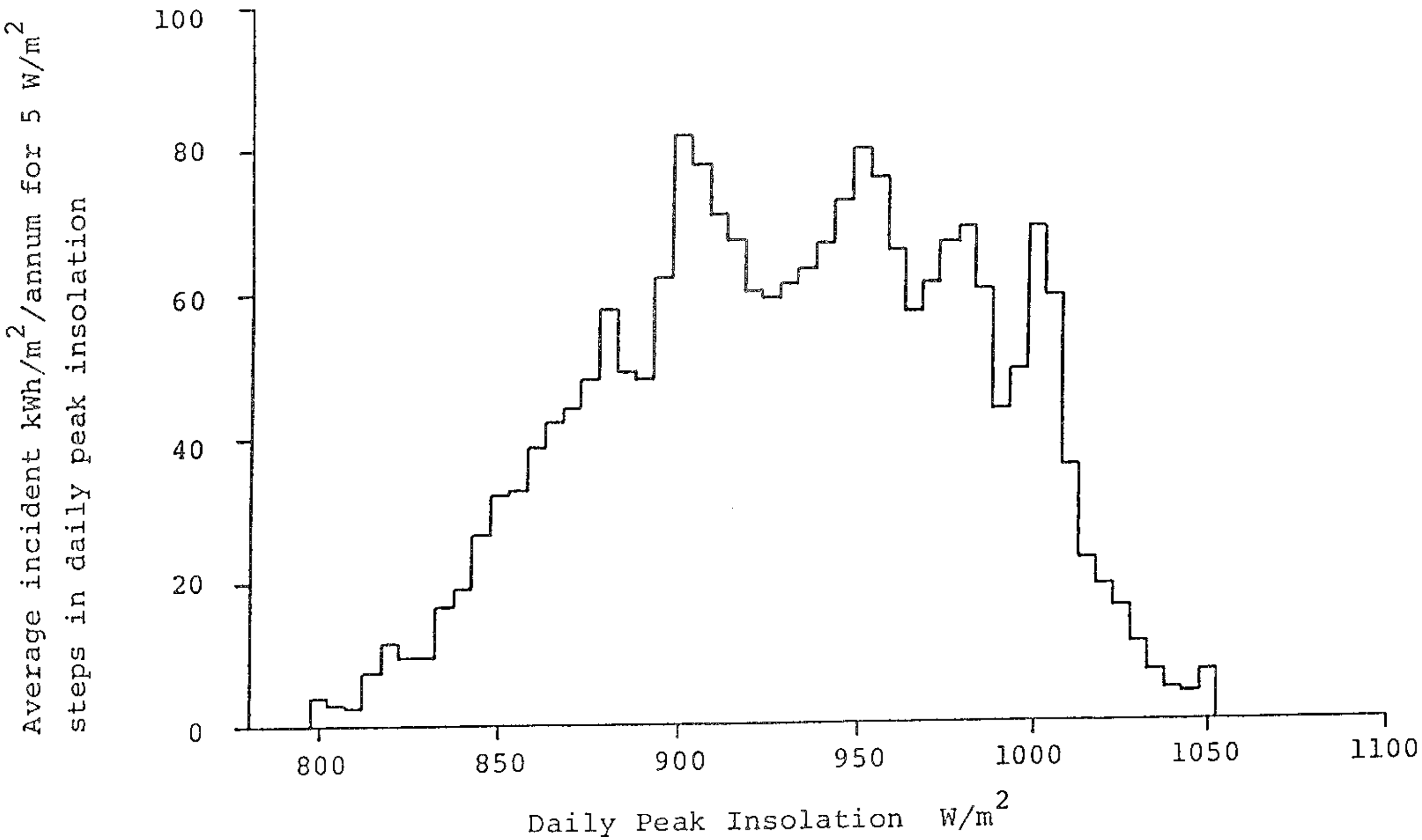


Figure 11(b). Average incident kWh/m^2/annum for 5 W/m^2 steps in daily peak insolation level vs. daily peak insolation level.

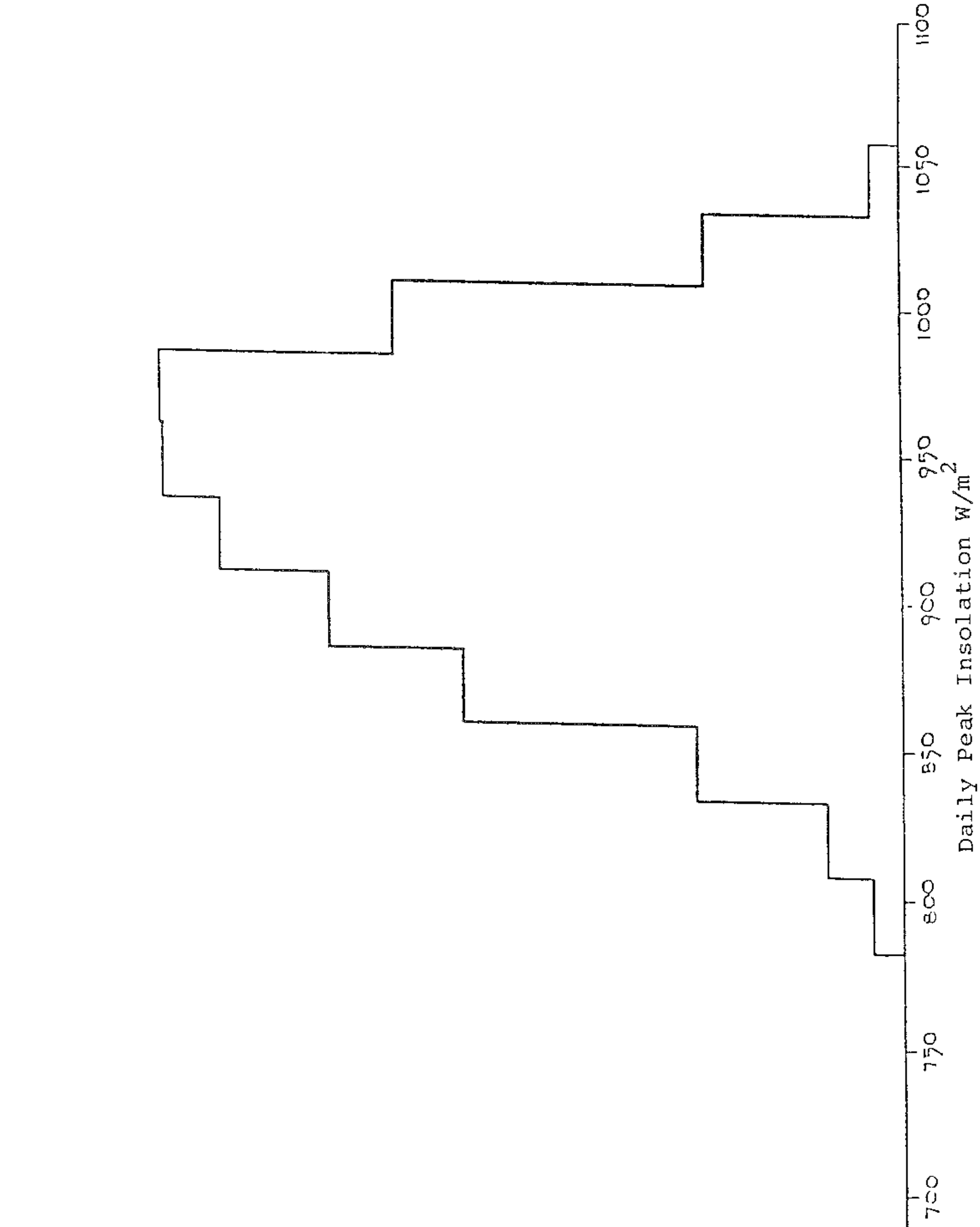


Figure 11(c). Integrated incident energy collected (kWh/m^2) over the period 1 Dec. 1983 - 30 Nov. 1986 over 25 W/m^2 steps in peak insolation vs. daily peak insoation

Integrated kWh/m^2 for the period 1 December 1983 to 30 November 1986 for steps of 25 W/m^2 in daily peak insolation grey/green carpet of growth over the whole region, to extreme drought every few years, when the countryside assumes a red/brown aspect with a great absence of moisture and plants.

A solar thermal power plant would be expected to require a regular water supply for steam condensing (unless using air condensing), feedwater, mirror cleaning, washing and general drinking and amenities for any personnel involved at the station from time to time. An early decision was taken to employ water for condensing since this appeared to require less auxiliary power than air condensing and could be implemented more readily and more cost effectively: this demanded an adequate supply of cooling water.

The township water supply came (in 1979) from two recently constructed earth tanks, the lower of which accepted surface runoff water which was pumped by windmill to the higher tank and reticulated to the town centre. All buildings have rainwater tanks which, properly sized, can supply good quality drinking and cooking water all-year- round and provide a vital supply for washing when the town supply dries up (in periods of drought). In recent years some water has had to be carted 95 kilometres from Wilcannia from the river Darling for washing purposes, but this, as with the earth tank water, is usually not potable.

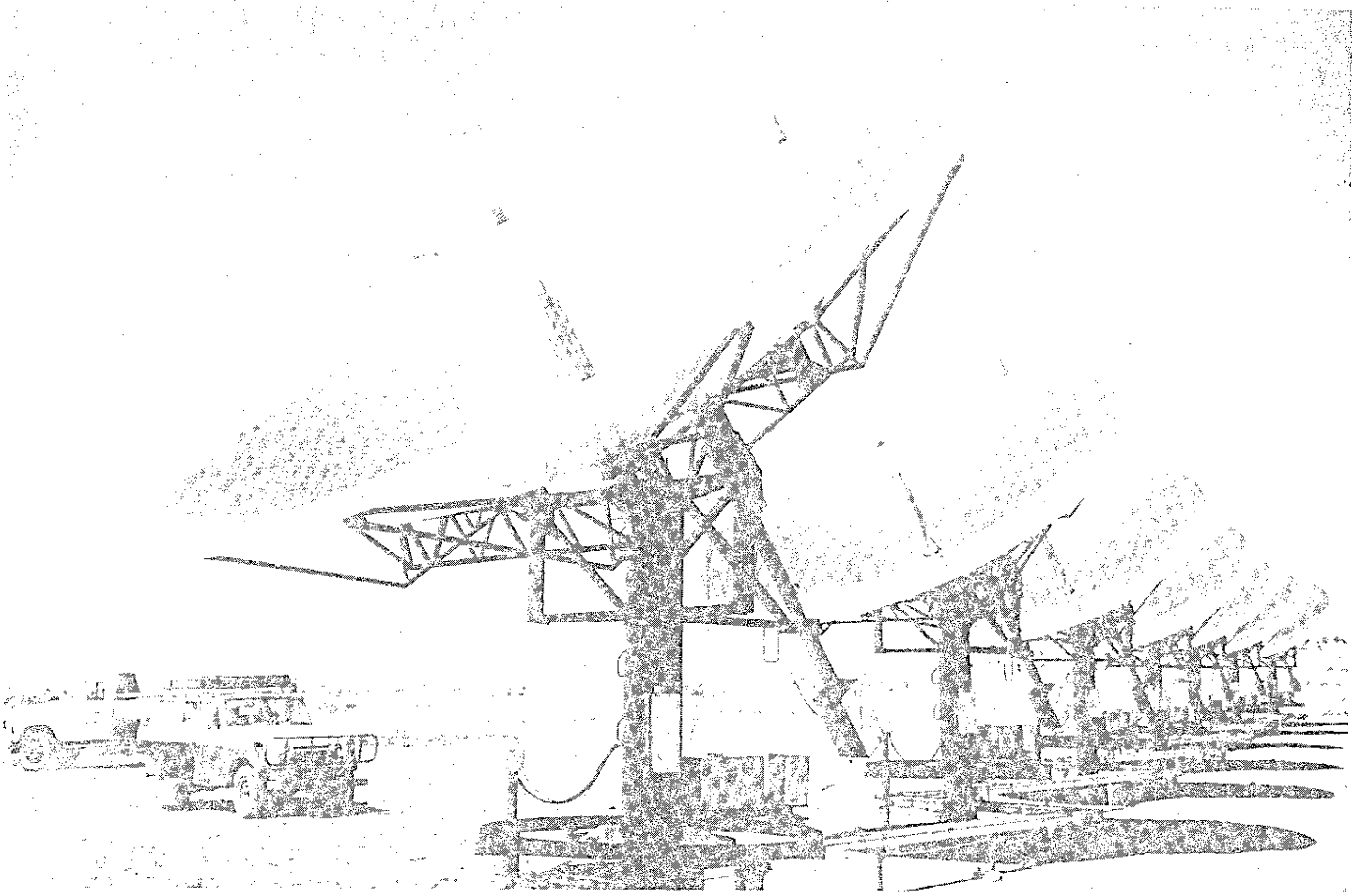


Figure 12. Eastern arm of the solar array.

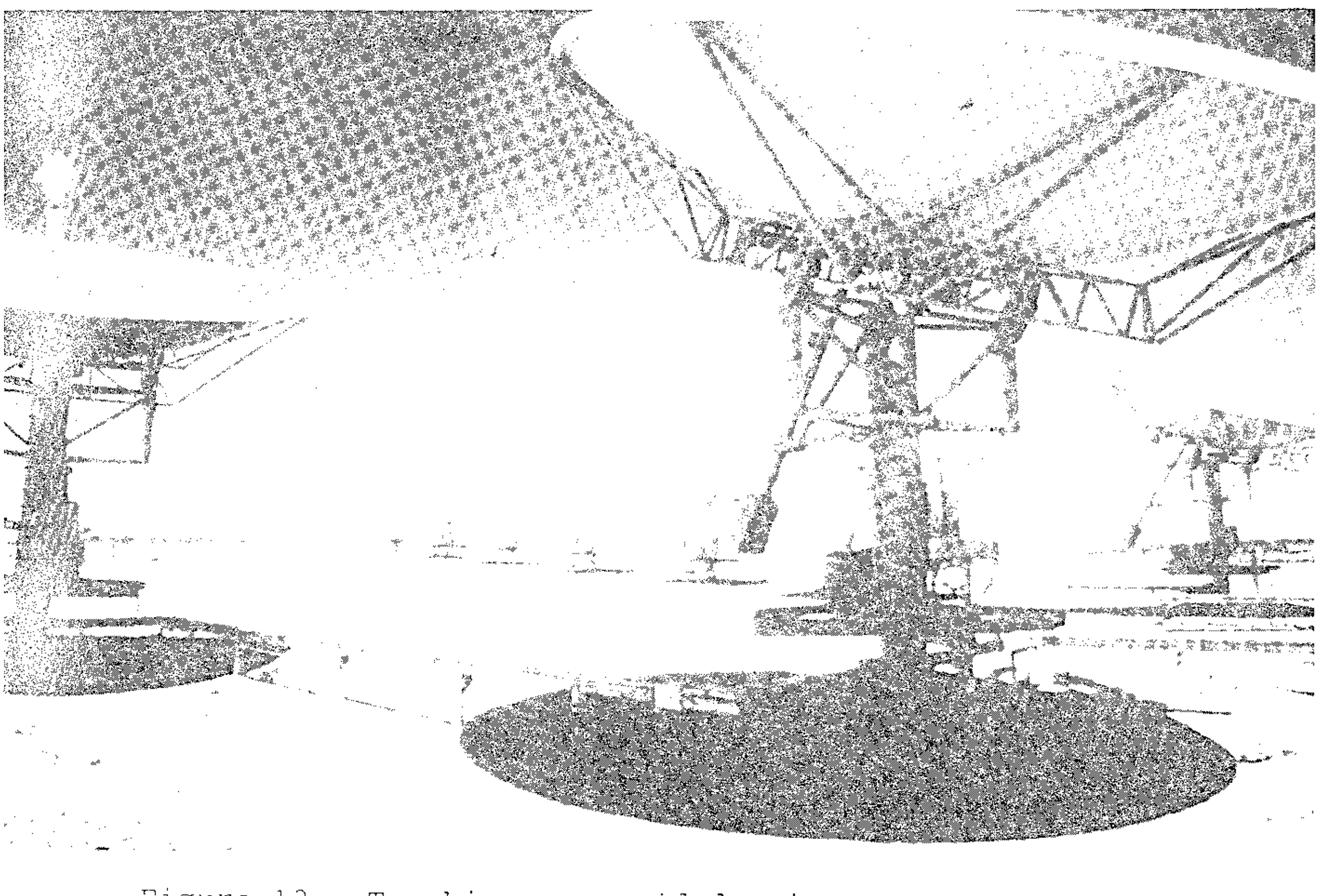


Figure 13. Tracking near mid-day in summer.

3 CONFIGURATION, COMPONENTS AND SYSTEMS

Choice of 25 kW output for the first system was based, as indicated earlier, on the need for a convincing demonstration without incurring excessive cost. Other factors played a part in selection of system size, however, including:

1. The apparent availability of a suitable high performance Rankine Cycle Uniflow Steam Engine of 25 kW output from T. Pritchard of Melbourne, who had 25 years experience in steam car engine development and had recently obtained a Commonwealth Government Grant to continue developing his engines — this would allow an entirely Australian development.
2. By rational use of the system, some 10 houses could be powered to a reasonable level of supply.
3. At a later stage of development, 25 kWe might be a reasonable size module using a single dish of 11m diameter with a new generation engine.
4. Experience could be gained in multi-dish operation.

In early July 1979, the 25 kWe system, as envisaged, involved the use of 14 pairs of 3.67m diameter thinshell paraboloidal collectors (280m^2 total aperture area), producing steam at 550°C and 7 MPa pressure, reticulated to a central plant which comprised a Pritchard steam engine driving an alternator at 1500 rpm to supply AC power to a load. Storage was specifically excluded at this stage and the use of waste heat for water desalination was mentioned only as a later possibility. The system was to be experimental in nature and was intended to prove the concept. A competitor engine from Commander G. Vagg appeared also to be available. The system was intended to employ as much as practicable of a research programme directed to produce cheap thin metal shell paraboloidal collectors [Carden 1980].

Selection of White Cliffs in September 1979 as the station site necessitated addition of storage, provision of diesel backup and automatic unattended operation. Over the period July 1979 to August 1980, a research programme was carried out to define the system and to develop various components, especially the collector dishes and frames, actuators and tracking systems. As a result of these studies, the system evolved as follows:

1. Time constraints indicated it would be unlikely that the Carden 3.7m-diameter thinshell vacuum pressed dishes could be ready in time, especially due to problems experienced with weld failures of the aluminium sheet during the pressing operations. Two other options were explored — spun aluminium dishes of 5m diameter produced for telecommunications purposes and fibreglass substrate dishes: the former were deemed too expensive and in August 1980 it was decided to employ 14x5 metre diameter fibreglass dishes, glassfaceted — this carried the additional advantage that we had control of shape, diameter and method of production.
2. The Pritchard engine, on which the system was originally based, turned out to be not available and Pritchard was unable to assure us on actual output. A contract was signed with Commander G. Vagg (a steam specialist in the Australian Navy and

a steam car enthusiast of long standing) to produce a working engine by June 1980. This engine, although conceptually excellent, was basically undeveloped and by far the greatest effort expended on this project has been in developing the engine to a level of performance and degree of reliability which is appropriate to the needs of the project; but there was no satisfactory alternative. [The engine, when eventually received about June 1981, required much modification and development to enable it to work even indifferently before all the equipment was transferred to White Cliffs in November. Eventually we were able to produce an engine of excellent performance, robustness and reliability.]

In August 1980 the project had evolved to a 25 kWe system employing 14 dishes each 5m diameter, tracking in azimuth and elevation, supplying steam at up to 500°C and 7 MPa pressure to a high performance reciprocating expander which drives an alternator/DC machine/battery combination to allow electrical storage — backup being provided by a diesel generator — with an auxiliary boiler being available for test and emergency purposes.

Consideration of the system (as illustrated in Figures 1 and 2) is facilitated by separation into subsystems, conveniently:

Energy Collection — Concentration and Absorption	:	the Solar Array
Energy Transport	:	the Field Ducting
Energy Conversion (Heat to Work)	:	the Steam System including Auxiliaries
Energy Utilization	:	the Electrical System and Load
Energy Storage	:	the ac/dc/Battery System
The Operating System	:	Automatic Controls and Operating Strategies, including Data Acquisition
Environmental Monitoring	:	Insolation, Wind.

Considering each in turn:

3.1 The Solar Array

The array is portrayed in Figures 1 (general layout), 12 (eastern arm), 13 (tracking near midday in summer), 14 (the full array), 15 (tracking near sunset), 16 (rear view of collectors).

To enhance overall system integrity, the collector field is structured and operated as a set of discrete modular units, each with its own battery supply charged from the station central supply, and is able to continue operation for more than one day in the event of loss of charging supply. In the case of communication failure between central control and any dish

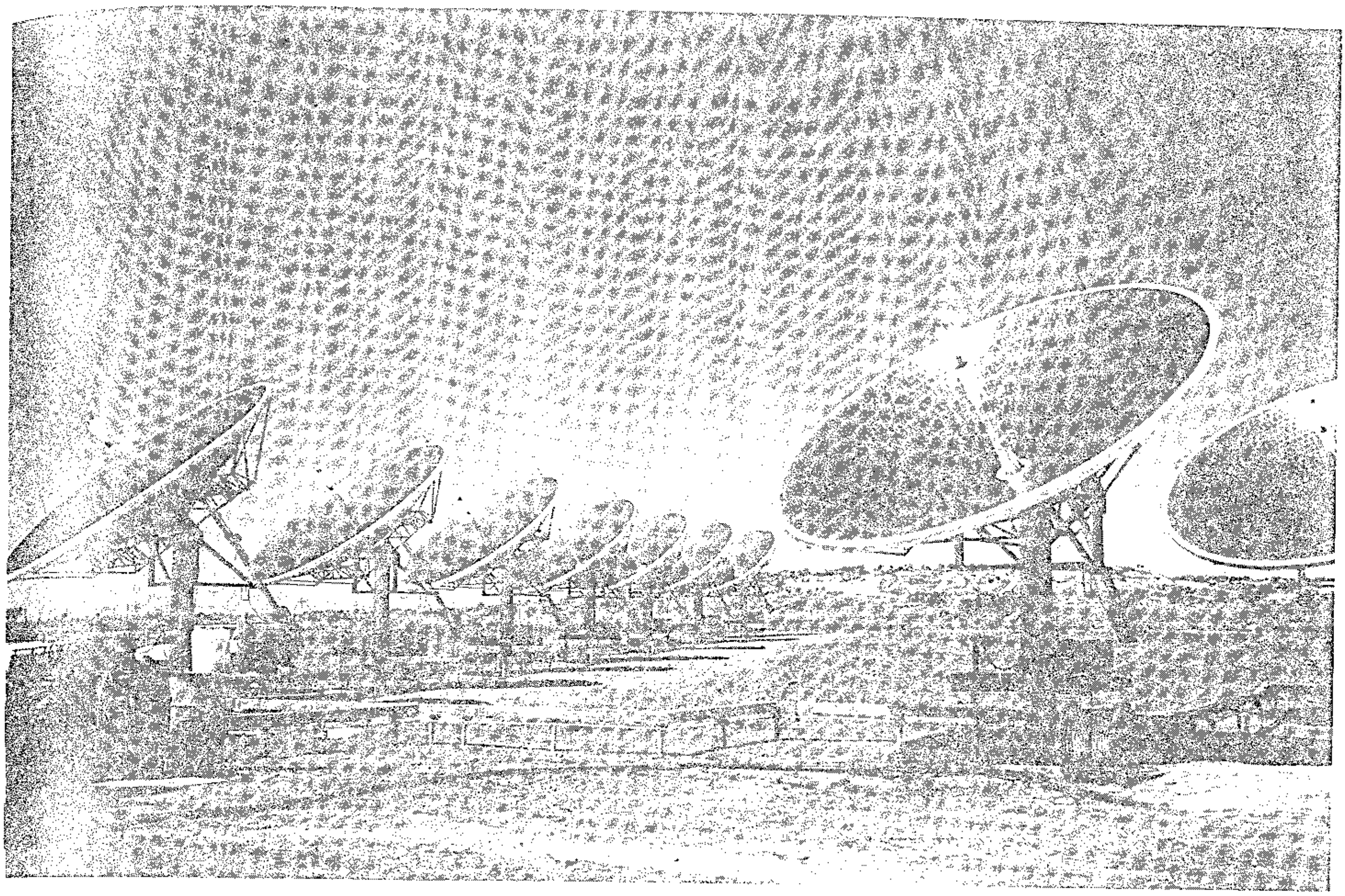


Figure 14. The array.

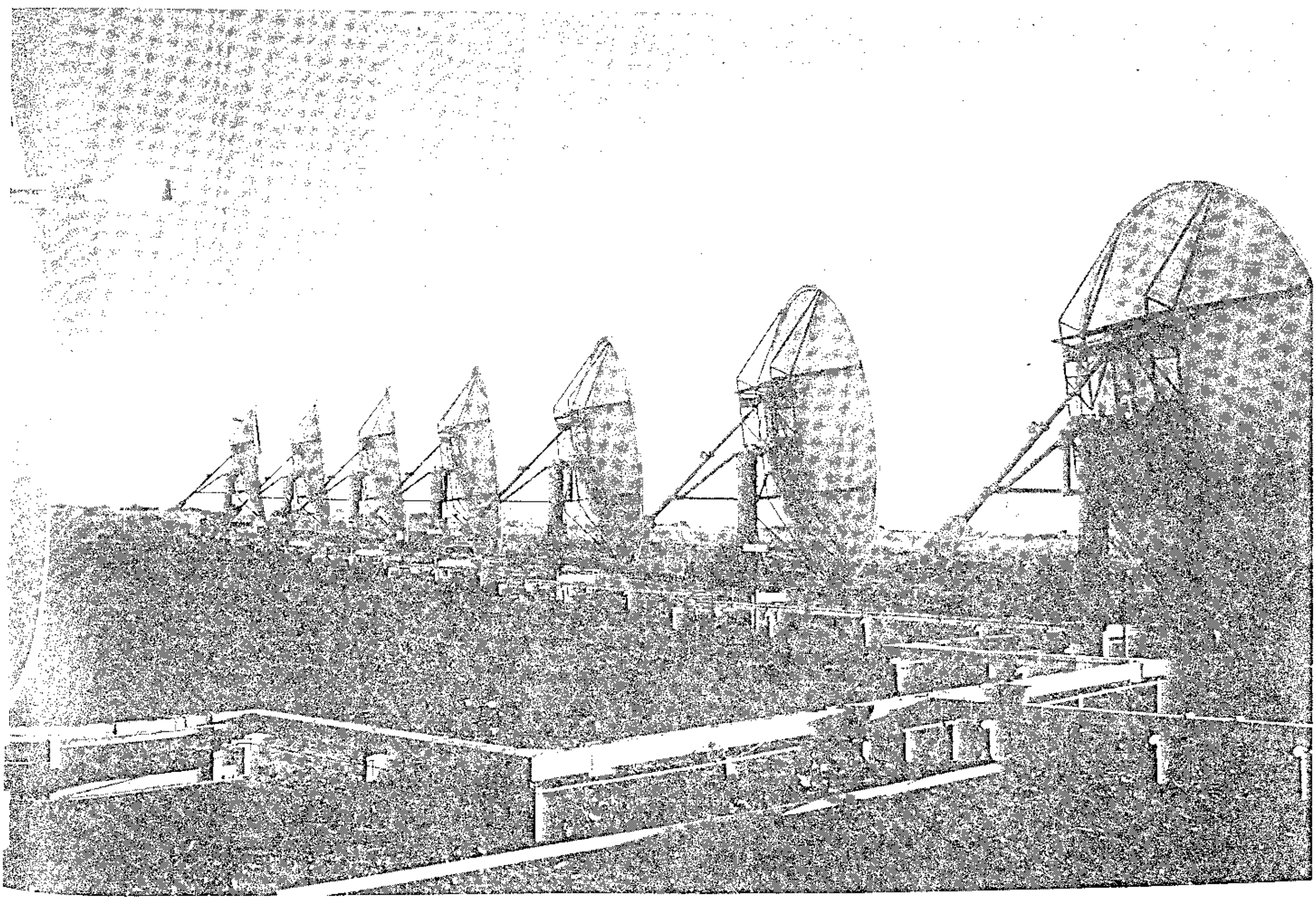


Figure 15. Tracking near sunset.

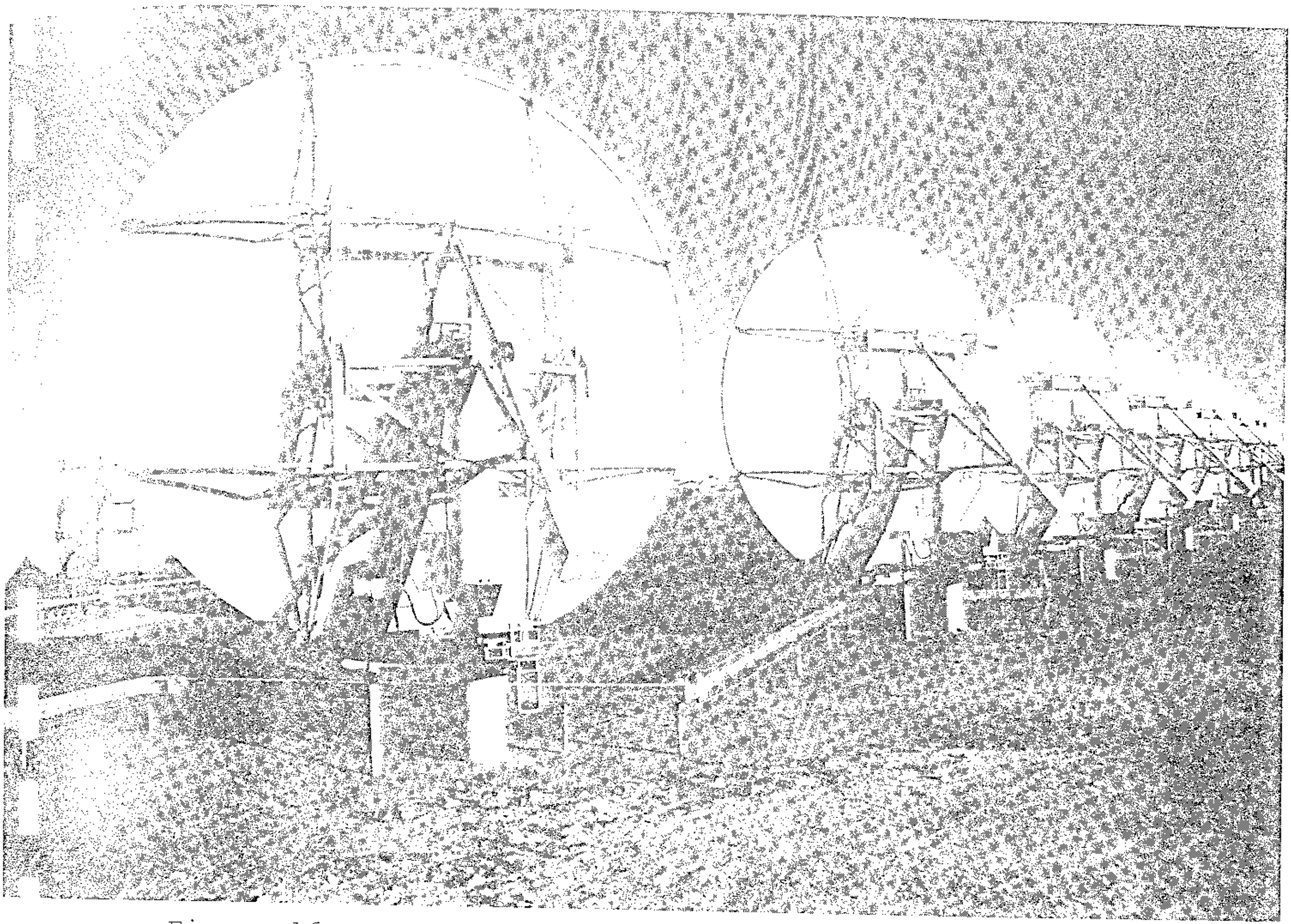


Figure 16. Rear view of collectors.

unit, such a unit can continue operation, can protect itself against absorber overheating, can carry on all day and park automatically in the late afternoon, notwithstanding loss of central control signals. A wind speed monitor causes each dish to park in a vertically-facing orientation whenever speed exceeds 80 km/h — this function operates so long as the wind monitor is connected to each dish and the individual control unit for each dish is operating (neither the central control nor the central station need be operational).

The control for each unit, therefore, takes care of all tracking functions, absorber overheating and parking in strong winds. Signals from the central controller initiate the "start" and "stop" tracking and signals generated by station faults cause collector offsteer. Manual "override" is available on all these functions as well as manually-controlled slewing in elevation and/or azimuth, parking and offsteering — either for single dishes or for all dishes (addressable).

3.1.1 Array Layout

In a suitable location, a single row of collectors lined up north-south, with the utilization plant in the middle of the line, is a suitable arrangement as there need be no shading of any collector at any time of day or year providing spacing is such that dishes just do not interfere on midwinter day (little is lost in energy by allowing some small overlap, thereby shortening ducts and saving losses all year round). This concept also allows short fluid path runs and low heat losses. [Added advantage would acrue if the more distant collectors ran at lower temperatures, the temperature profile increasing towards the closest collector — but absorber design and possibly system control could turn out more complex.]

Other arrangements, involving more than one north-south row, suffer from shading loss (which may or may not be significant) and have the advantage of fitting more easily into what is normally considered as an array arrangement; they can carry various cost penalties in terms of fluid line lengths and losses.

A complicating factor intruding in all layouts which involve the transport of hot fluids is the need to provide for expansion in lines; this can become very demanding where, as in the case of the White Cliffs array, temperatures of hot lines can vary over wide limits (some 0°–500 °C) and can do this daily and more often.

Due to existing fencing limitations, we had to specify the layout of the White Cliffs station in terms of two north-south rows (as illustrated in Figure 1), the V-form arising from the manner in which expansion of steam lines was handled, as discussed in Section 3.2.

3.1.2 Paraboloidal Dishes

Considerable care was taken in this area, particularly as we were breaking new ground.

1. <u>Dish Design Coniderations</u>

   Design in this application, as usually is the case, involves a balance among many factors and requirements, some conflicting — various tradeoffs can be made in the process of producing successful designs and, to do this, requires the taking of specific points of view. Among the more substantial standpoints and attitudes taken in the design of the White Cliffs paraboloidal collectors, while such collectors are as yet at an early stage of development and still relatively expensive,included the following:

(a) Each dish unit should produce the maximum output consistent with the extra cost penalty being lower than the cost resulting from increase in number of units and their maintenance and operation, which would otherwise have to be used.

(b) Relatively trivial cost penalties in enhanced control functions can allow substantial hardware savings in dish structures by compensating for relaxed tolerances in resilience, backlash and hysteresis, and other manufacturing and inherent imperfections.

(c) A simple dish-cleaning routine or mechanism can enhance considerably the total energy output in relation to what it would otherwise be without cleaning, and seems worthwhile.

(d) Technology of the level of sophistication of agricultural/automotive engineering practices can produce robust, reliable economical systems which can be handled by those without unusual skills.

(e) Advantage can be taken of the natural strength of paraboloidal shells to produce simple, accurate basic dish shapes which can be simply supported and lined with appropriate reflecting surfaces to concentrate the direct beam solar radiation.

(f) To simplify receiver configuration and support, a relatively deep paraboloidal shell was chosen (70° rim angle) which has adequate self-rigidity and relatively short focal length, allowing the receiver to be mounted on a central duct through a hole in the base of the dish.

(g) The volume and form of the focal region should be such that tolerable stresses are present in the receiver during its operating cycles; this implies either

    - A very acute optical focus which allows the use of a high performance low loss cavity receiver the stresses within which are limited by properly sizing the cavity; or
    - A receiver which achieves low losses and high efficiency by maintaining a small physical size thereby minimizing convection and radiation losses in particular; such a receiver obtains some of the illumination from an external surface(s) which can be, however, at a relatively low temperature.

    In the present case, the relatively short focal length and relatively 'fuzzy' focus results in receivers following the first option above, being of lower efficiency and higher cost than those satisfying the second option. The second option was used. We have called these kinds of receivers semi-cavity receivers and have studied their characteristics theoretically and experimentally, confirming in specific applications such as the White Cliffs dishes, they can be superior in performance and cost to true cavity receivers [Williams 1980, Kaneff and Kaushika 1987, Kaushika and Kaneff 1987, Kaneff and Co-Workers 1985].

(h) On the rationale that overall costs are likely to be least if all construction and nearly all of the assembly is carried out in the factory with minimal installation requirements in the field, each dish unit was constructed as:

    - A paraboloidal shell, lined with reflective surface.
    - A space frame to carry the dish and absorber/duct.

- A head frame to carry the horizontal axis (on which the dish and dish frame are mounted).
- A column set in the ground carrying the head frame rotating about a vertical axis.

Assembly then simply involves drilling a hole in the ground, setting the column in concrete, then mounting head frame and dish/dish frame.

Each of the 14 collectors in the array consists of a 5m diameter 70° rim angle paraboloidal dish — rim supported fibreglass substrate 6mm thick — holding some 2300 mirror tiles of 2. 5mm backsilvered windscreen glass (cut to conform to the paraboloidal shape) with no side longer than 105mm, attached to the substrate by GE 2000 silicone adhesive applied also along all edges to provide a seal. The dish is supported on a frame pivoting on a horizontal axis (the absorber being mounted on this axis, not on the dish) which in turn can rotate about a vertical axis carried on the pedestal pipe (set in concrete in the ground), as illustrated in Figure 17.

2. Dish Specifications

Fibreglass substrate paraboloidal shell 6mm thick with integral rim ring of 51mm x 51mm x 3mm mild steel, holding 8 support flanges.

Diameter of reflective surface	:	5.02m surface
Over diameter	:	5.18m
Aperture area	:	$19.8m^2$
Rim angle	:	70°
Focal length	:	1.808m
Glass facets	:	2.5mm thick, backsilvered 105mm maximum side
Number of facets	:	2300 approximately
Weight	:	690 kg

The dish shape was considered sufficiently deep to take advantage, in the interests of cost reduction, of the inherent strength of thin paraboloidal shells and the consequent simplification of their mounting and support needs, but not too deep to rule out the use of cavity absorbers. The proportions also allow absorbers to be readily mounted on a column projecting from the centre of the dish, carrying the inlet water and outlet steam, the overall arrangement having simplicity and potential economy.

While it is possible to optimize dish size and shape on the basis of more detailed and quantified criteria, in the end there are practical considerations which intrude and force decisions which are of greater importance or relevance than idealised optimization indicators which are most useful in the presence of adequate information and experience, factors very lacking in this case.

Dish Frame

Square section tubular steel members, pivoted on two horizontal bearings to allow the dish to move from facing horizontally to facing vertically, ie by 90°.

Pedestal Head Frame

Tubular steel frame supporting the dish on its horizontal axis, in turn located and supported by tapered roller bearings held on top of a pedestal pipe and by 4-ball races pressing against an extended skirt which holds the azimuth drive system, allowing 360° rotation, restrained to 300° to avoid fouling of control and power cables

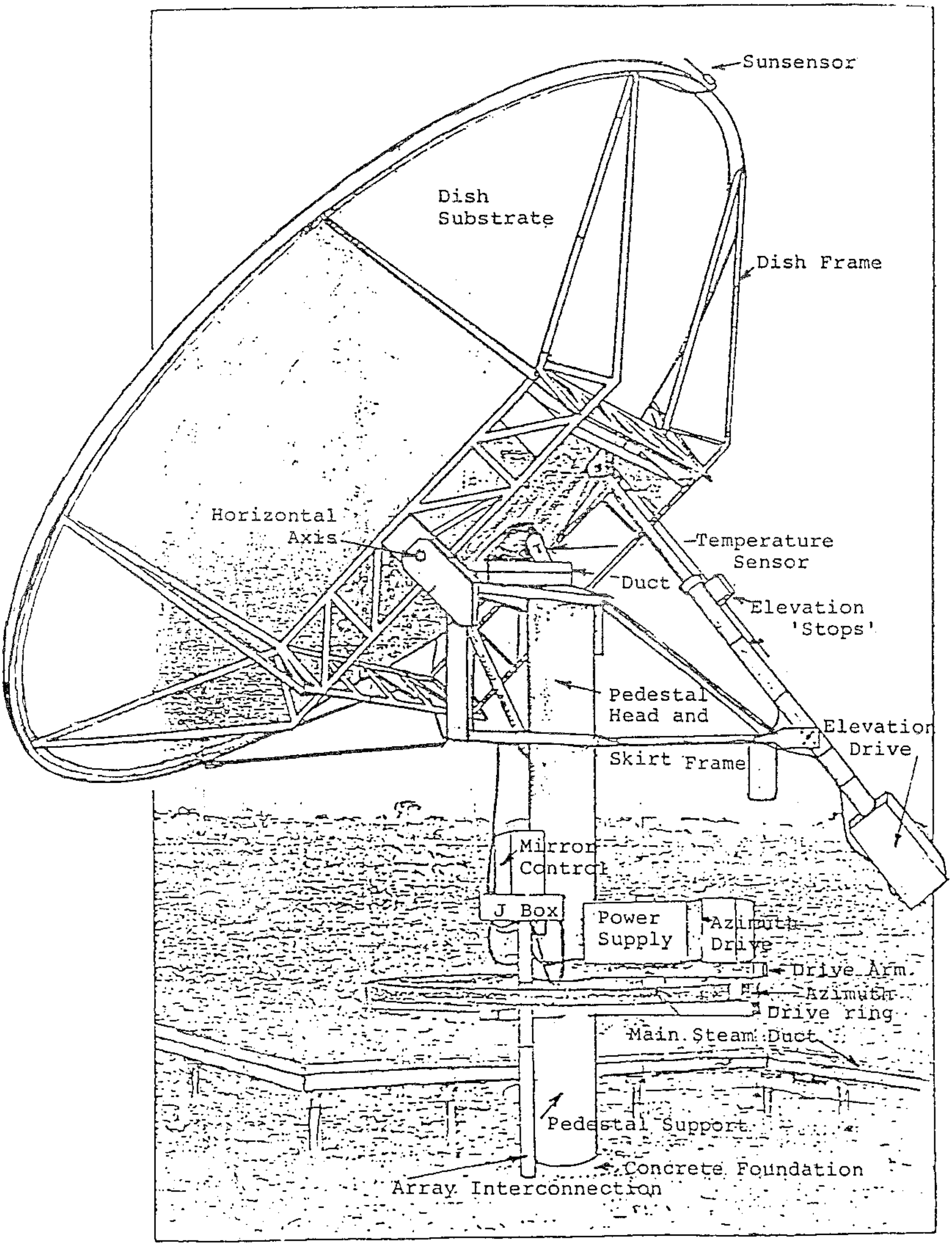


Figure 17. White Cliffs paraboloidal dish unit.

to the dish unit.

Pedestal Pipe and Foundations
Steel pipe 5.5m long 300mm diameter x 6mm thick, set 3m into the ground (Figure 17) to support the collector unit.

3. Dish Tracking Mode

While polar/equatorial tracking has the advantage of only ±90° rotation on the polar axis and $\pm 23\frac{1}{2}^\circ$ rotation on the equatorial, counterweights are usually required and, unless more complex mountings are used, positioning dishes in attitudes for convenient maintenance or attention during sunny days can pose problems. Altitude/azimuth tracking, on the other hand, while requiring more rotation (±150° desirably in azimuth and ±45° in elevation), allows counterweights to be readily avoided and dishes can be parked facing south (southern hemisphere) out of the sun for maintenance during the day. Overall, it was considered that altitude/azimuth tracking could use simpler structures and was accordingly specified (we have in the past built both kinds of tracking systems). For units located within latitudes $23\frac{1}{2}^\circ$ south and $23\frac{1}{2}^\circ$ north, polar equatorial tracking has some advantage in simpler analogue servo systems, if such are used. Choice of altitude/azimuth tracking resolved several factors:

- Because of the degree of axial rotation required, rotary joints were specified (and developed) for conveying both water and steam via each axis. This proved to be a more economical solution (and was easier to insulate effectively) than employing flexible connections.
- Dish foundations could economically and effectively be in the form simply of a pipe set in concrete in a deep hole in the ground (as indicated in Figure 17).
- Dishes could be parked conveniently to avoid the sun during the day, facilitating work and requiring no moving out of the sun during periods of being out of service.

Simple printed circuit motors are employed to drive the azimuth axis through cyclodrive gear reduction and a further roller/ring reduction, while the elevation axis is driven through a cyclodrive gearbox in turn driving a lead screw reduction. Slewing (up/down, forward/reverse) is accomplished simply by running the drive motors continuously instead of only intermittently (as in tracking).

Each collector has its own battery power supply (charged from 240V 50Hz AC from the station) which permits operation, protection and survival even if communication (or AC power) is lost from the central station — in such an event, each collector continues operation (unless it overheats its absorber when it will offsteer and stop) until the end of the day when it will hit a stop and automatically park.

4. Sun Tracking and Dish Attitude Control

A tracking control system which employs a computer to provide signals to the drive motors causing the dish(es) to move in a trajectory calculated to follow the sun

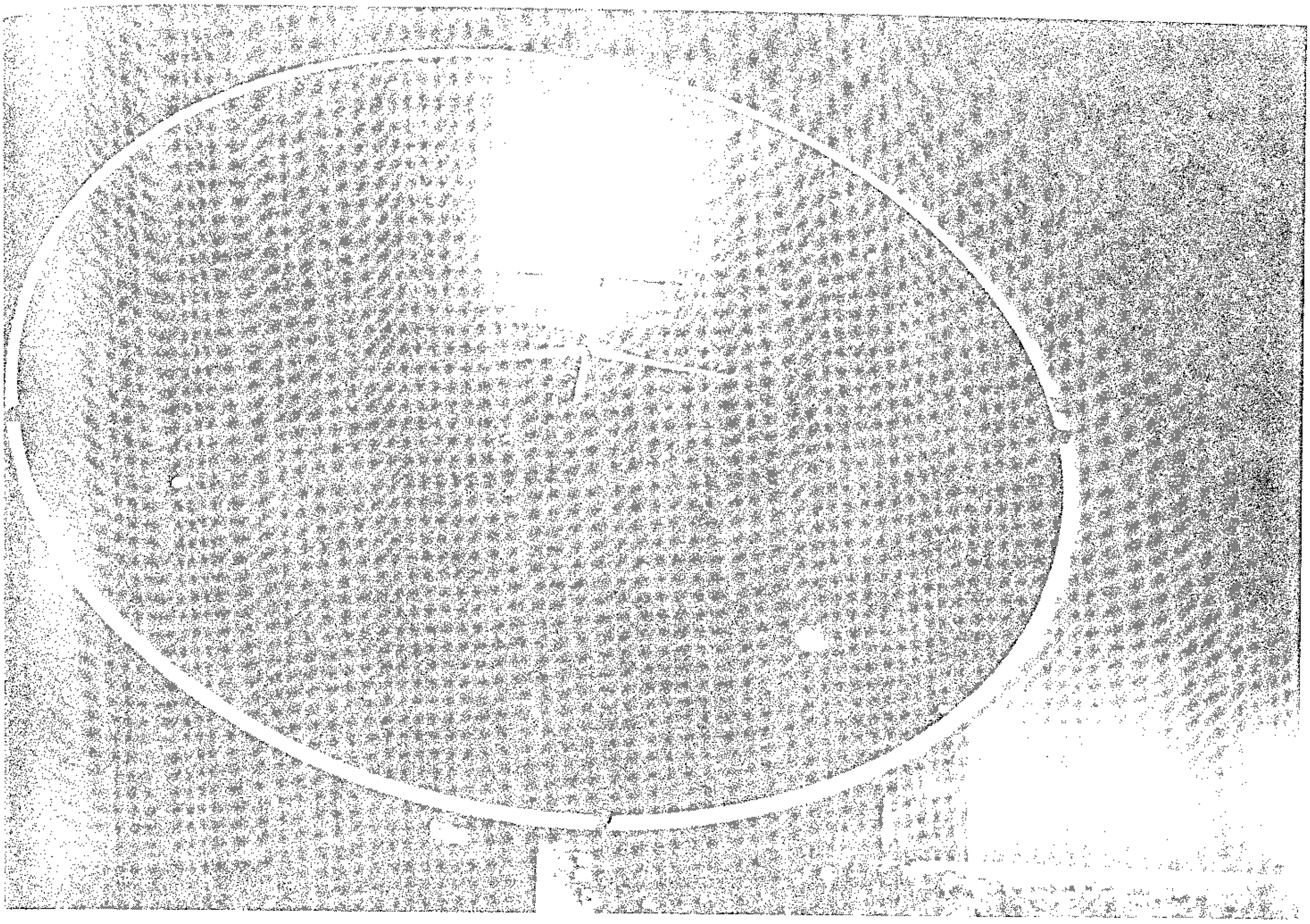


Figure 18. Measurements on dish focal region by moonshots.

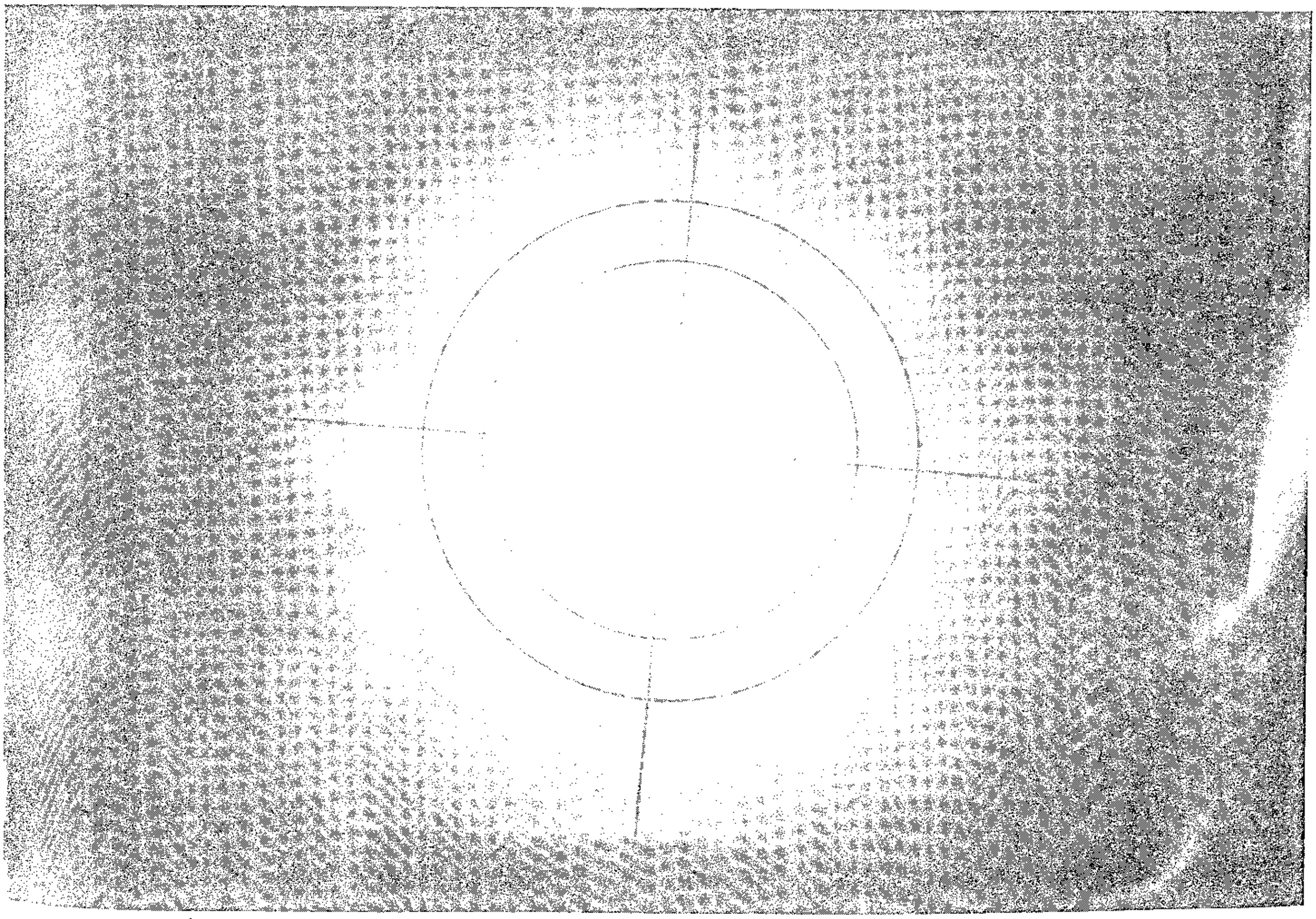


Figure 19. The focal region target - circles increasing by 50 mm radius.

continuously, supplemented by a fine acquisition control receiving signals from a sun sensor and employing these to achieve accurate pointing, has several advantages, but simplicity is not one of them.

In this control philosophy, the computer signals (one computer can be used for all the dishes) are intended to give a relatively coarse (ie not precise) pointing, whose coarseness depends on the instantaneous actual alignment between each dish's true orientation (affected by manufacturing tolerances, foundation support alignment and others) and the actual position of the sun. Any discrepancies are taken care of by the fine servo which employs signals from the sun sensor to effect accurate alignment. [Alternatively, a computer control can take account of foundation and other deflect ions and guide the dish accurately at all times.] Main advantages are that any dish or all dishes can be addressed and pointed to any required position; in addition, spurious tracking of bright parts of clouds when the sun is obscured — a characteristic of some analogue sun sensor tracking systems — is obviated by not allowing the dishes to move far from the computer-directed positions.

Nevertheless, in the interests of cost simplicity and development time, we specified sun sensor controlled analogue servo tracking (obviating the problems of dishes 'wandering' in cloudy periods to lock onto bright sections of cloud) by setting appropriate sensor thresholds and keeping the dishes moving in approximate trajectory during cloud by pulsed signals (overridden when the sun is shining) of suitable magnitude and duration — thereby producing an adequate and inexpensive system.

5. Intermittent Tracking Signals — Forced Oscillations

No structure can economically be completely rigid, but retains some resilience in one way or another. Nor are moving structures without backlash and hysteresis. When such structures are controlled by closed loop servo systems and subjected to strong buffetting winds, under certain conditions it is not difficult for mechanical oscillations to build up as a result of phase differences between sensor signals (and drive motor torque) and the responding movements of the various parts of the structure. Such oscillations may be adequate to move the absorber off focus and in any case waste driving energy.

Rather than attempt rigorously to prevent such oscillations by design of structural components — which generally means expensive structures — we hold to the philosophy that the whole dish unit (including foundations) should be designed to be sufficiently strong, but its rigidity and imperfections in backlash and hysteresis can be relaxed (within reason) thereby ensuring a more economical unit. The problems arising from these imperfections should be solved by appropriate control strategy — the extra control system cost being relatively quite trivial.

In this case it is simply necessary to allow only intermittent tracking: each axis (azimuth, altitude) has a separate sensor signal for that axis. As the error signal for an axis is reduced to zero, its respective motor drive circuit is clamped, inhibiting further drive torque, in which case no oscillation can buildup. The inhibiting signal is removed after a time, typically 10–20 seconds or so, and a further tracking correction is allowed. Due to the relatively slow motion required, in the inhibiting period the absorber does not move significantly out of the true focus position.

Indeed, even without the provision of inhibiting signals to avoid oscillation, a tracking strategy whereby the dish moves in small steps is to be eminently preferred since by running for (say) $\frac{1}{2}$ second every 20 seconds. The same drive arrangement can be used for fast slewing (at 40 times the tracking rate in this case). During 20 seconds inactivity, the angular difference between sun and absorber changes usually will be less than 0.002 radians. A similar strategy can be used for computer-controlled tracking.

6. Properties of the Dish Focal Region

Dish substrates were produced from an accurage fibreglass male mould which in turn was moulded from a female mould formed from a master male mould accurately formed on a steel base with plaster of Paris paraboloidal surface. Properties of the 14 dishes (which turned out very constant in parameters due to care in construction) were measured by moon shots taken on the night of full moon, which was tracked and the properties of the focal region mapped by moving a calibrated target above, through and below the focal plane, recording the images produced on this target by a calibrated film and camera.

Figures 18 and 19 show the dish and target, respectively, on test. Figure 20 presents some of the results from these measurements which indicate [Thomas and Whelan 1981] :

Dish Focal Measurements

99% Capture Focal Diameter	:	350–375mm
95% Aperture Concentration Ratio	:	175
Flux Concentration Ratio	:	410

Dishes were substantially similar, sufficient to allow absorber design based on these measurements to be identical for each dish, both in shape, size and position.

7. Characterisation of the Dish Focal Region

The experimental determination of flux distribution in the focal region is usually required for the design of the receiver. One approach is to perform slope error measurements with optical or contact probe methods and to obtain slope error statistics which may be used to compute focal flux distribution by numerical methods which are generally tedious. A more direct method is that suggested by the measurements indicated in par 6. above and described in Kaushika and Kaneff [1987]. In this method flux distribution is represented by the composition of two Gaussian functions. The method applied to the White Cliffs dishes gives the results shown in Figure 21, where the observed flux distribution is represented by the composition of two Gaussian distributions whose peaks coincide in the focal plane and are displaced apart on other parallel planes. An expression of the intercept factor as a function of receiver aperture size can also be obtained, as indicated in Kaushika and Kaneff [1987].

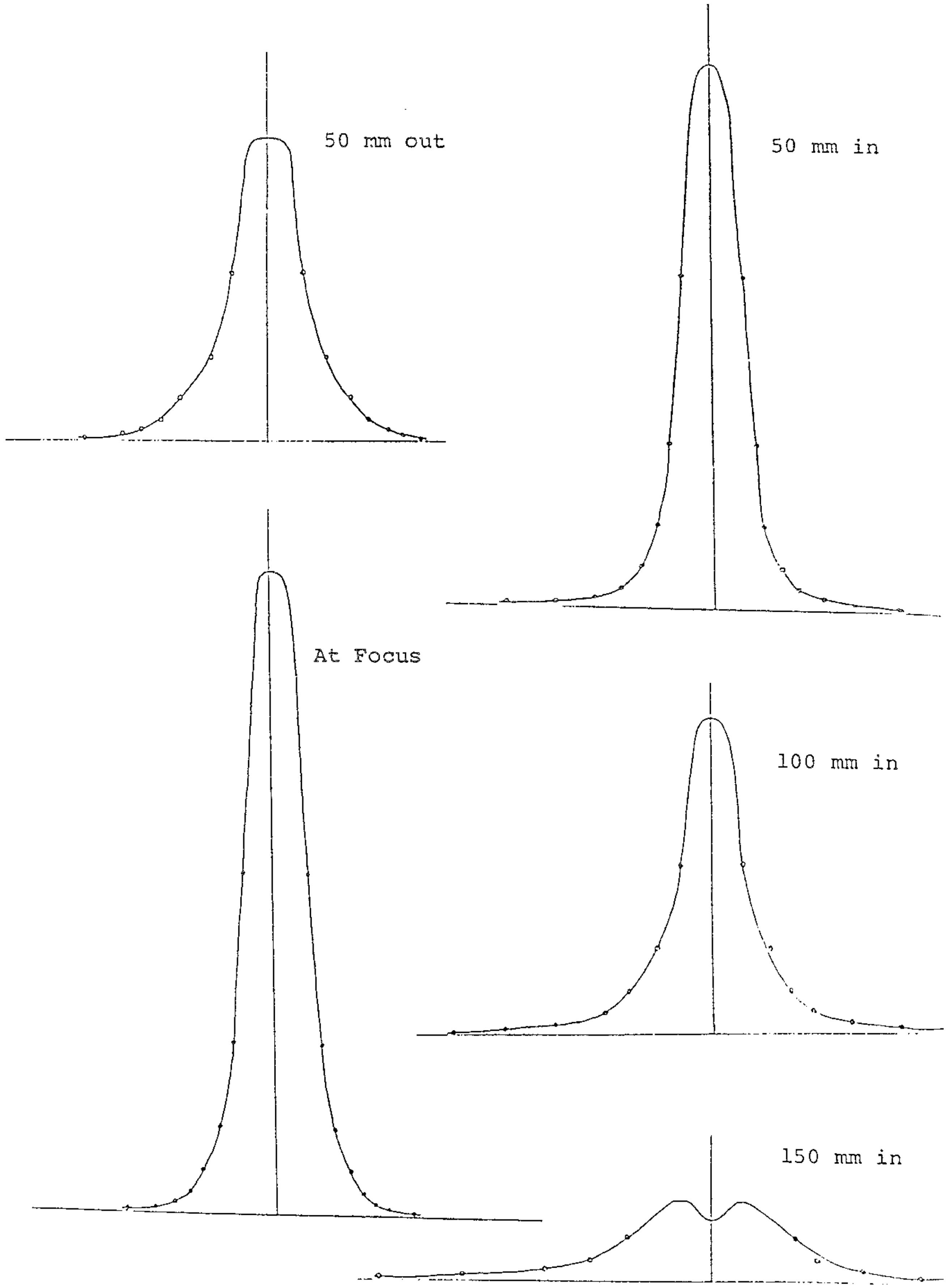


Figure 20a. Dish Focal Region Intensity Profile across Planes near Focus.

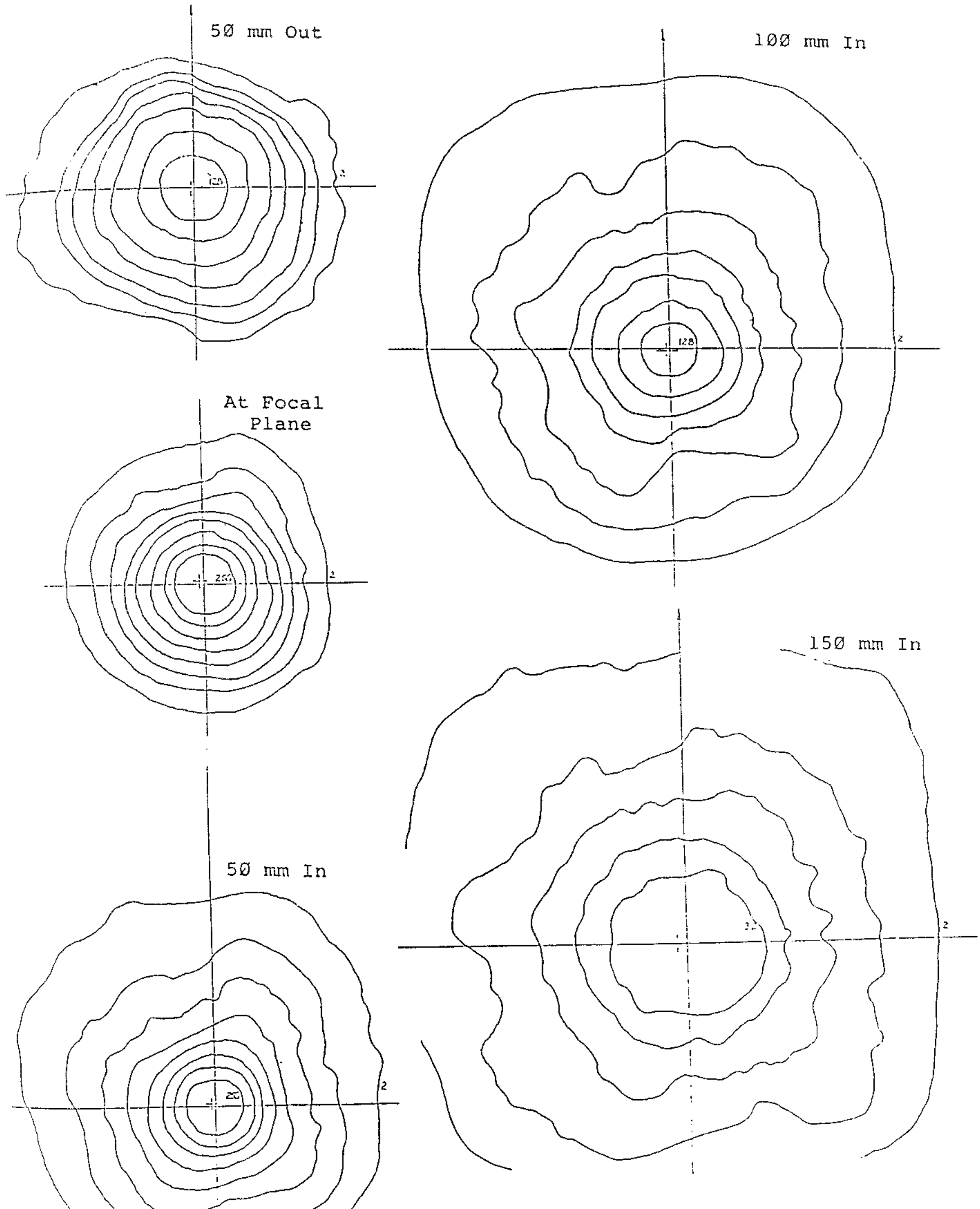


Figure 20b. Equal intensity contours on planes near focal plane.

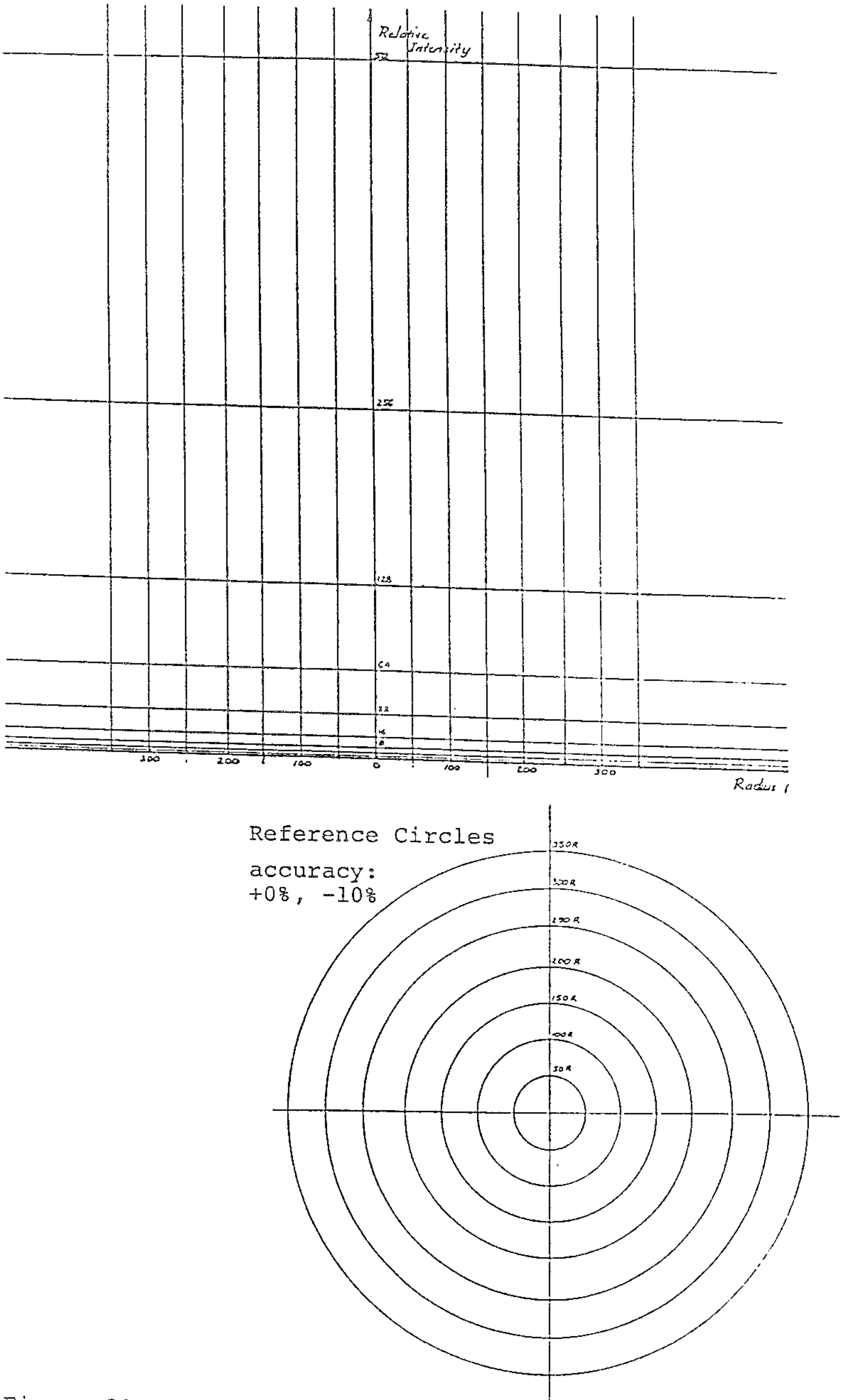


Figure 20c. Calibration Information for Figures 20(a),(b).

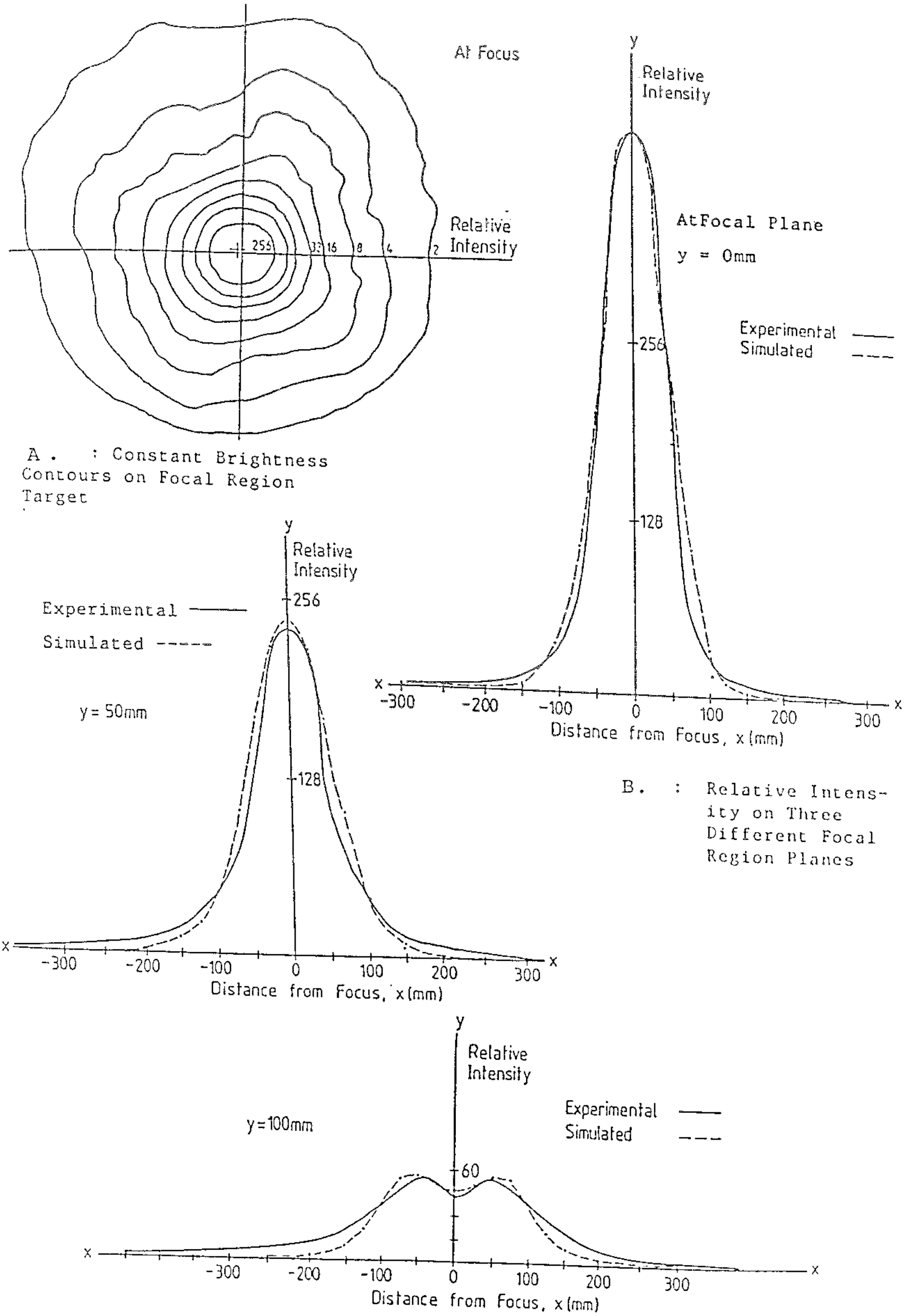


Figure 21. Representation of Focal Region Flux Distribution by the composition of two Gaussian Distributions whose peaks coincide in the focal plane and are displaced on other parallel planes.

3.1.3 Solar Absorbers (Receivers)

The principle of extracting maximum possible energy from each dish unit suggested use of a good cavity absorber which, at 500°C, could be expected to convert to heat energy in the steam, up to 96–97% of the intercepted reflected energy from the dish for favourable cavities.

But with the low cost dish design of short focal length with imperfect optics and relatively large focal 'neck' diameter, these and other factors militated against achieving such a high efficiency, not the least because of the larger aperture required and the consequent greater convection and radiation losses.

An efficiency of up to 90% was deemed more realistically attainable in the circumstances. The cost of such a relatively large and complex absorber (including mounting means) was assessed to be considerable.

1. Semi-Cavity Absorbers

   A good competitive alternative appeared to be the use of a semi-cavity absorber, simply mounted on the central focal column [Williams 1980]. Such an absorber can be made considerably smaller and formed very readily by winding a helical stainless steel tube, simply supported. Yet over 90% of the intercepted reflected energy can be absorbed and production costs (relative to a cavity absorber) would be very much less. Tests confirmed these expectations and subsequent studies [Kaneff and Kaushika 1987] have shown that semi-cavity absorbers in this application are superior to true cavity designs. Over the period 1981–1986, various designs Mark I–VIII were developed and tested [Kaneff,Inall and Whelan 1986].

   Figure 22 illustrates the cone of rays reflected from a tracking dish and its minimum 'neck' at the focal plane. This information is used to configure absorbers such that almost all, if not all, reflected rays are intercepted as shown in Figure 23.

   Figure 23 illustrates several options considered and tested, shown in comparison with a notional cavity absorber. The physically smaller sizes attainable reduce radiation and convection losses and so compensate for some convection and radiation losses inevitable from parts of the absorbers exposed to outside illumination.

   Taking into account the overall extra costs in providing good cavity absorbers and comparing with the semi-cavity designs and their lower costs, it appeared that the simpler semi-cavity designs had the advantage. This advantage may not always carry over to significantly larger, shallower dishes, but studies by Kaneff and Kaushika [1987] suggest that the principle has a wider application than for only relatively deep dishes.

   Figure 24 and Table III provide a quantitative comparison between semi-cavity Mark I–VII absorbers and cavity absorbers [Kaneff and Kaushika 1987].

   Of all the array components, the solar absorbers have received, and needed, the most attention. This area of study is expected to be ongoing for a long time to come. Much scope exists for tor new concepts to be introduced.

   Figures 12–15 portray Mark II absorbers in use; Figures 25,26,27 and 28 show respectively Mark III,IV,V and VI units. Figure 59 shows construction of absorbers.

   The parameters in Table IV are typical of those used in the above designs [Williams 1980].

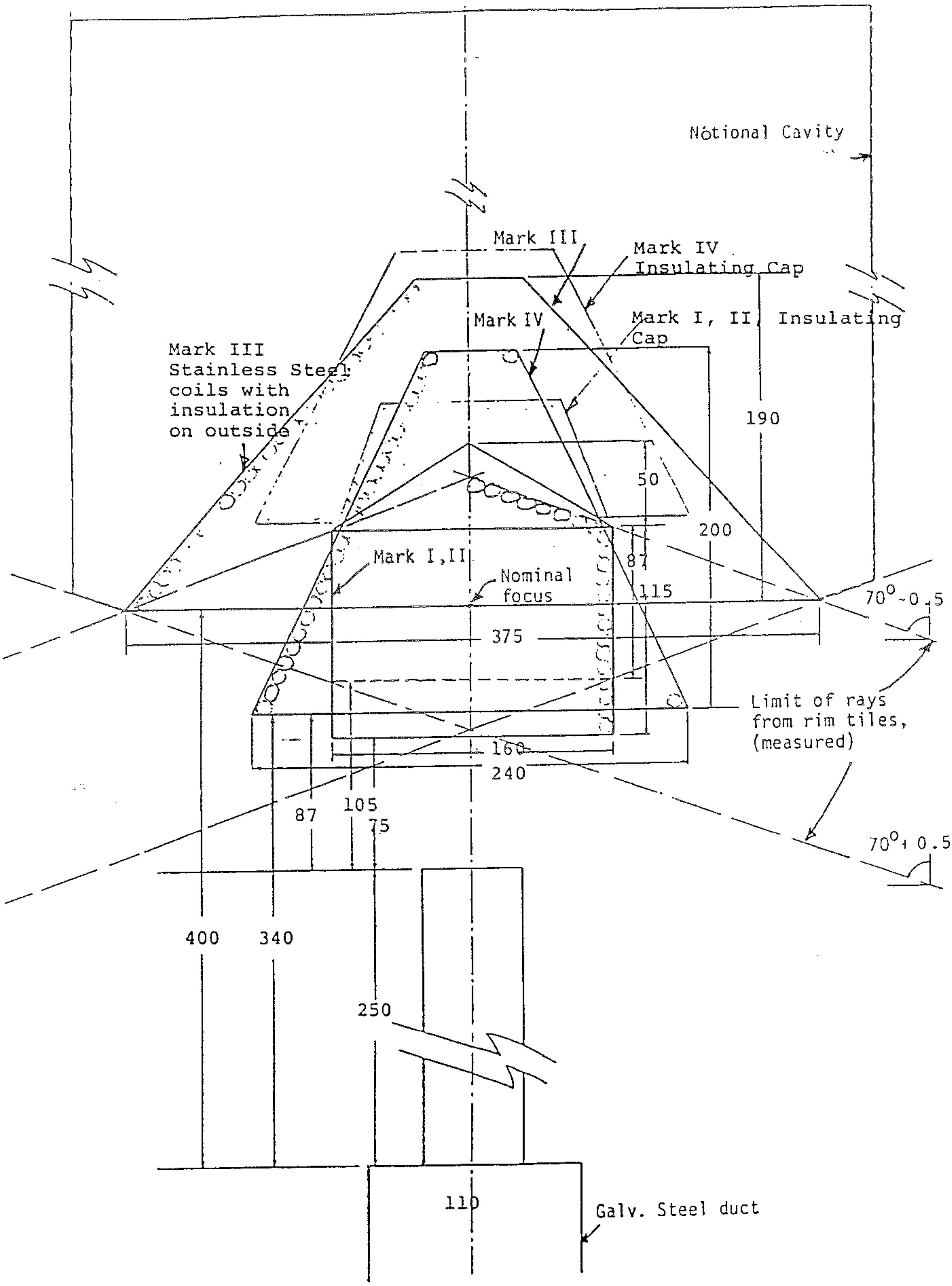


Figure 23 (a) Early absorber configurations

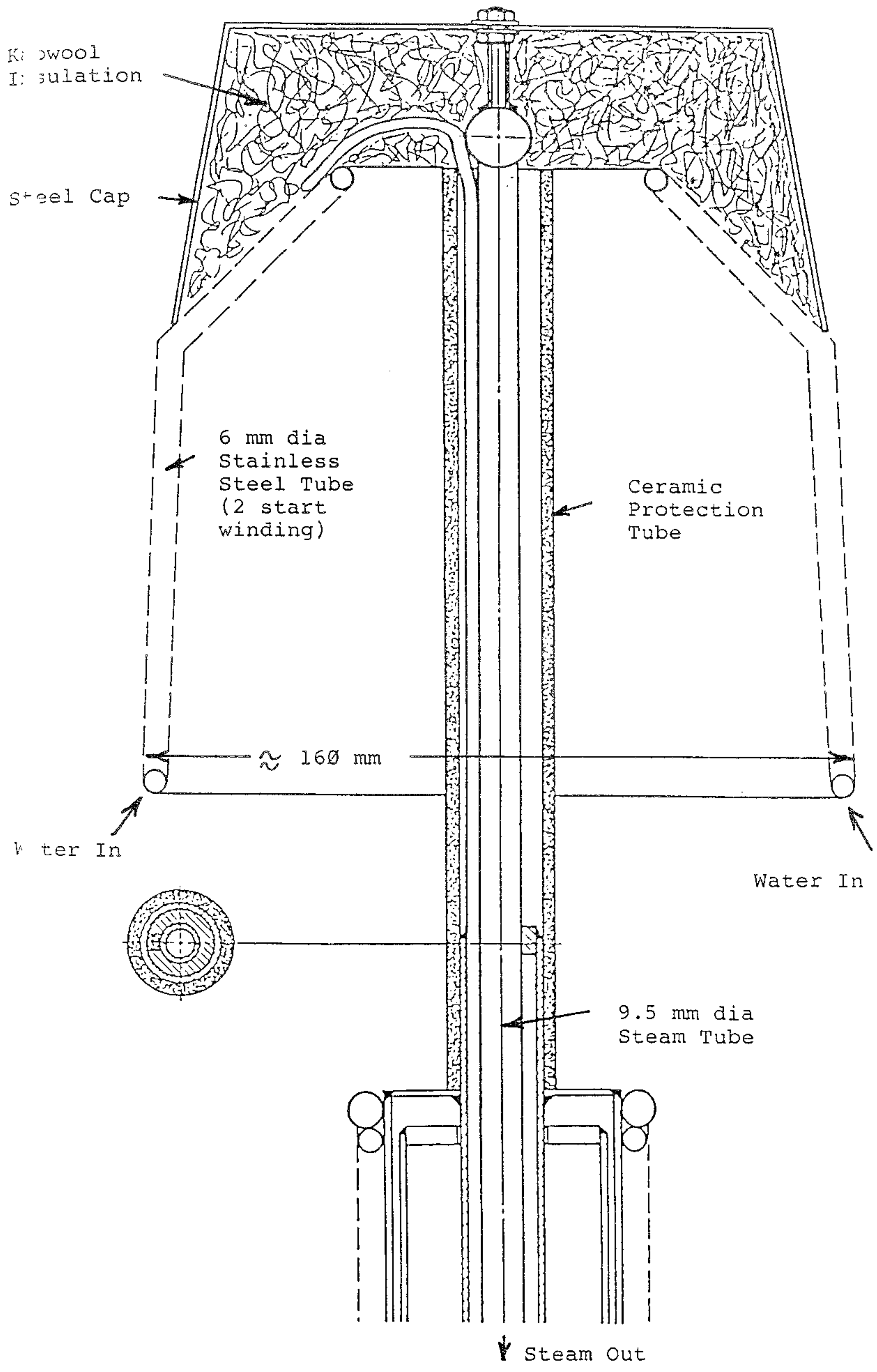
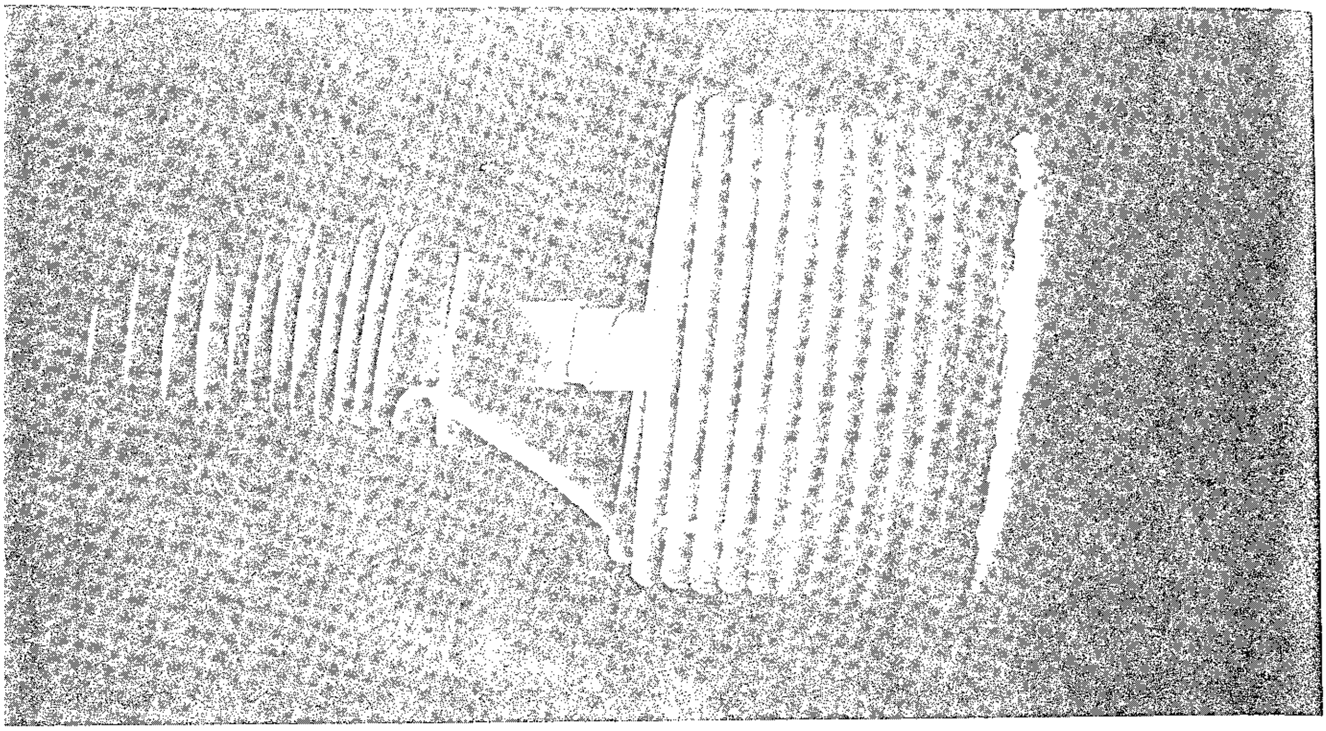


Figure 23 (b). The original Mark I absorber.



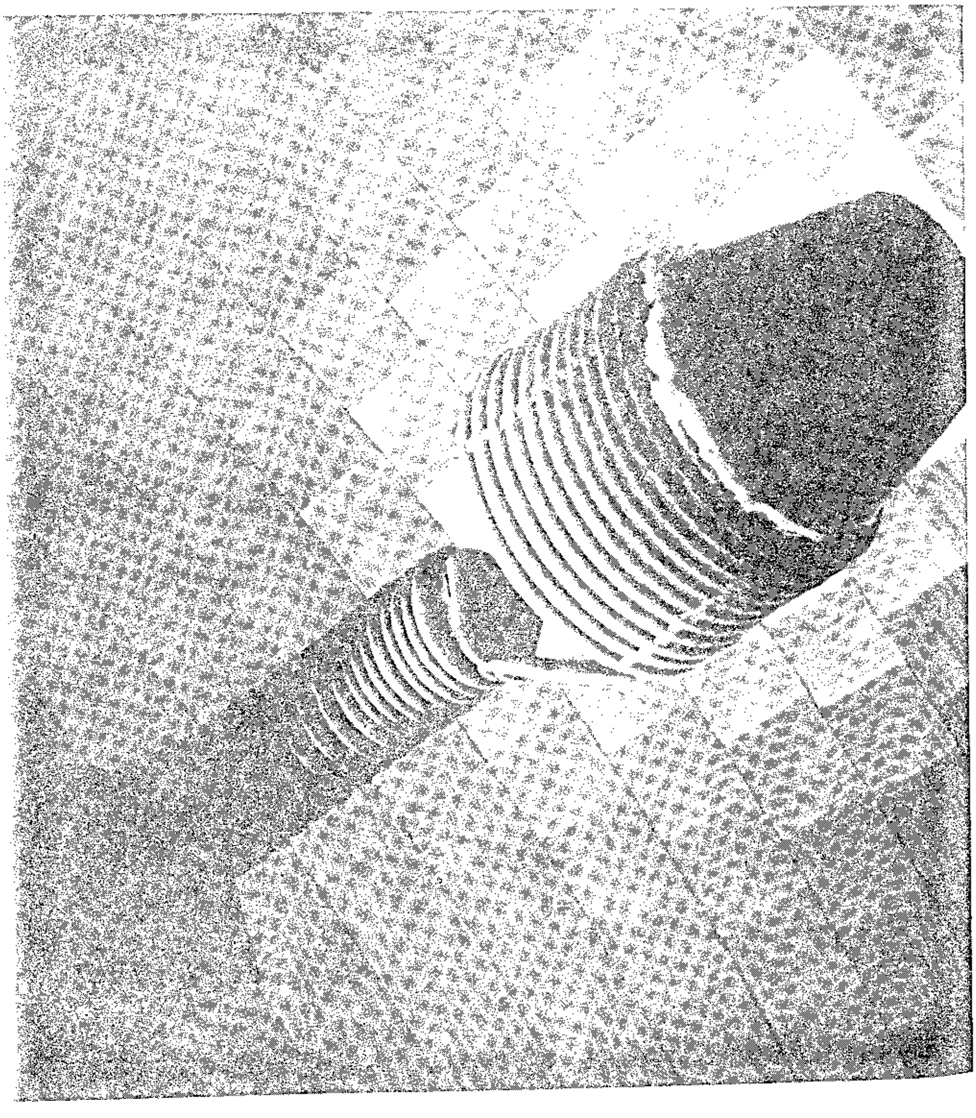


Figure 23(c) Original Mark II absorber with central steam tube

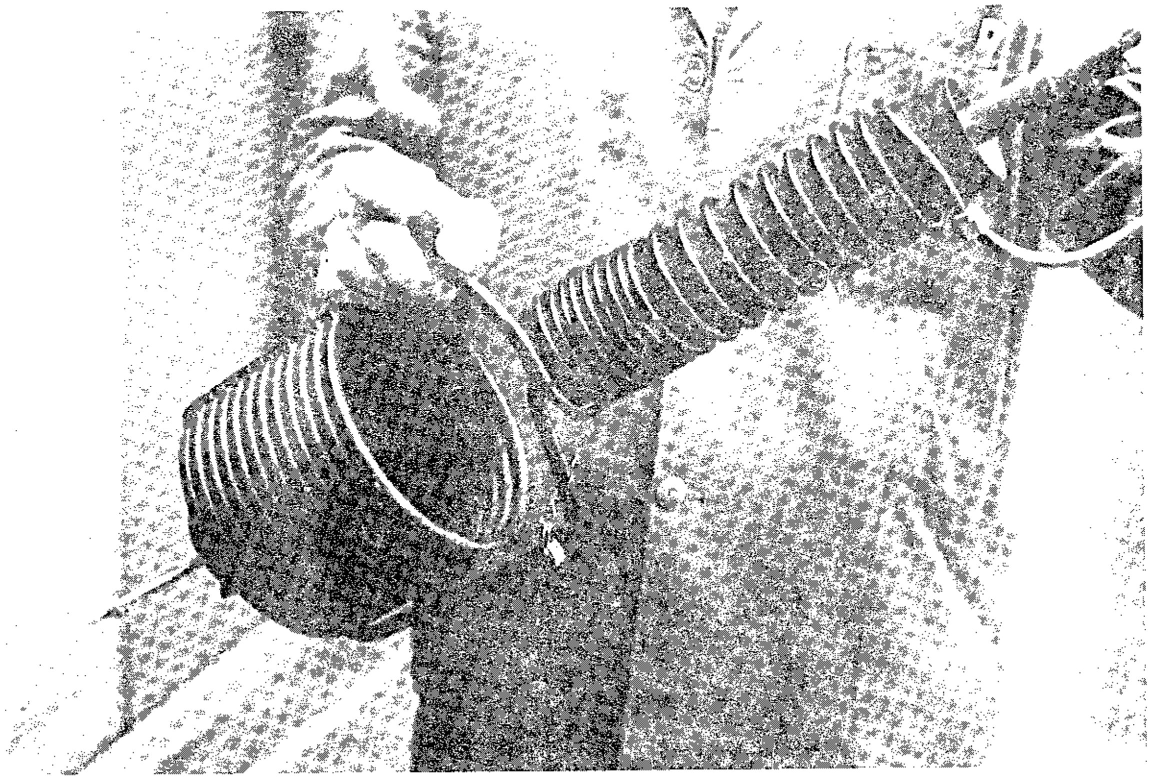


Figure 23(d) Modified Mark II absorber
(cf Figure 23(b) with single start winding and no central steam tube. This design has been used longest at White Cliffs.

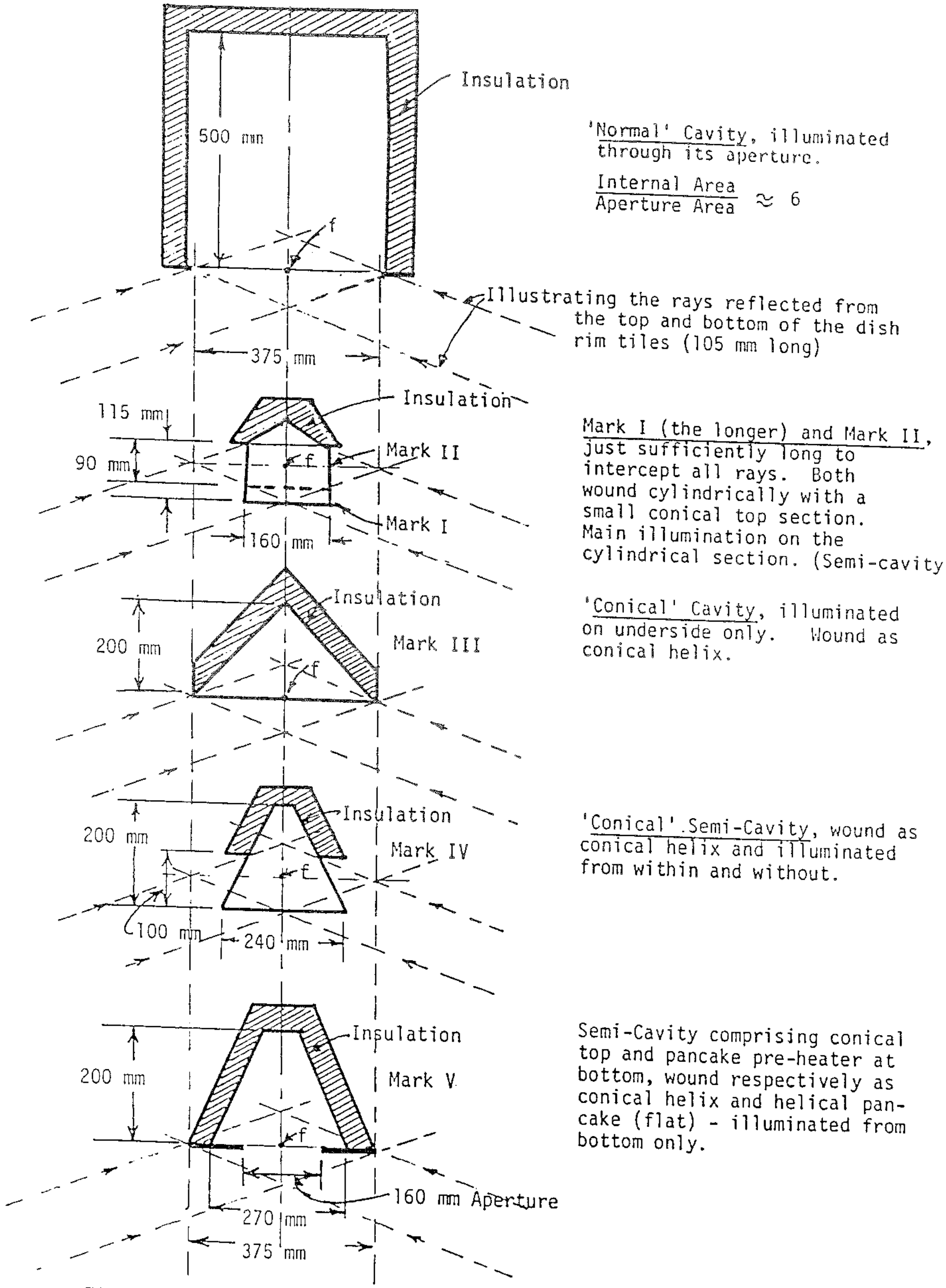


Figure 24(a) Some Alternative Absorber Configurations, dimensioned for the White Cliffs 5 m dia. 70° rim.angle dishes. See Figure 23(a) also. Coils formed from steel tubing, typically 9.5, 12 mm dia.

Efficiency of Thermal Conversion

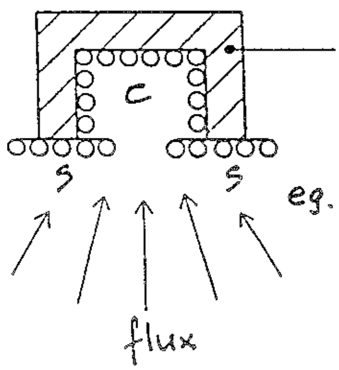
$$\eta = [\phi \alpha_{eff.} + (1-\phi)\alpha] - \frac{Q_L}{IA_p}$$

where: Q_L = Total Heat Loss of Receiver

= Total Conductive, Convective and Radiative Losses

$$= Q_{CK} + Q_{CC} + Q_{SC} + Q_{CR} + Q_{SR}$$

Q_{CK}	Q_{CC}	Q_{SC}	Q_{CR}	Q_{SR}
cavity conductive	cavity convective	surface convective	cavity radiative	surface radiative



eg. Mark VI Absorber

$$Q_{CK} = \left[\frac{1}{\frac{1}{A_0 h_1} + \frac{l}{K\sqrt{A_0 A_w}}}\right](T_1 - T_A)$$

$$Q_{CC} = A_1 h_0 [T_1 - T_A]$$

$$Q_{SC} = A_2 h_2 [T_2 - T_A]$$

$$Q_{CR} = A_1 \varepsilon_{eff.} \gamma [T_1^4 - T_{sp}^4]$$

$$Q_{SR} = A_2 \varepsilon . \gamma [T_2^4 - T_{sp}^4]$$

where: T_A = Ambient Temperature

T_{sp} = Temperature of Space

Figure 24 (b). STEADY STATE THERMAL CONVERSION

(Kaneff and Kaushika - 1987)

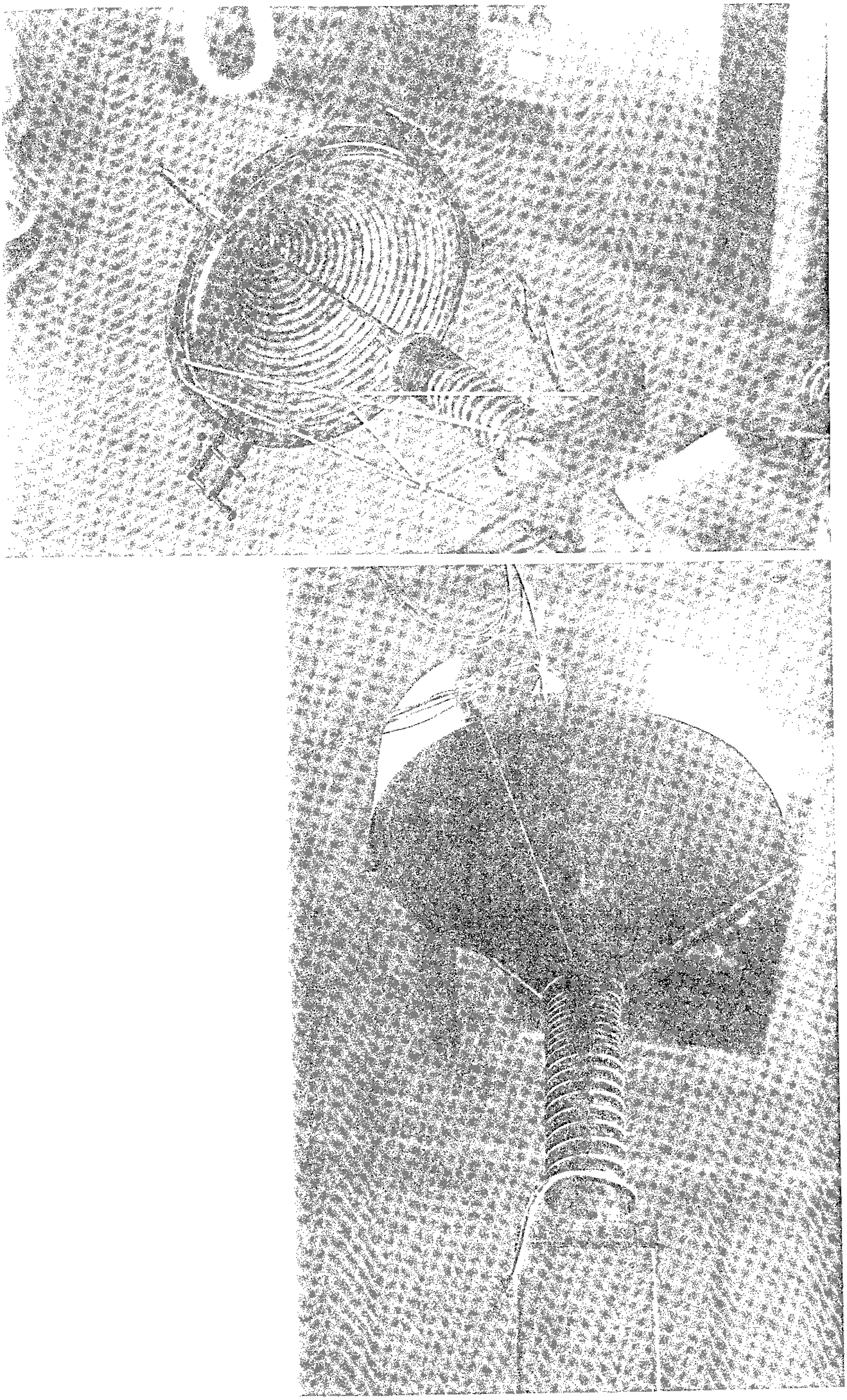


Figure 25. Mark III absorber
(Top - assembly, prior to mounting insulated cap
Lower - completed Mark III unit)

TABLE III — COMPARATIVE ABSORBER PERFORMANCE

Relevant to the White Cliffs 5m diameter 70° rim angle dishes.
See also Figures 23(a), 24(a).

Absorber Type	Absorber Efficiency (calculated)[#] $= \frac{\text{Energy Absorbed}}{\text{Energy Intercepted}}$ at Insolation of 1 000 W/m^2 and producing 500°C steam.	
	In Still Air	In Wind of 5 m/s
Normal Cavity (optimum configuration)	90.4%	87.4%
Cylindrical Semi-Cavity		
Mark I*	93.9%	92.1%
Mark II	94.2%	92.5%
Conical Cavity		
Mark III	86.7%	83.6%
Conical Semi-Cavity		
Mark IV	90.6%	87.7%
Conical plus Pancake Semi-Cavity		
Mark V	94.8%	93.1%

+ Mark number refer to the order of development of the various receivers for the White Cliffs Solar Station.

In accordance with the relations in Figure 24(b).

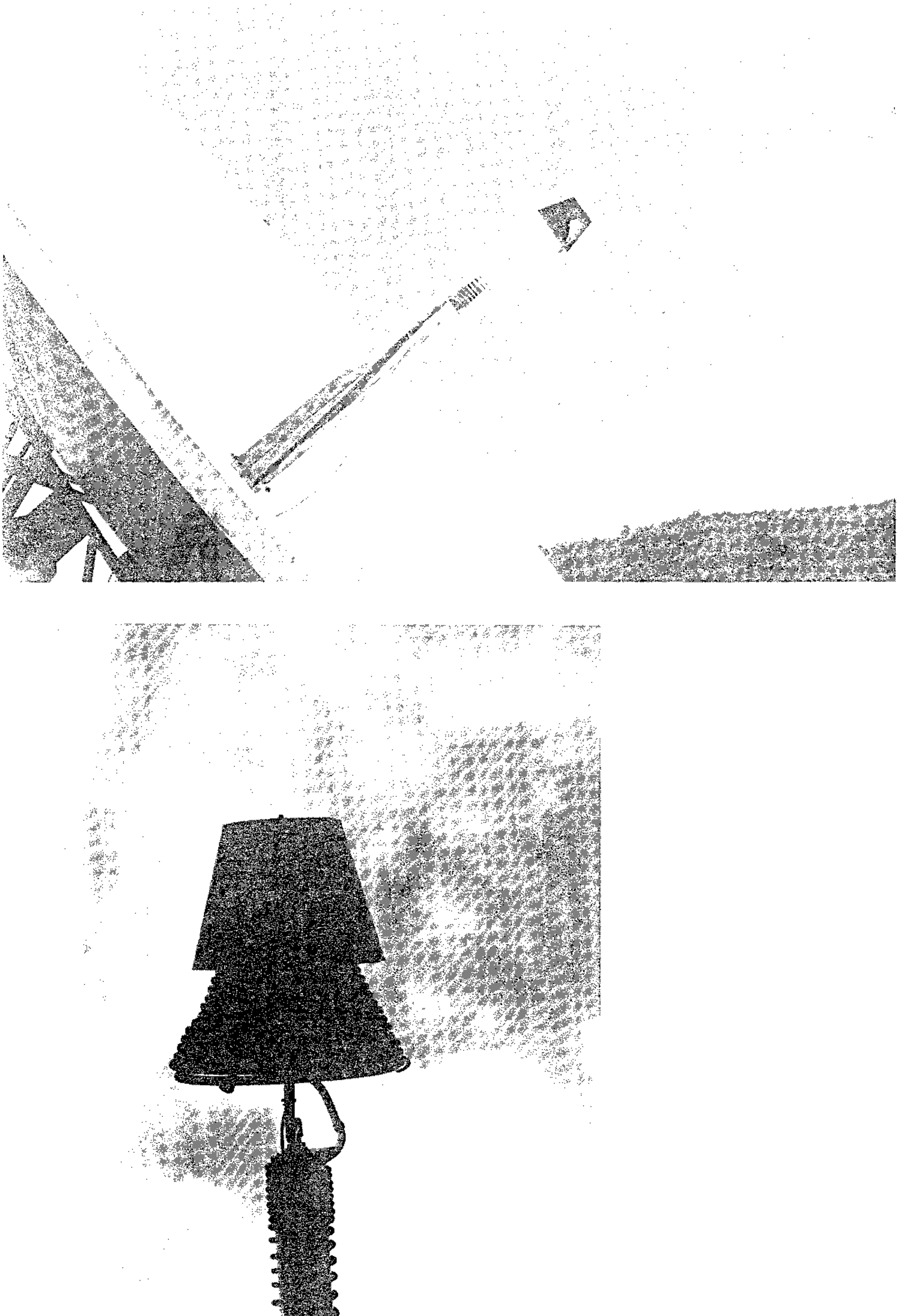


Figure 26. Conical Mark IV absorber
(Top of absorber has an insulated cap)

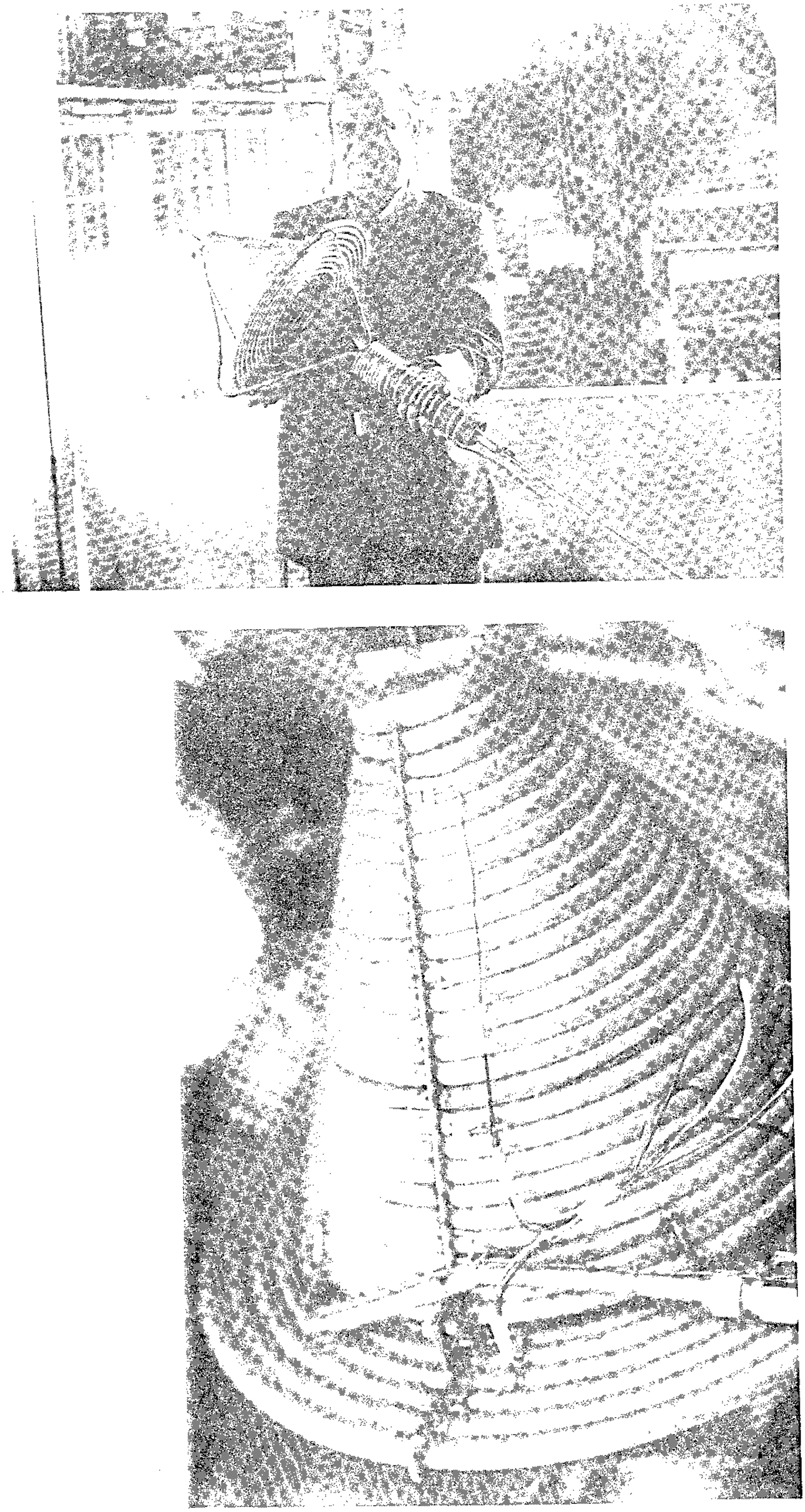
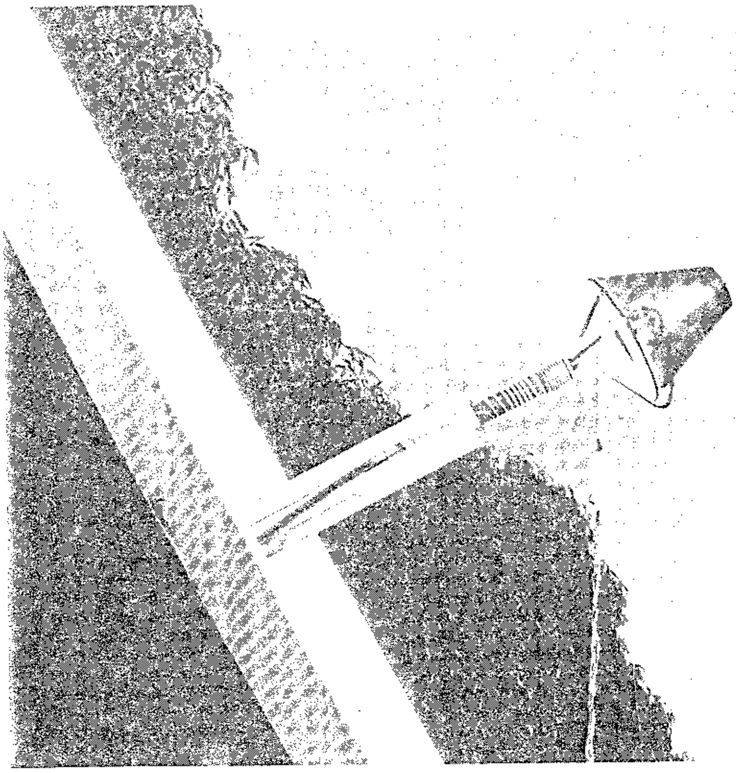


Figure 27(a) Mark V absorber without insulated cover
(Note instrumentation thermocouples)



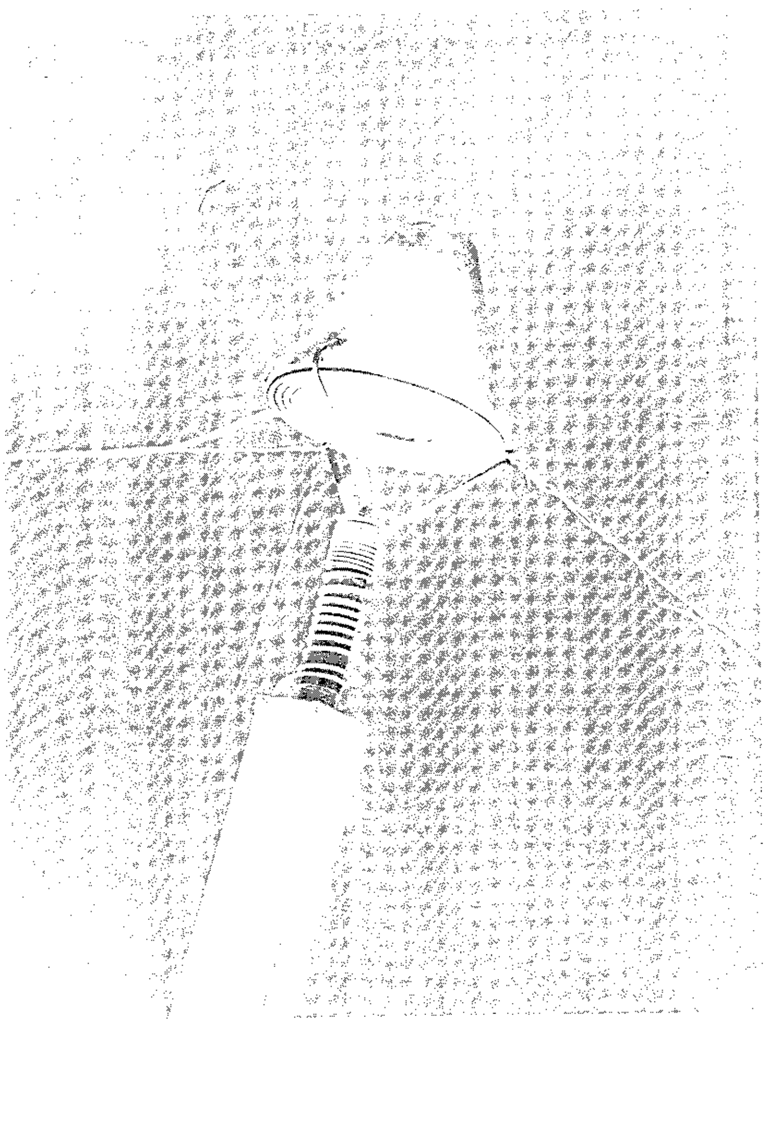


Figure 27(b) Mark V absorber under test
(Instrumentation leads may be observed)

Figure 28. Mark VI absorber, instrumented and ready for testing.
Upper - the complete unit
Lower - with insulated cover removed

TABLE IV — TYPICAL ABSORBER PARAMETERS

Absorber Material

Single tube spiral	:	0.375" dia (9.6mm) x 22 SWG 321 stainless steel
Feedwater tube	:	0.25" dia (6mm) x 22 SW 321 stainless steel
Exit steam tube	:	0375" dia (9.6mm) x 20 SWG 321 stainless steel
Absorber surface treatment	:	Pyromark 2500 paint
Intermediate insulation former	:	2" (51mm) x 16 SWG 316 stainless steel
Lower absorber support column	:	Galvanized steel
Steam tube insulation	:	Microtherm block
Absorber cap	:	stainless steel sheet
Absorber cap insulation	:	Calcium silicate

Absorber Stresses (Representative)

Absorber tube wall stress	:	280 kg/cm^2 (4 000 psi)
Steam tube wall stress	:	330 kg/cm^2 (4 800 psi)
600°C allowabel 0.2% yield stress	:	1 060 kg/cm^2 (15 300 psi)
600°C allowable creep rupture stress	:	580 kg/cm^2 (8 400 psi)
100 000 hours 650°C creep rupture street	:	470 kg/cm^2 (6 800 psi)
10 000 hours 700°C creep rupture stress	:	485 kg/cm^2 (7 000 psi)

Absorber Fluid Flow and Heat Transfer

System pressure	:	7 MPa (1 000 psi)
Absorber pressure drop	:	7kPa (1 psi)
Maximum steam exit temperature	:	550°C
Maximum wall temperature	:	600°C
Typical heat transfer coefficient	:	0.2 W cm^{-2}°K^{-1}

Dish/Absorber Inputs and Losses

Design insolation at dish	:	1 000 W/m^2
Design reflectivity	:	0.86
Fractional interception	:	0.95
Absorptivity	:	0.89
Convection loss (still air)	:	100 W
Re-radiation loss	:	200 W
Conduction loss from steam tube	:	200 W
Conduction loss from cap	:	50 W
Design output power	:	14.0 kW$_{th}$ at 1 000 W/m^2

There are several ways in which absorbers may be designed to intercept most if not all of the energy reflected from the dishes. In the present concepts, the general philosophy employed has been to allow the most concentrated energy to enter the actual cavity provided, through a hole narrower than that required for a true cavity, and to collect the remaining energy by outside illumination. Cold water is arranged to feed the externally illuminated section first, before entering the tubes of the cavity itself, in this way ensuring that only the lower temperature sections of the absorber are subjected to direct convection and radiation losses to the outside.

Depending on the configuration itself, so the absorber can be made physically larger or smaller, each arrangement carrying advantages and disadvantages; the larger units tending to have lower flux density on the water/steam carrying tubes but greater mass and potential losses than the smaller, more highly stressed units. Thus generally, the Mark I and II units are the smallest and most highly stressed, while the later configurations are larger and less stressed.

Further considerations involve the matter of flux distributions and heat flow coefficients. A practical dish does not give a uniform, or even truly symmetric illumination in the focal region, and some small areas of illumination on an absorber can have considerably higher flux densities than those of nearby regions. Such imperfections can be alleviated by lowering the average design flux density everywhere (ie effectively increasing the absorber size) and by ensuring proper mounting alignment of each absorber. Absolute size cannot be increased substantially without seriously affecting collection efficiency and increasing cost.

A further problem involves the changes of state which occur at different points in the absorber tube. Water changes to wet steam, then to dry steam, these changes being complex; their position is almost continually varying due to insolation changes, tracking movements and convection effects as well as the highly variable heat flow coefficients which depend on the nature of fluid flow and the environment within which this occurs. Bansal and Kaneff [1987] have described, and partly resolved, some of these effects which have still to be adequately formulated and analysed.

As a consequence of the abovementioned factors and of the general harsh environment in which solar absorbers are expected to work, the design of these components is not straightforward. Indeed this represents probably the most difficult area of solar thermal power design. Clearly a compromise must be struck between efficiency (losses) and size, materials, configuration, cost, operation and maintenance requirements, and lifetime, as well as the many other constraints which apply (fluid flows, pressures, temperatures for example). Generally, although simple absorbers can be made large enough to reduce adequately the flux density to tolerable levels, such units tend not to be cost effective. On the other hand, the smaller units (even using relatively exotic materials), although economical to make, tend towards lowered cost-effectiveness due to reduced lifetime and the cost of replacement at regular intervals.

Our current approach is in the direction of providing a configuration which evens out flux density and at the same time provides a heat store, thereby not only reducing peak stresses on absorber tubing, but very considerably slowing down the rate of change of flux due to insolation and other variations.

2. Absorber Performance

Table V and Figure 29 give Mark II absorber performance. The curves are typical of the class of absorbers Mark I–VIII. At any given steam temperature, efficiency is seen to drop with insolation in accordance with the fact that conduction, radiation and convection losses depend on temperature, not throughput of energy — so by

TABLE V — TEST RESULTS FROM ANU 5 METRE DISH

Location of Test: White Cliffs NSW, Collector No.1.

Date: 7 April 1982.

Description of Test:

An individual collector tracked the sun while fed with feedwater from a 3-cylinder reciprocating pump whose back pressure can be adjusted. Flow of feedwater was measured from calibrations of the pump and array system taking into account back pressure. Readings of insolation were taken from the pyrheliometer at the station. Temperature was measured at two points: the absorber coils on the side away from the sun (under the insulating top cap) and in the steam line between the two rotating joints respectively conveying steam and feedwater via the azimuth and elevation axes. J-type thermocouples, whose voltage was read by high impedence meters, were employed for temperature measurement. Enthalpy was obtained from steam tables.

Average relectivity of mirror glass was ascertained at 0.84, using a pyrheliometer measuring the direct and reflected beams. [Glass was operationally clean.]

Tests in Still Air

Time	Insolation	Input Power	Feedwater Back Pressure	Steam Pressure	Feed-water Flow	Absorb Temp	Steam Temp	Output	Efficiency	Projected Output at Insolation
pm	W/m^2	kW	psi	psi	ml/s	°C	°C	kW	%	of 1 kW/m^2
3.33	860	17.05	150	100	4.4	348	254	12.6	74	14.6
3.48	853	16.91	250	200	4.45	337	243	12.5	74	14.7
3.53	849	16.83	380	330	4.1	368	334	12.3	73	14.5
3.56	847	16.79	500	460	4.1	372	343	12.25	73	14.5
4.00	8 42	16.69	640	600	3.87	466	413	12.2	72.5	14.4
4.04	837	16.59	780	740	3.74	507	439	11.9	72	14.2
4.07	833	16.51	900	860	3.56	587	482	11.7	71	14.0

Input Power = Nett Aperture Area × Insolation = 19.82 × Insolation = 19.82 m^2.

Coldwater calorimetry gave values of 75.0% efficiency, or 14.8 kW output at an insolation level of 1 kW/m^2 and inlet water temperature of 22°C.

The values in the last column in the table are projected for an insolation level of 1 kW/m^2 on the reasonable assumption that the efficiency will not drop (in fact it will increase) in moving to this output.

maintaining a particular temperature of steam, as the energy absorbed depends on insolation, the lower the insolation, the lower the efficiency. Comprehensive performance for the various absorber designs is given in Kaneff, Inall and Whelan [1986] and Kaneff and Kaushika [1987].

Convection losses due to wind can be significant as indicated in Figure 24 and Table III.

Comments on Table V

The series of tests carried out in the field (of which Table V is an example) point to the difficulties faced in attempting to gain reliable operational information about system parameters in normal operation. On this occasion in mid-autumn, it was past mid-afternoon (as the day had intermittent cloud until 3.00 pm). Accordingly, insolation was changing significantly and the system did not have the opportunity to stabilize adequately between readings (every 3–5 minutes). Moreover, because of lack of convenient access in the absorber/duct combination, steam temperature was measured at a point between the two rotary joints (see Figure 31). some distance from the absorber itself. However, the known rotary joint heat transfer from steam to feedwater inlet, together with duct and other losses, enable quantities to be derived for other parts of the absorber/duct system satisfactorily.

Figure 29 gives absorber efficiency versus exit steam temperature as functions of the insolation under much more stabilized conditions; the efficiencies for the Mark II absorbers recorded therein relate added energy to the emerging steam from the absorber outlet to added heat which is intercepted by the dish —that is account is taken of mirror reflectivity, energy intercepted by absorber, energy converted into fluid heat energy, and conduction, convection and radiation losses from the absorber. The figures of Table V appear to be superior in performance to those in Figure 29, but when account is taken of heat losses in the absorber duct (0.05 kW) and in the heat transfer across the two rotary joints — this heat subtracts from the steam output but adds on to the absorber feedwater input (as studied in more detail with respect to Table X and Sections 5.5.1 and 5.5.5) — a reasonable agreement is apparent. In the measurement configuration employed, the heat transfer across the second rotary joint gives an apparent increased output by some 0.35 kW. Consequently, the outputs from Table V, when corrected for the effect, are as follows (with corresponding modified efficiencies):

Time	Insolation W/m^2	Absorber Temperature °C	Steam Temperature between Rotary Joints °C	Output kW	Efficiency %
3.33	860	348	254	12.3	72
3.48	853	337	243	12.2	72
3.53	849	368	334	12.0	71
3.56	847	372	343	11.95	71
4.00	842	466	413	11.9	71
4.04	837	507	439	11.6	70
4.07	833	587	482	11.4	69

It is worth noting that the losses in Table X designated "losses in absorber convection to duct" were not significant in the above measurements because the absorbers were connected to their ducts as illustrated in Figure 31; that is, the connecting steamline was centrally located and collected (rather than lost) energy.

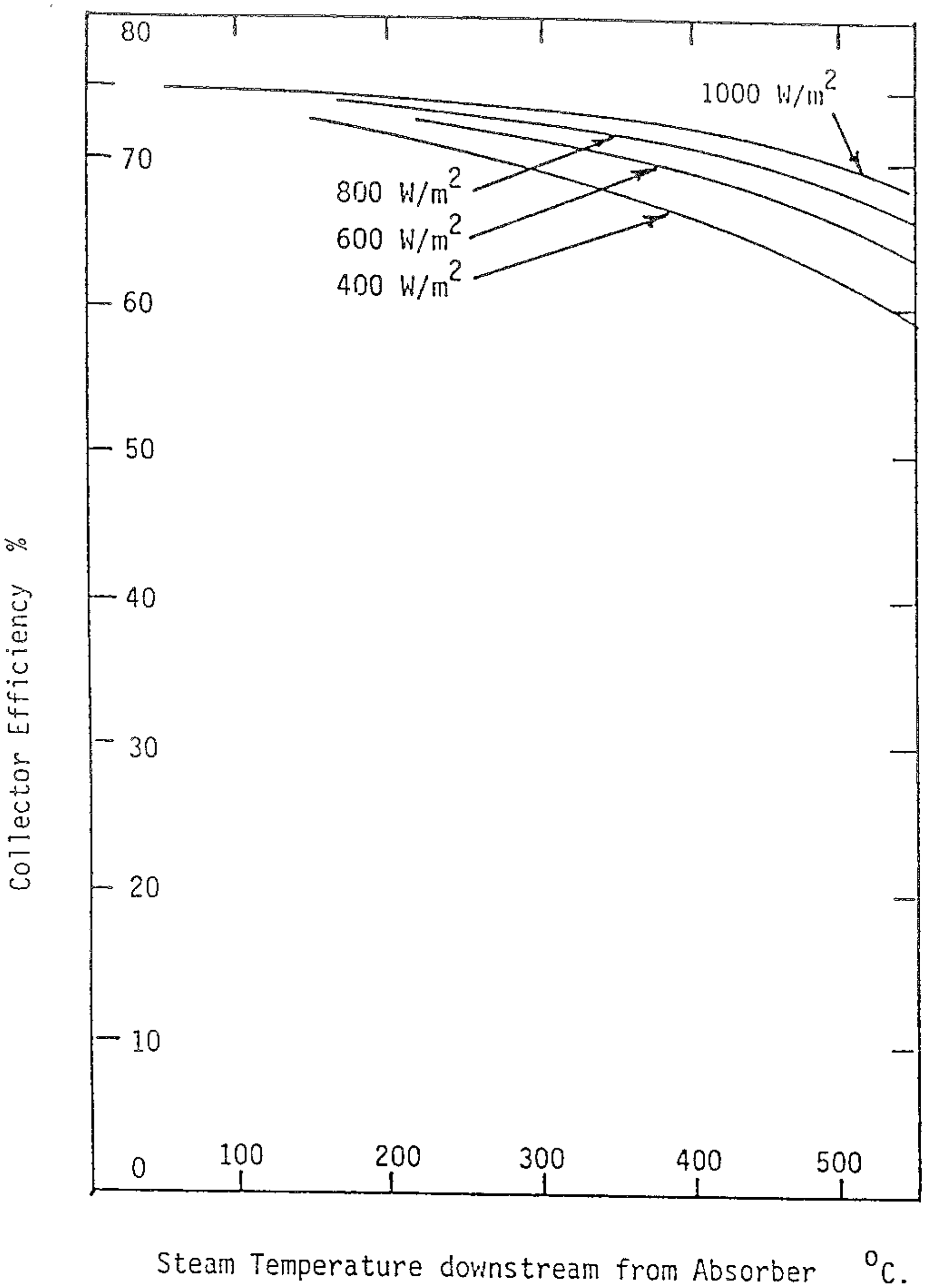


Figure 29(a) White Cliffs 5m diameter collectors: Overall collection efficiency (including dial reflectivity at Mark II absorbers) versus steam temperature at different insolation levels in still air.

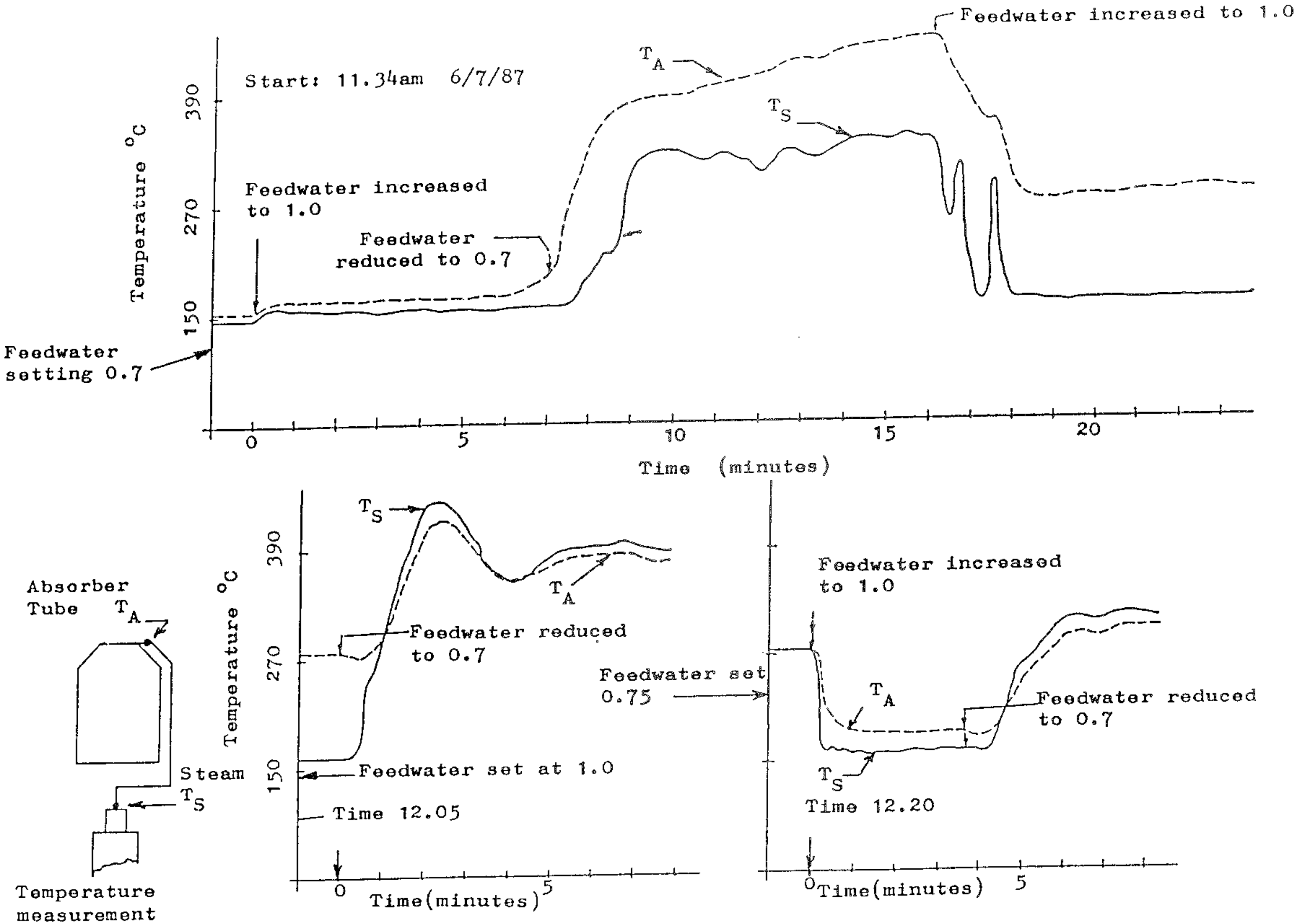


Figure 29(b) - Transient response of Mark II Absorbers to change in Feedwater Flow.

Generally, the efficiency of the Mark I and II absorbers is higher than or not less than that of the other configurations; manufacturing and installation cost is least. The Mark III unit has proved the longest-lived absorber, but the least efficient; its manufacturing and installation costs have been intermediate between the Mark I, II and the Mark V and VI. When run continually to produce steam at 450°C–500°C, Mark I and II absorbers do not last more than one year. Reducing operating steam temperatures reduces heat quality but increases lifespan to a degree depending on temperature. Mark III absorbers producing steam at 400°C, last over two years.

We have found it practicable and reasonably efficient to run the Mark II absorbers of the array at about 350°C as a means for extending life and reducing heat losses in the system even though the reduced heat quality results in somewhat less output; the increase in component lifetime (and consequent reduced costs) tends to even out the loss in output.

Eventually, the traumatic temperature and mechanical stress cycling of the absorber tubes results in failure, usually by a split in the tube in the region where the water changes to wet steam — a region where heat flow coefficients vary to a major degree depending on the fluid state. System pressure plays a strong part in the process by providing superimposed mechanical stress, but the main cause seems to be the continual heating and quenching of the absorber tubes in this region whose position changes often within a range of two to three turns of the tubular winding. If an unusually high flux density area happens to coincide with this region as a result of absorber misalignment, then failure is more rapid. We also have reason to suspect manufacturing imperfections in the seamless stainless steel tubes as a possible additional factor in failure.

Tube Coatings

As a means of improving absorptivity of the tubes making up each absorber, we have used Pyromark 2500 high temperature black paint (said to be workable up to 2500°F). Our experience has been that such coatings last in good condition only a few months. Indeed, after an absorber has overheated (beyond 500°C due to feed-water loss or reduction), the Pyromark paint seems to flake and turn grey rather than black and thereafter absorptivity appears to deteriorate. As a consequence, we have sometimes not used this treatment and have found that the stainless steel tubes soon darken in colour from their matt silvery appearance, and seem to have a not inferior absorptivity to the treated tubes after being in service for several weeks. Interestingly, we have no evidence to believe that normal operational over-heating (due to the loss of, or inadequate, feedwater) — which is protected by a thermocouple signal causing a dish offsteer — causes absorber failure even after a large number of such overheat cycles. On the other hand, on one occasion when an operator succeeded in causing the array to track on manual control with the flow protection circuit deactivated, causing several absorbers to become red hot, then turning on the feedwater pump in a misjudged effort to correct the mistake, several absorbers failed almost immediately. [Not all absorbers had heated up since acquiring the sun occurs individually for each dish at somewhat different rates; had no feedwater flow been established, the absorbers would have cooled down probably without damage.]

Generally, although some eight different absorber configuations have been tested, we still employ the Mark II version which is simple, efficient and cost effective overall so long as units are properly aligned with the dish focal region. We expect to change this configuration when our new Mark VIII and Mark IX units have been checked out thoroughly. Because of the small dish sizes (5 meters in diameter), it is not cost effective to attempt too high a degree of sophistication in absorber hardware — a sophistication which appears well warranted for larger dishes however.

3. Feedwater Supply and Control

As is evident in Figure 2, the 14 parallel-fed absorbers need to receive equal rates of feedwater flow to produce steam of uniform quality. Without such flow equalization it is impracticable to transmit steam of adequate and controlled quality to the engine room.

In the interests of simplicity this flow equalization is provided by capilliary tubes in series with each absorber. By providing a pressure drop across each capilliary (typically 1.7 Mpa, ie 17 kg/cm or 250 psi at rated water flow/absorber of 3.6 ml/s) that is very much larger than any pressure drops in the absorber itself, reasonable flow equalization is attained. This equality is disrupted if oil or otther impurities enter the capilliaries — also if the rotary joints which convey both water and steam via the two moving axes leak between the water and steam paths.

Feedwater pump rated back pressure was chosen as 8.7 MPa; steam and water pressure relief valves were set at 9 MPa.

With engine exhaust steam temperature of 70°C (corresponding to a vacuum pressure of −85 kPa) feedwater tank temperature of around 55°C results when cooling water temperature is some 30°C. Feedwater purity is maintained by 5 micron filters, skimming surface oil and subsequently centrifuging, plus removal of emulsified oil to such a degree as to produce visually crystal clear water.

Feedwater flow is maintained by a continuously variable flow rate pump, controlled by thyristor drive to produce steam of required quality. Signals from an optimizing unit which takes account of insolation, absorber characteristics, array heat-transmission losses, engine characteristics and cooling water temperature, are to be provided as an update feature.

Separate flow controls for each absorber are desirable in the light of experience, all factors considered, in order to be able to provide effective system optimization; an ongoing study is directed to this end with the objective of realising an economical approach. Nevertheless, system operation is not unreasonable without such further refinement; again, the considerations are basically a matter of cost-effectiveness — refined controls are more affordable for large dishes. In the present case the extra flow control feature can be justified on the grounds of proving a concept which becomes more cost effective on larger units.

4. Research and Development Directions

The White Cliffs project has provided what is probably the longest continuous experience of paraboloidal dish receivers supplying superheated steam of any similar programme; the objective of cost-effective components has led us to employing wound tubes for forming receivers to generate steam, as this requires relatively simple workshop techniques and permits easy installation, as well as providing units of good efficiency. The concept of semi-cavity receivers has much to contribute in this area.

With a fair experience and knowledge regarding this class of receiver, we are currently developing in two directions:

(a) Wound Tubular Receivers With Storage and Longer Life — Mark IX

By retaining the simplicity of wound tubular absorbers but adding a heat flow equalisation component, at the same time providing a greater heat storage capacity, stresses can be reduced both in magnitude/frequency and speed of variation. This can be achieved by inserting a highly conducting barrier between the direct insolation and the absorber tubes, which are firmly attached to this conducting member by "sweating" or by similar techniques. This is illustrated in Figure 30, with four variants on the basic design which incorporates, because of the extra mass of metal, a heat capacity preventing rapid temperature changes. This family of shapes forms the basis of further development which has initially avoided the addition of a conducting barrier, in favour of a better ability to determine solar flux density on all parts of the absorbers and to design accordingly (See Kaneff, Report on the Third Generation Dish/Engine Project", EP-RR-55, August 1990). The barrier may still be introduced with advantage. No absorber tubes are subjected to direct insolation in this approach. This program of research will provide the next generation absorbers. Table VI gives the calculated conversion efficiencies for these units.

(b) Direct Absorption Receivers (DAR) — Mark X

As a complete contrast to the approach in (a) above, the direct absorption receiver allows the insolation to impinge directly on the fluid to be heated, through a low absorption (eg quartz) window. While this is a relatively long-term program — the problems of appropriate pressure vessels, highly transparent windows, and reasonable cost being paramount — potential rewards are extensive since this kind of absorber will enable advantage to be taken of not only heating effects on the fluid (or particles to be illuminated and heated), but photon effects can play a role in certain reactions where heat alone is not sufficient or where photon effects may even be all important — as in various chemical reactions.

Such approaches are very much in their infancy and will receive a great deal of attention in the coming years.

Because of the complexity involved in achieving effective design of high temperature solar receivers, it is expected that research and development in this area will be ongoing for many years. Optimum design becomes essential as size of units increases. While White Cliffs absorbers handle some 20 kW thermal energy, our new generation absorbers are being developed for 300 kW thermal

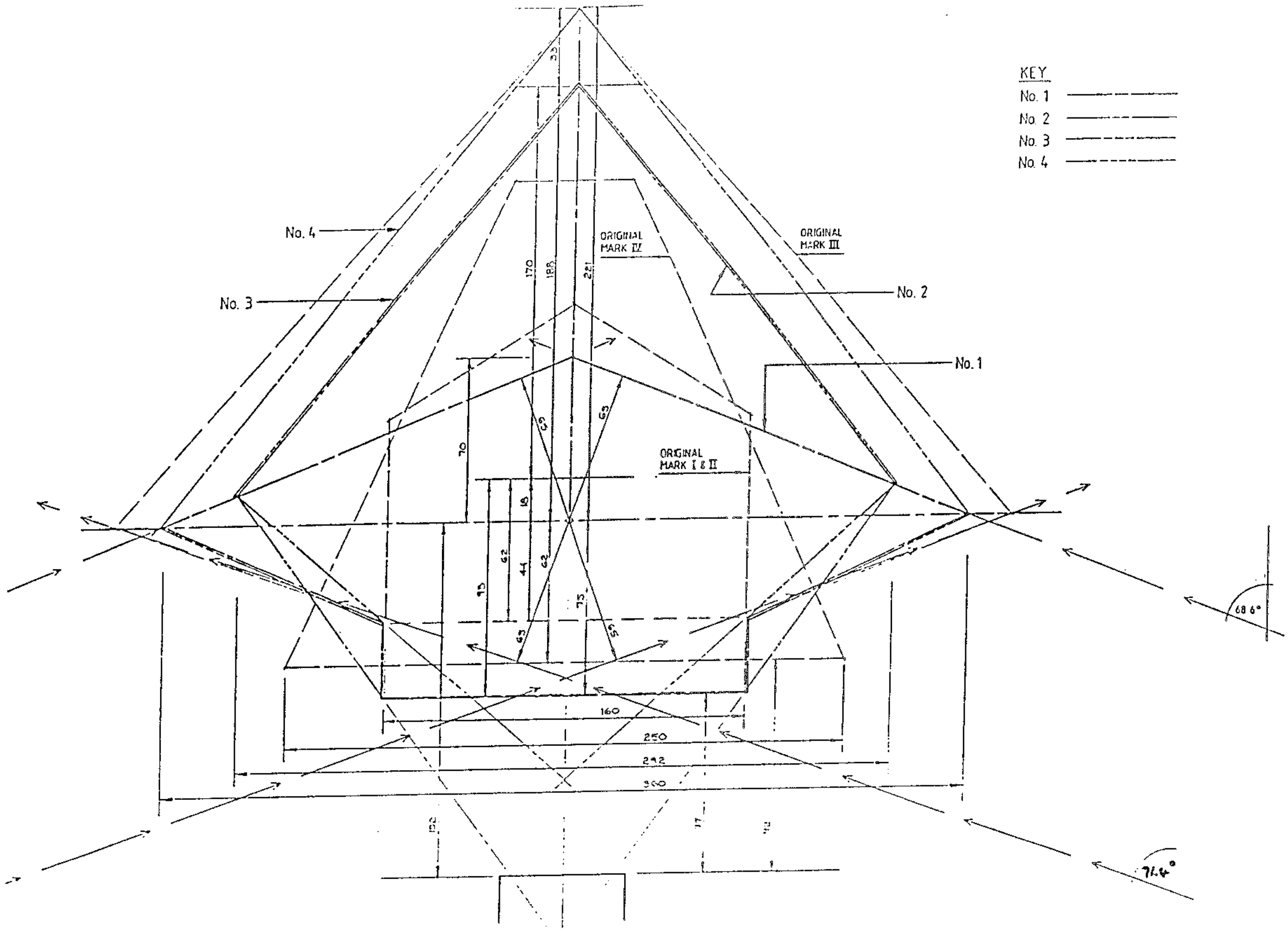


Figure 30(a). Mark IX Absorbers, Versions 1-4.

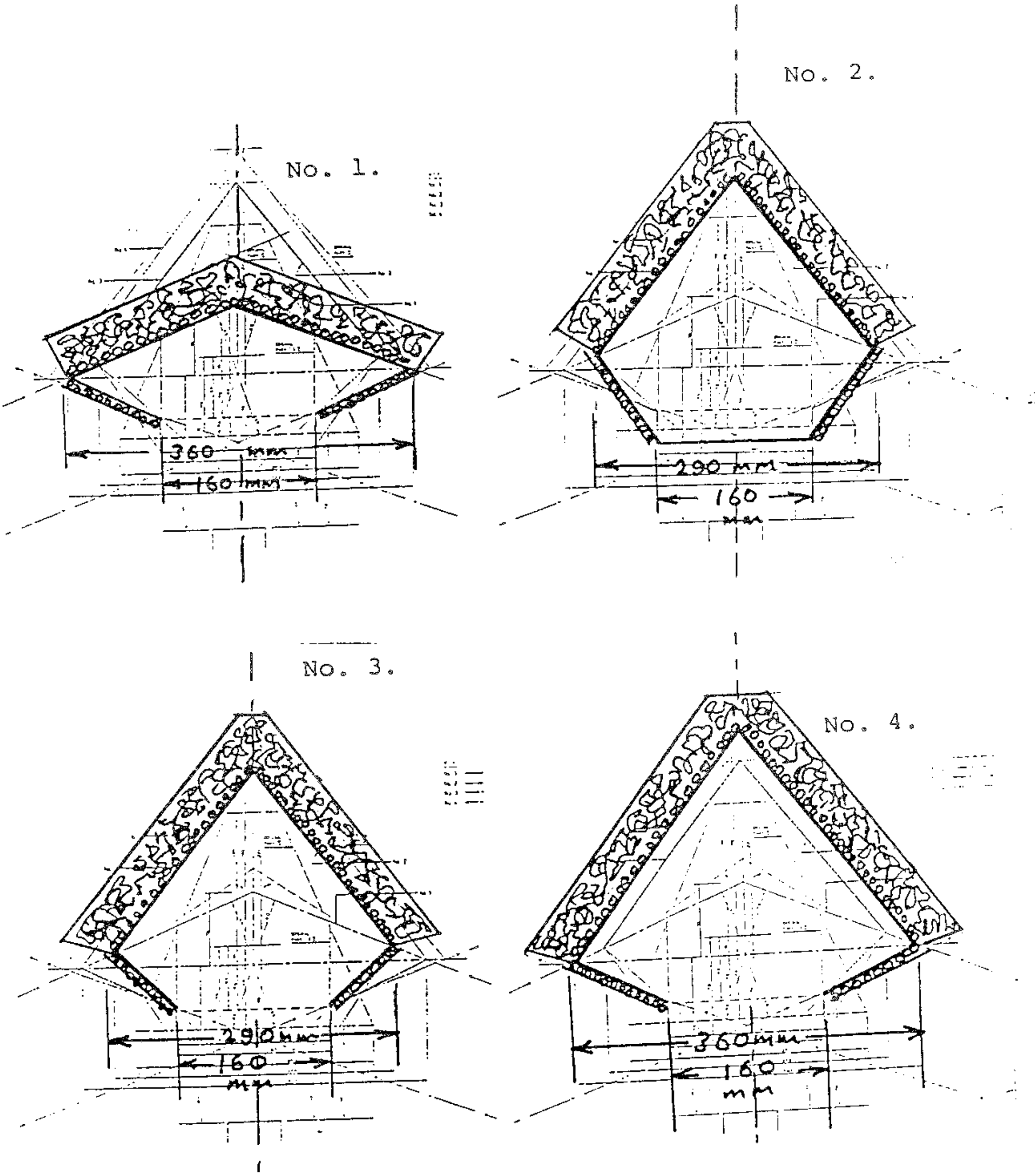


Figure 30(b). Cross sections of Mark IX Semi-Cavity absorbers versions 1 - 4.

The absorber windings receive no direct solar illumination because of metal shields which distribute the incident flux and provide a heat storage, so reducing transient stresses. The hotter absorber regions are insulated.

TABLE VI — CALCULATED EFFICIENCIES FOR MARK IX ABSORBERS (VERSIONS 1–4). See Figure 30.

Absorber Design (see Figure 30)	Absorption Efficiency Not Including Dish Reflectivity	
	In Still Air %	In Wind %
No 1	91.7	86.4
No 2	89.2	83.9
No 3	92.0	87.5
No 4	91.7	86.3

and in due course we expect to move to more than 1 MW thermal units as a result of our research programs.

3.1.4 Coping with 2–Axis Tracking

Dishes move on a vertical (azimuth) axis and horizontal (altitude) axis in following the sun, necessitating means being available to connect control and power cables from the central plant to appropriate points on the moving members and to allow high pressure feedwater and high pressure high temperature steam respectively to enter and be collected from the absorbers.

To permit a simple arrangement of cabling, a vertical pipe out of the ground carries all wires and cables to the moving members via a strategically suspended loop which is effective over the full 330° movement of the dish on a vertical axis. To simplify motor power supply connections, the battery-charger/storage battery is carried on an arm fixed to the moving vertical axis, thereby obviating the need for hanging these cables.

Figure 17 shows the dish configuration.

Conveying water and steam via the moving axes presents a more difficult problem: we were not able to find manufacturers with reliable flexible tubes to handle the design pressures and temperatures simultaneously (ie7–9 MPa and 500°C operating conditions). Morever, it is not easy to insulate such flexible tubes which in any event are expensive items. We obtained a design for a suitable rotary joint from a chemical process engineering organisation which was, however, too expensive to manufacture.

1. Rotary Joints

   Eventually it was decided to carry out our own design and construction of rotary joints, each of which conveys both cold water and hot steam in the one unit (two such units are needed per dish) which have turned out to be very suitable and economical [Whelan 1986]. These units have been in service since 1981 and have required attention only in replacing O-rings about every 2 years.

   The appropriate circuit is illustrated in Figure 31, which indicates the series capillary for flow equalization as well as the absorber and the two rotary joints per dish. Rotary joint details are illustrated in Figure 32(a) where the main feature is an elastomer seal (O-ring) placed in a designed temperature gradient established between the steam and water channel such that the temperature of the elastomer ring is maintained within its operating range.

   There is a symmetry about the steam flow axis. In operation, the elastomer seal has only the pressure difference between the water and steam to cope with (so tolerance to fit and finish are not stringent). A compact joint results whose outside body is near feedwater temperature, requiring little insolation, if any.

   The configuation does reduce heat quality of the steam depending on the steam pipe size through the joint and on the amount of flow. Figure 32(b) shows experimental results obtained for the White Cliffs rotary joints (20 m^2 aperture dishes) with 6.4 mm diameter joint pipe; in this case, at rated flow, some 300 watts of heat transfer from the steam to the feedwater (the heat is not lost) causing a degradation of the steam (at 56 atomspheres) from about 550°C to 518°C.

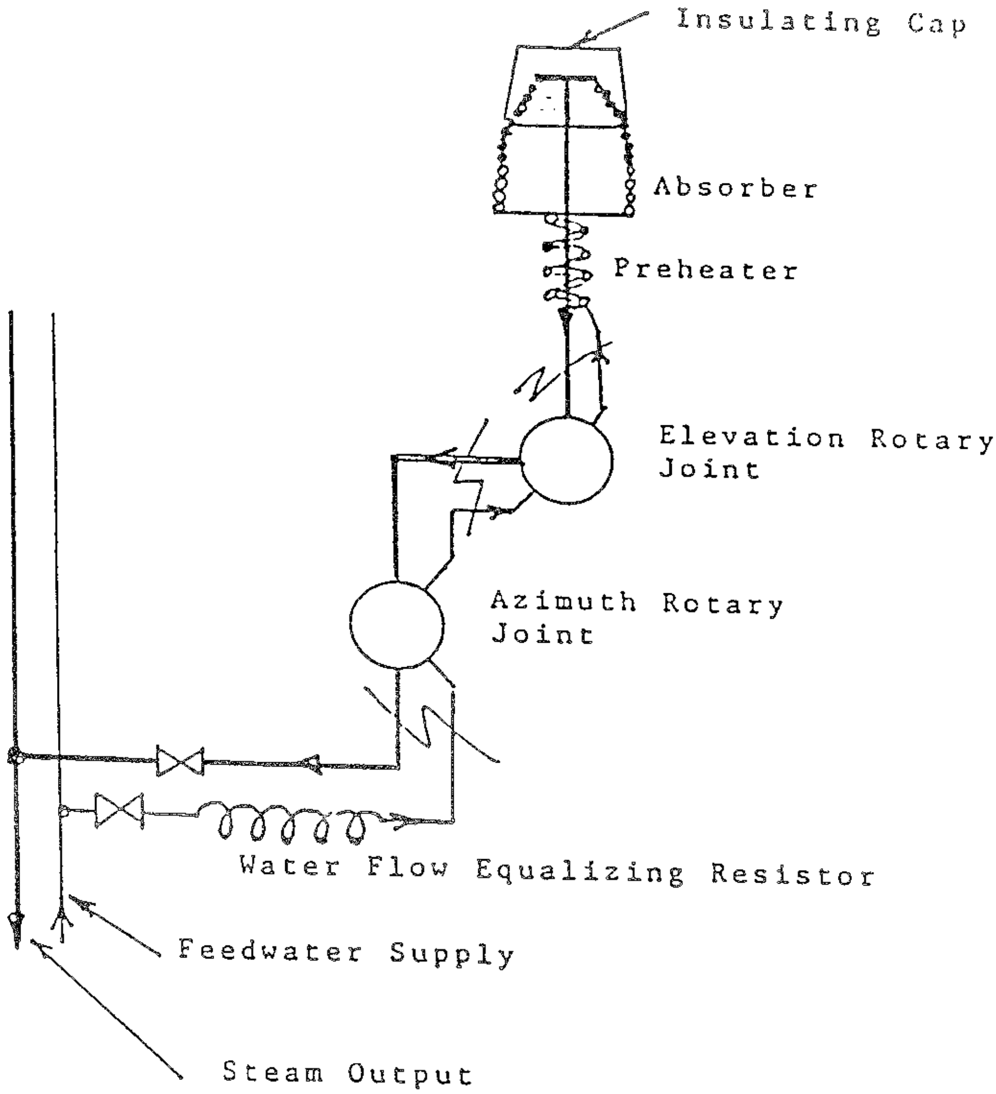


Figure 31. <u>Collector Fluid Circuit</u>

Note the two rotary joints and water flow equalizing capilliaries.

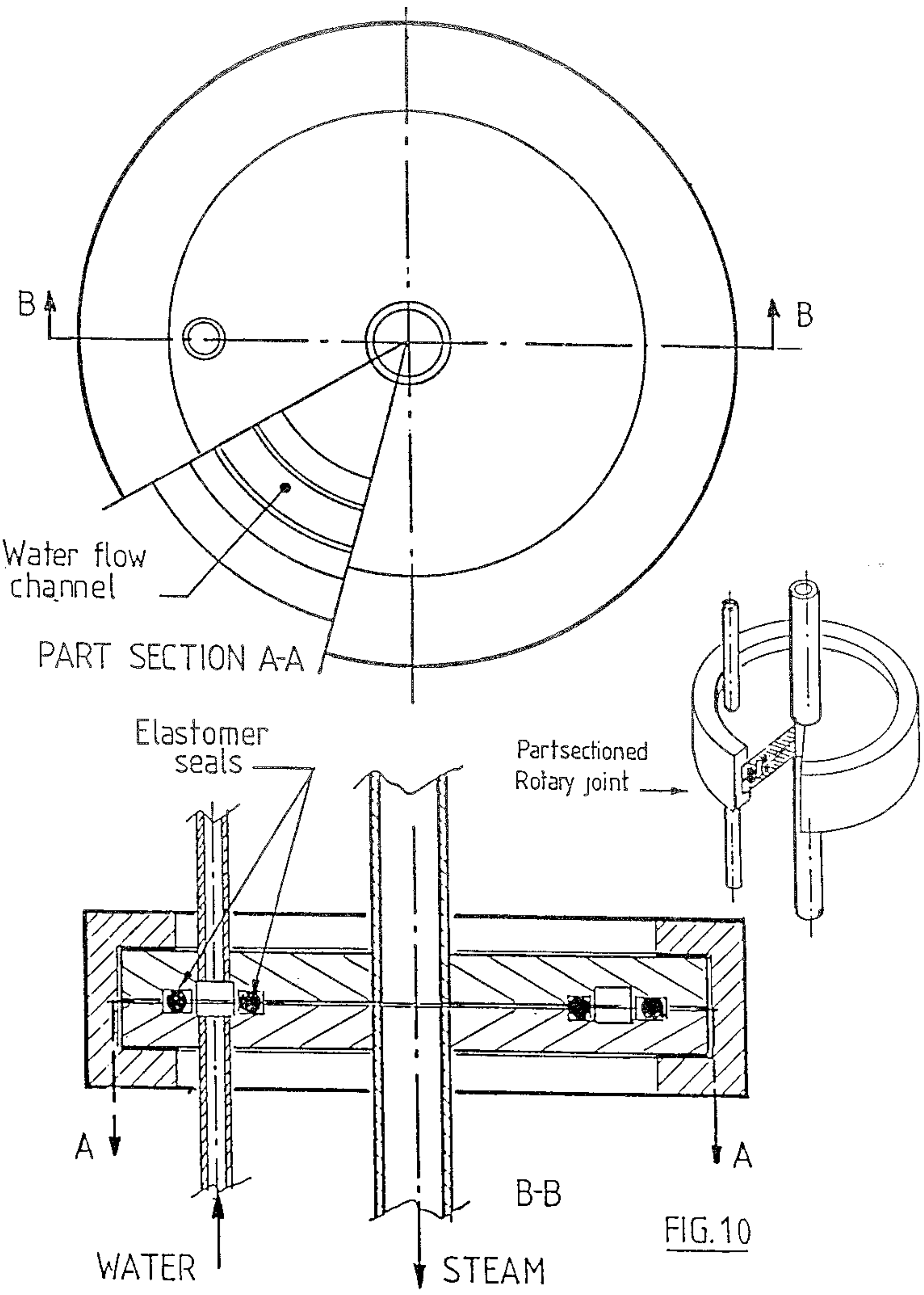


Figure 32(a). Details of White Cliffs Steam/Water Rotary Joint.

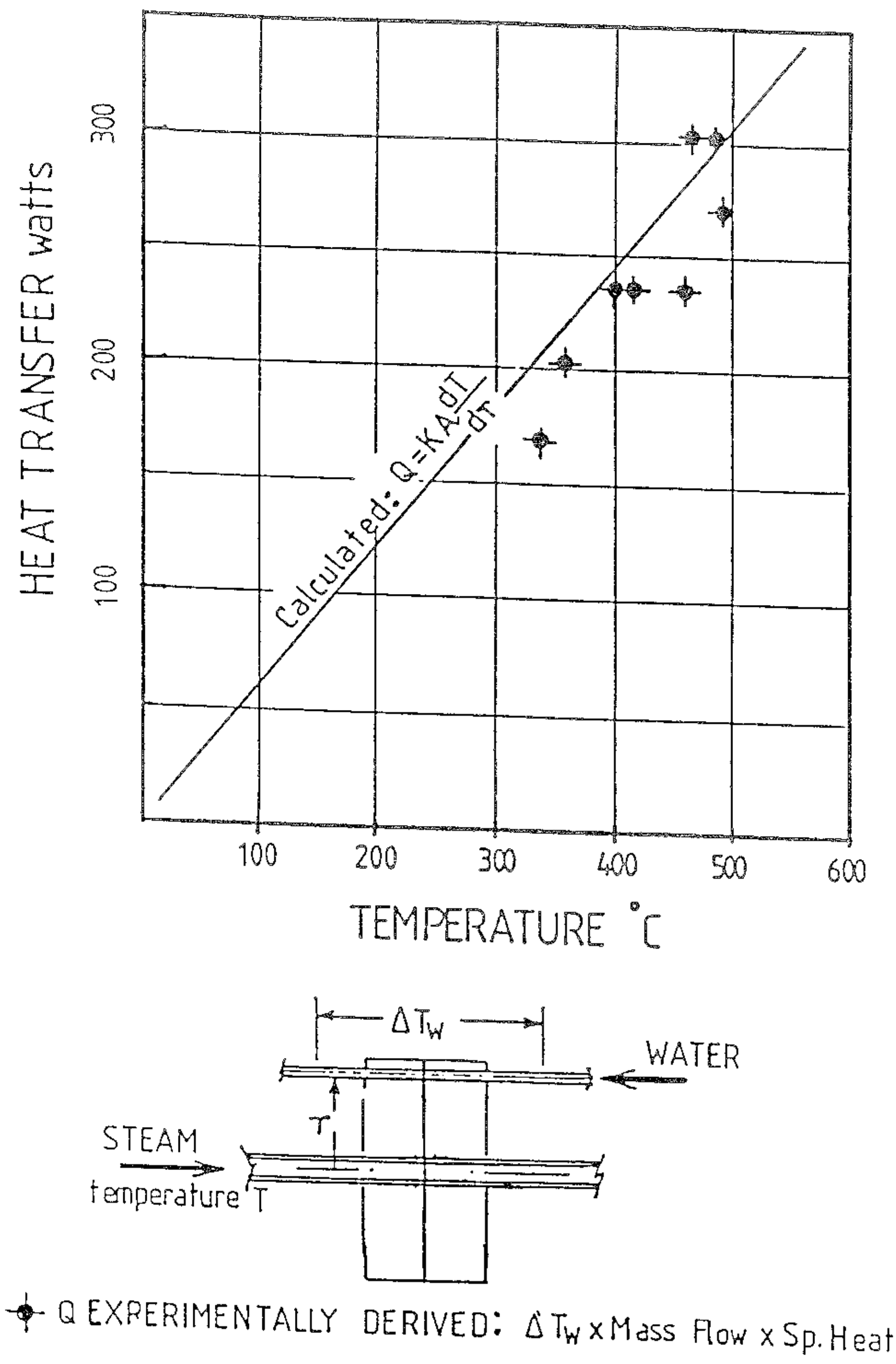


Figure 32(b). Performance of White Cliffs Steam/Water Rotary Joints.

Twenty eight rotary joints of this design have been in operation at White Cliffs since January 1982 and have operated at steam temperatures of over 450°C. Some failures have occurred in the elastomer seals due to incorrect alignment and steam injection into the water passage ways during tests. A satisfactory desing is now operating.

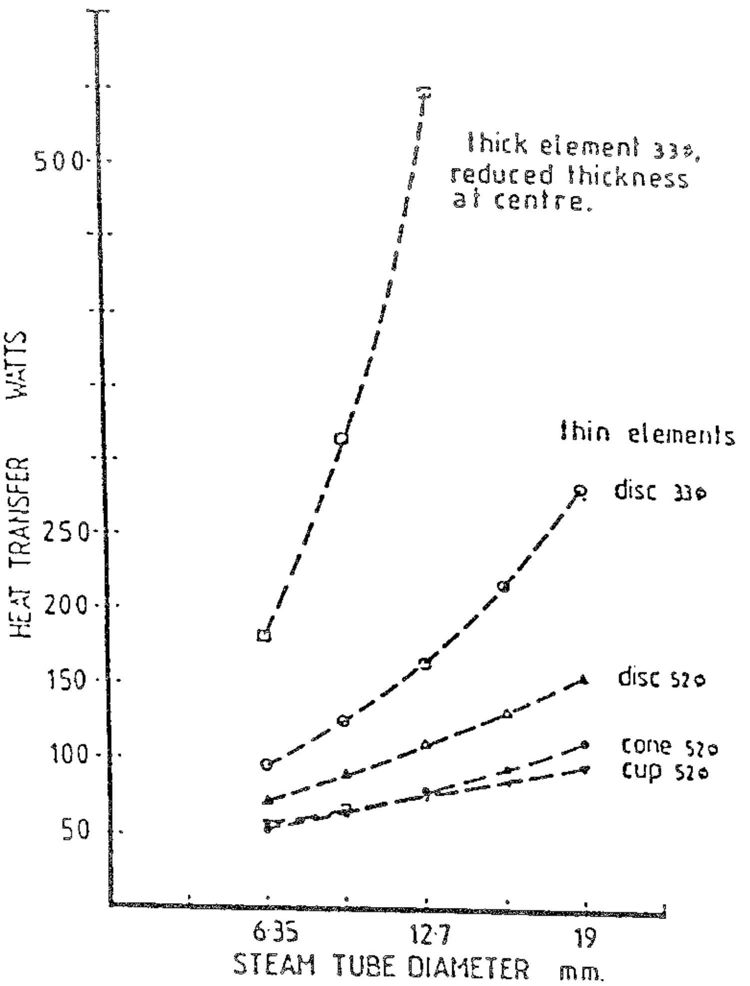


Figure 33(a). Improved Rotary Joint - heat transfer properties of various element profiles.

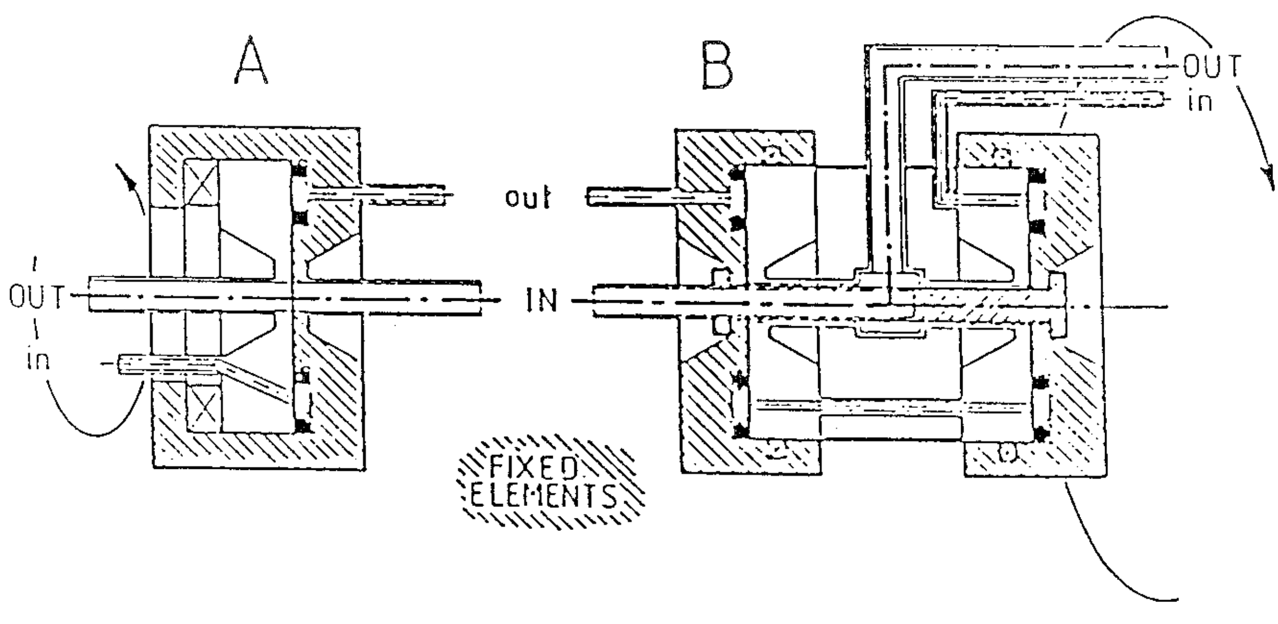


Figure 33(b). Cross section of improved rotary joint showing flow path for 2 element (A) and 4 element force balanced (B) rotary joints.

The major difference between this and Figure 32 is not in the shape but in the doubling of seal carrying elements to four.

For much larger dishes with higher mass flows, for example say 300 m^2 aperture concentrators operating at 15 times the flow with a steam pipe of 19 mm diameter, a heat transfer of about 600 watts occurs with a steam degradation from 550°C to 545°C (at 56 atomspheres pressure); this indicates an economy relating to size.

The White Cliffs rotary joint design uses a thrust bearing to reduce greatly the torgue requirement, and a means for improving component alignment; the essential feature, however, is the establishment of a temperature gradient which determines the seal position. In considering design for larger dishes (300 m aperture) Whelan [1987] has studied a number of seal carrying element profiles, leaning towards a cone profile because of inherent strength against pressure-generated forces, ease of manufacture and flexibility of length/diameter ratio. Figure 33(a) shows heat transfer for a number of different seal-carrying element profiles as a function of steam temperature.

A new dual flow force-balanced rotating joint for high temperatures and pressures has emerged and is illustrated in Figure 33(b) [Whelan 1987]. There are now four seal-carrying elements, while the centre rotating section is subjected to equal and opposite axial forces so that apart from simple plain bearings for radial location, no expensive thrust bearings are required. This design is expected to facilitate very considerably the development of much larger concentrators, as well as being relevent to other applications.

2. Actuators and Drives

Figures 12-17 inclusive show dish configuration and the two actuator/drive systems used:

- For horizontal axis (altitude) positioning, by a lead screw driven by a small printed circuit motor through a cyclodrive gear reduction which causes rotation from horizontal to vertical, facing.
- A further small printed circuit motor driving the azimuth (vertical) axis through an arm which is moved by polypropylene rollers spring-clamped onto a 2 m diameter ring, again through a cyclodrive gearbox. This drive system, even in strong winds, poses only small power and energy demands, the average power required during the tracking being only a few watts [Kaneff 1980a].

The drive motors are supplied through transistor power amplifiers by signals generated by a simple shadow disk sensor, arranged so that on perfect tracking alignment, the penumbra of the disk's shadow just shades a ring of four phototransistors equally spaced [Cantor 1979]. Any off-track movement gives 'error' signals from each pair of diametrically opposite phototransistors. The two sets of signals control respectively the altitude and azimuth motor drive amplifiers which cause motor rotation on non-zero error signals. As already indicated previously, to obviate the possible build up of oscillations due to system resilience, backlash and other imperfections, each time an error signal is reduced to zero, the appropriate amplifier is deactivated for 15-20 seconds. This intermittent tracking mode, while producing adequate following accuracy for the absorbers, reduces overall actuation energy demands and permits slewing without further hardware by allowing continuous motion for this function.

The sensors allow acquiring the sun within a cone whose angle is over 100°.

3.1.5 Protection

The array is comprised of 14 modular units (each semi-autonomous) allowing deactivation of any number of units without requiring station close-down. In the event of loss of communication and control signals from the central plant, each unit continues (under its own power supply) to track and deliver steam until it hits a stop past sunset and automatically parks, or until an absorber overheat occurs, when the unit offsteers and stops.

A themocouple attached to the absorber hot end steam tube provides a signal which causes dish offsteer if a preset temperature (about 580°C) is exceeded; offsteer involves movement down and reverse, then stop, a manoeuvre adequate to take an absorber out of the concentrated sun for the rest of the day. Offsteer is also invoked as the result of a control signal from the control room of the station, in the event of steam or electrical system malfunction.

The array is designed to keep tracking for winds of up to 80 km/h; for wind gusts lasting more than a few seconds beyond this velocity, each dish slews rapidly to point vertically upwards, when winds of up to 180 km/h can be withstood, the aerodynamic "lift" being downwards and the drag being sideways. Signals from the wind monitoring system are reticulated to each dish for this purpose.

Although stronger winds than 80 km/h have been measured since December 1979 (when the wind monitor was installed), these have not coincided with solar operation and no interruption to tracking has occured due to excessive wind.

3.1.6 Summary of Collector Array Details

Each Collector Dish	:	5.06 m diameter reflective surface, lined with 2 300 plane mirror tiles.
Number of Collectors	:	14.
Rows (V-form)	:	2.
Fluid Path	:	Parallel flow in all absorbers.
Flow Equalization	:	Capilliary tubes in series with each absorber; pressure drop of 1.7 MPa across capillary at rated flow.
Rated Mass Flow	:	50 ml/s total or 3.6 ml/s/absorber.
Total Aperture Area	:	277 m^2.
Antifreeze Protection	:	Not required.
Duct Length	:	230 metres total.
Feedwater Pump	:	Positive displacement (3 piston) unit driven by thyristor-controlled servomotor; the unit draws 0.3–0.9 kW, depending on pump speed and load. Maximum back pressure 8.7 MPa.
Pressure Relief Value	:	Set at 9.0 MPa.
Feedwater Treatment	:	Water treatment plant (hydrazine) pH = 9.0 automatically (not used at present) Oil/water treatment to remove oil from feedwater by: (1) Vortex chamber following engine exhaust (−85kPa, 70°C exhaust conditions) (2) Water-cooled condenser (3) Condensate skimmed for surface oil. (4) Special filters to remove emulsified oil from water (5) Skimmed and de-emulsified oil centrifuged — oil returned to oil tank and water to feedwater tank. A later improvement involves elimination of the skimmer and centrifuge, oil collection being accomplished by rotating stainless steel disks — see Section 3.3.

3.2 Field Ducting — Insulation

The task of conveying high quality steam from each absorber to the engine room posed four major problems:

3.2.1 Expansion of Tubes Conveying Steam

Steam and water temperatures in the array fluid transport tubes fluctuate over wide limits (approximately 30°C or less up to 500° and more) in response to insolation changes and control processes. Steel, with a coefficient of expansion of more than 1.2×10^5/oC therefore may vary in length (many times per day during intermittent cloud) by up to 70 parts in 1000, or 70 mm in 10 metres — this requires careful and sensitive attention to the design of tubing, insulation and layout within appropriate ducts.

The solution used is indicated in the zig-zag layout of ducts evident in Figures 1 and 34. This permits lines to expand and contract, the movement being taken up in the widened diverging horizontal grooves in the insulation in the vicinity of duct corners, as shown in Figure 34. Figures 35 and 36 show construction details.

3.2.2 Heat Losses — Duct Insulation

Because of the need to operate the engine on superheat, the degree of insulation required demanded attention to heat loss, retaining the maximum practicable amount of heat collected; we decided to employ a high quality insulation to minimize such losses.

Using microtherm insulation (65% SiO_2, 32% TiO_2, with 3% various trace materials) a loss of no more than 50 W/metre run can be realised while using 50 mm thickness of insulation all round on a 19 mm diameter tube carrying steam at 500°C. This is the largest diameter tube for transporting the steam which is called for with the array layout used. Smaller diameter tubes (16, 13 and 10 mm) are used where the mass flow is less than maximum, resulting in even lower losses when employing the same thickness of insulation. An additional amount of energy is 'soaked up' as the microtherm warms up slowly, starting at up to 50 W/m run and tapering off to negligible amounts within about 1 hour; some of this energy is recovered on cooling down. These losses represent about the best reasonably attainable without increasing insulation thickness substantially, with consequent increase in costs. Total length of steam lines is about 230 metres and (as noted later) total duct losses of about 10–13 kW thermal were achieved by this means (depending on conditions) — main ducts accounting for about 8 kW.

Figures 35 and 36 show duct details; Figure 37 gives some microtherm characteristics. The superiority of this material over other insulating products may be noted. It will also be noted from the measured characteristics of Figure 37(f) that the low loss property of microtherm is modified by heat absorption (or soak-up) during the first hour or more of operation from cold. In Figure 37(f), operation at 550°C causes about double the energy to be withdrawn compared with later operation; half of this energy is lost as heat leakage, half is stored in the microtherm and some of it is usefully recovered when the temperature of the conveyed fluid drops again.

3.2.3 Connecting Absorbers to the Ducts

Connecting absorbers into the steam lines has proved a difficult detail with central column absorber support.

The original Mark I and II absorbers were designed to be mounted on the end of the central dish duct (projecting from the base of each dish) by a central tube from the top of the absorber (hottest section) straight into the insulated duct, as indicated in Figures 12-15, 31 and 38. Expansion of the steam tube within this duct was arranged to cause the absorber itself to move axially outwards into the correct focal region as soon as steam temperature had risen — an outward movement of about 13 mm was usual.

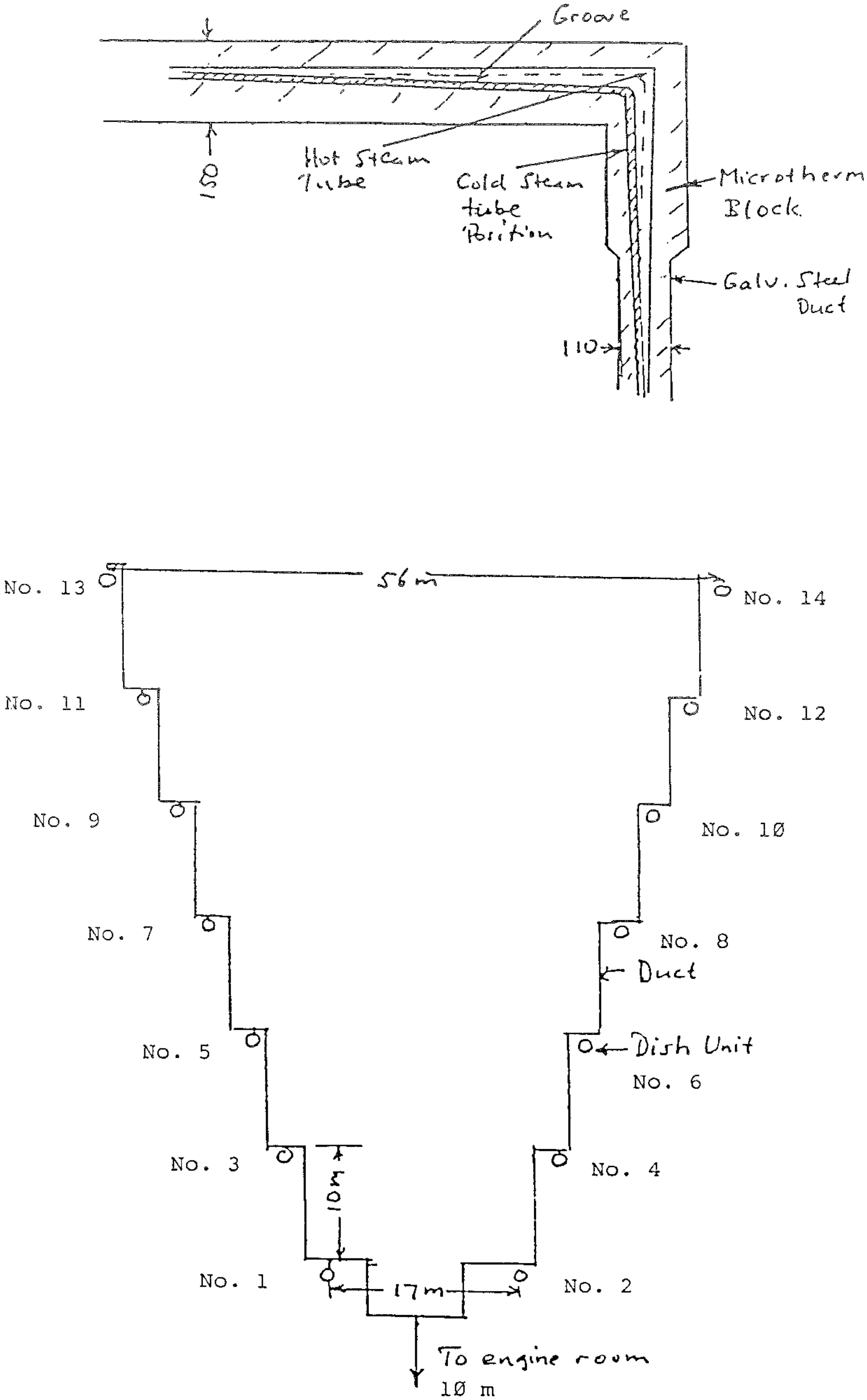
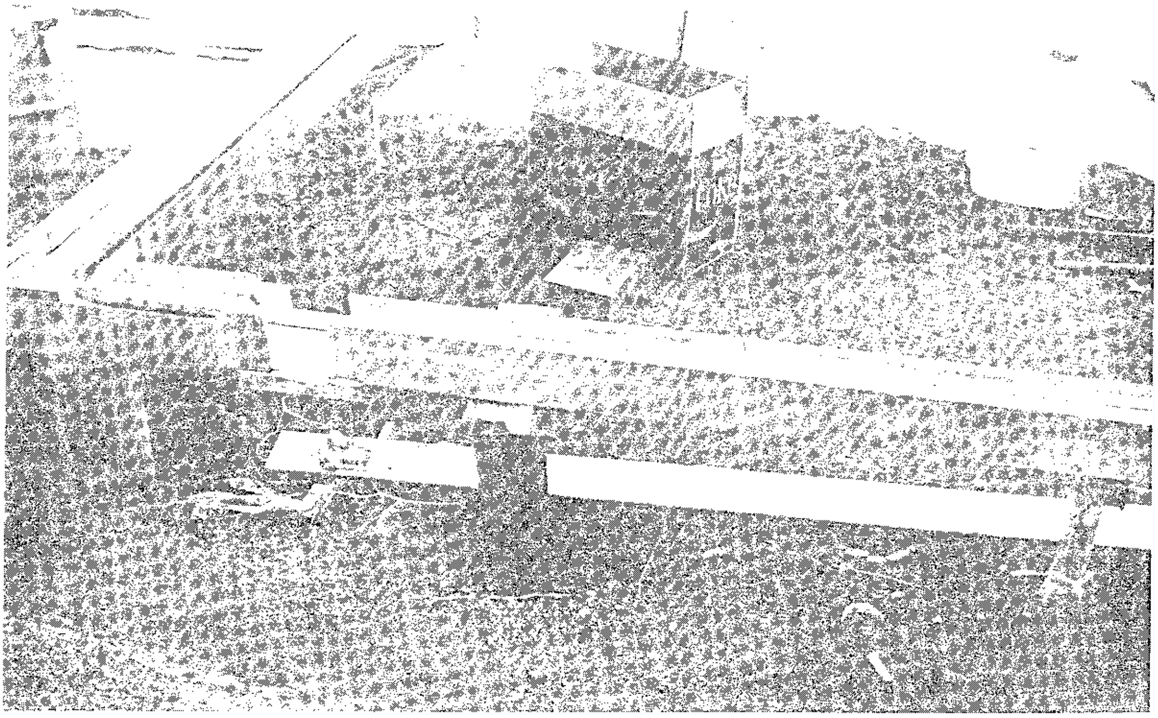


Figure 34. Array layout and duct details.



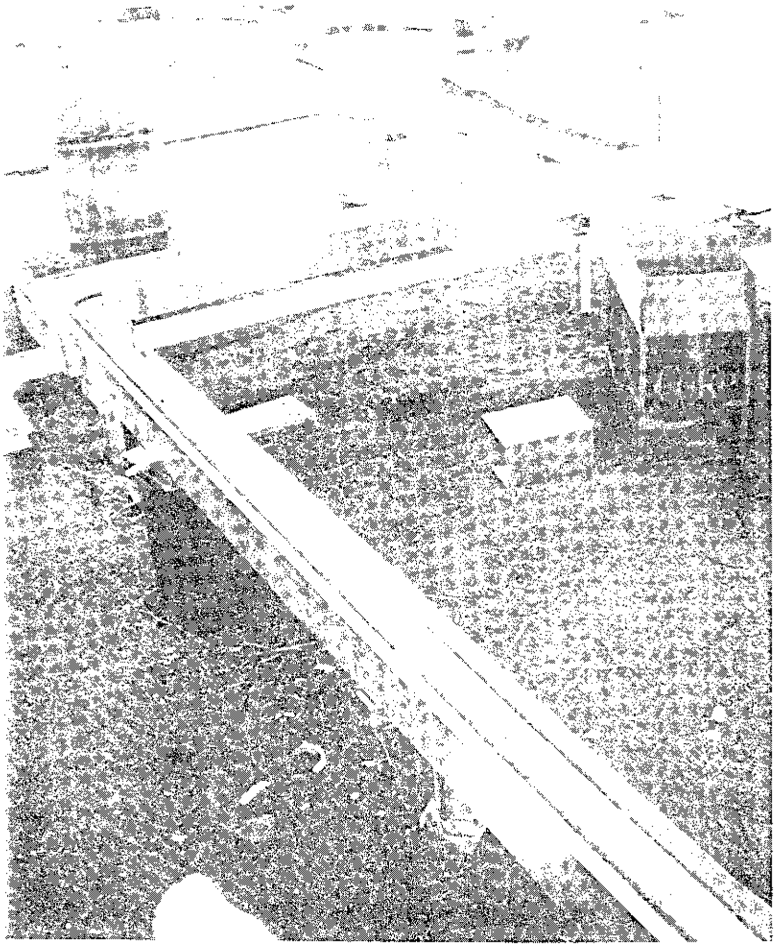


Figure 35. Duct details.

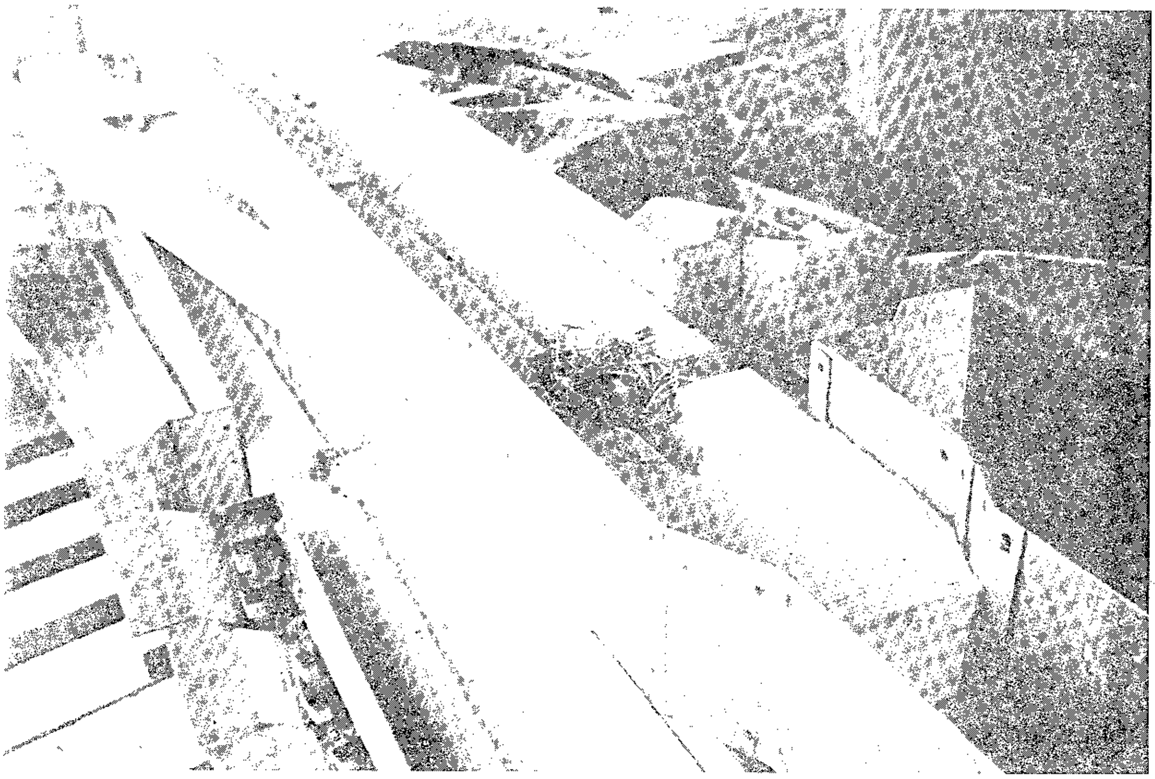


Figure 36. Duct details showing microtherm blocks (White Cliffs birds work intensively during weekends!)

Hot Face Temp. °C	Cold Face Temp. °C	Mean Temp. °C	K. Values		
			Btu.in / ft² hr. °F	k-cal / hr. m °C	W / m °K
170	30	100	0·146	0·018	0·021
355	45	200	0·155	0·019	0·022
535	65	300	0·175	0·022	0·025
720	80	400	0·194	0·024	0·028
910	90	500	0·222	0·028	0·032
1100	100	600	0·270	0·034	0·039

Figure 37(a) - Thermal Conductivity of Microtherm in Air

PERFORMANCE OF MICROTHERM

How Microtherm compares with other insulations.
Note: The thermal conductivity value measured for any insulation material at a given mean temperature depends on the temperature gradient across the material being tested.

For Microtherm two curves are shown. The one assumes a large temperature gradient and should be used in calculations where Microtherm is the sole insulation. The lower dotted curve applies when Microtherm has a small temperature gradient as when it is used as a hot face layer with back-up layers of other insulating materials.

The curve for alumina fibre is also shown dotted because the figures apply for small temperature gradients.

All figures are based on manufacturers' literature.

THERMAL CONDUCTIVITY VALUES

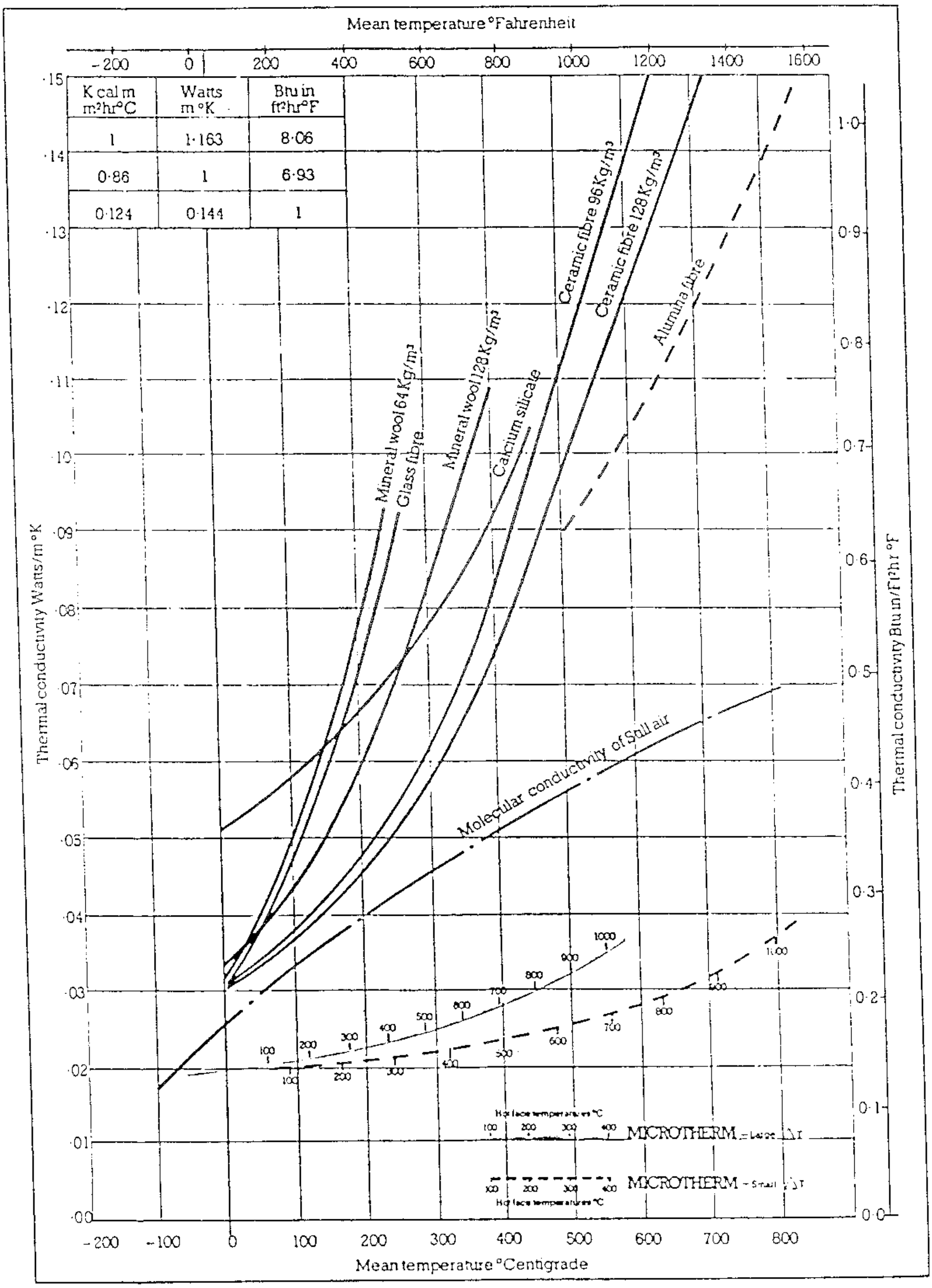


Figure 37(b) - Thermal Conductivity of Microtherm

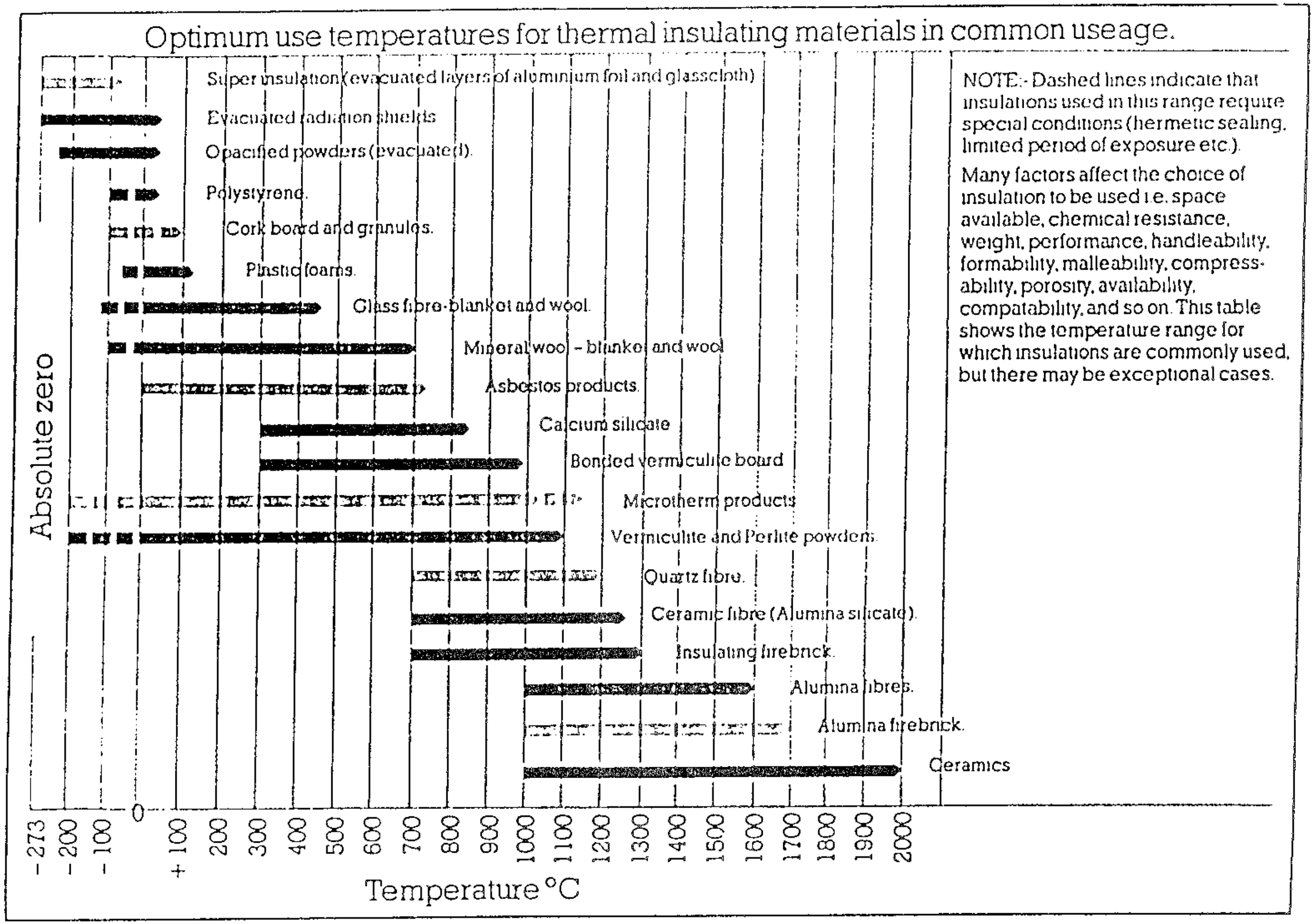


Figure 37(c) - Optimum Use Temperatures for Common Thermal Insulating Materials

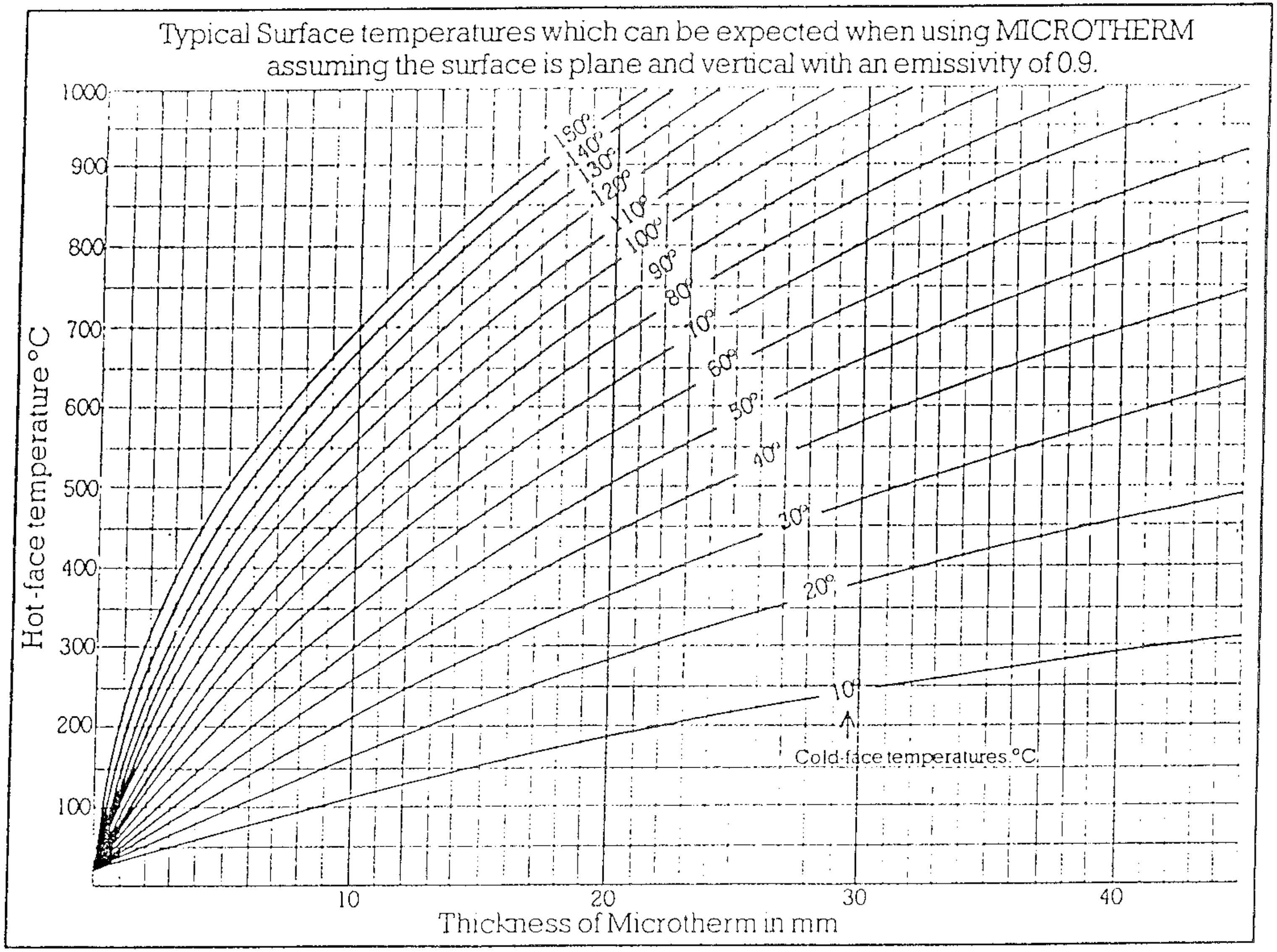


Figure 37(d) - Surface temperatures when using Microtherm

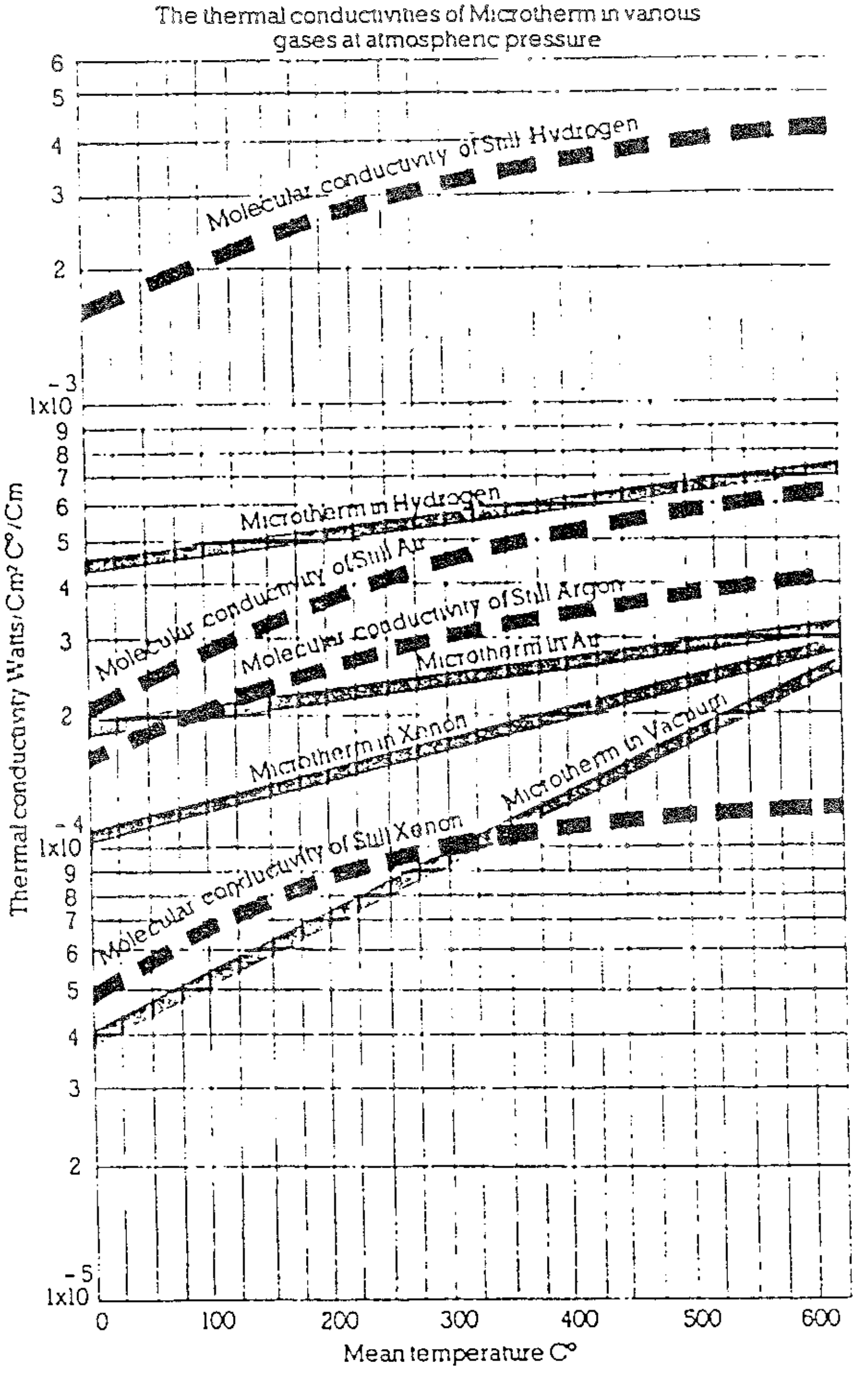


Figure 37(e) - Thermal Conductivity of Microtherm in various gasses at atmospheric pressure.

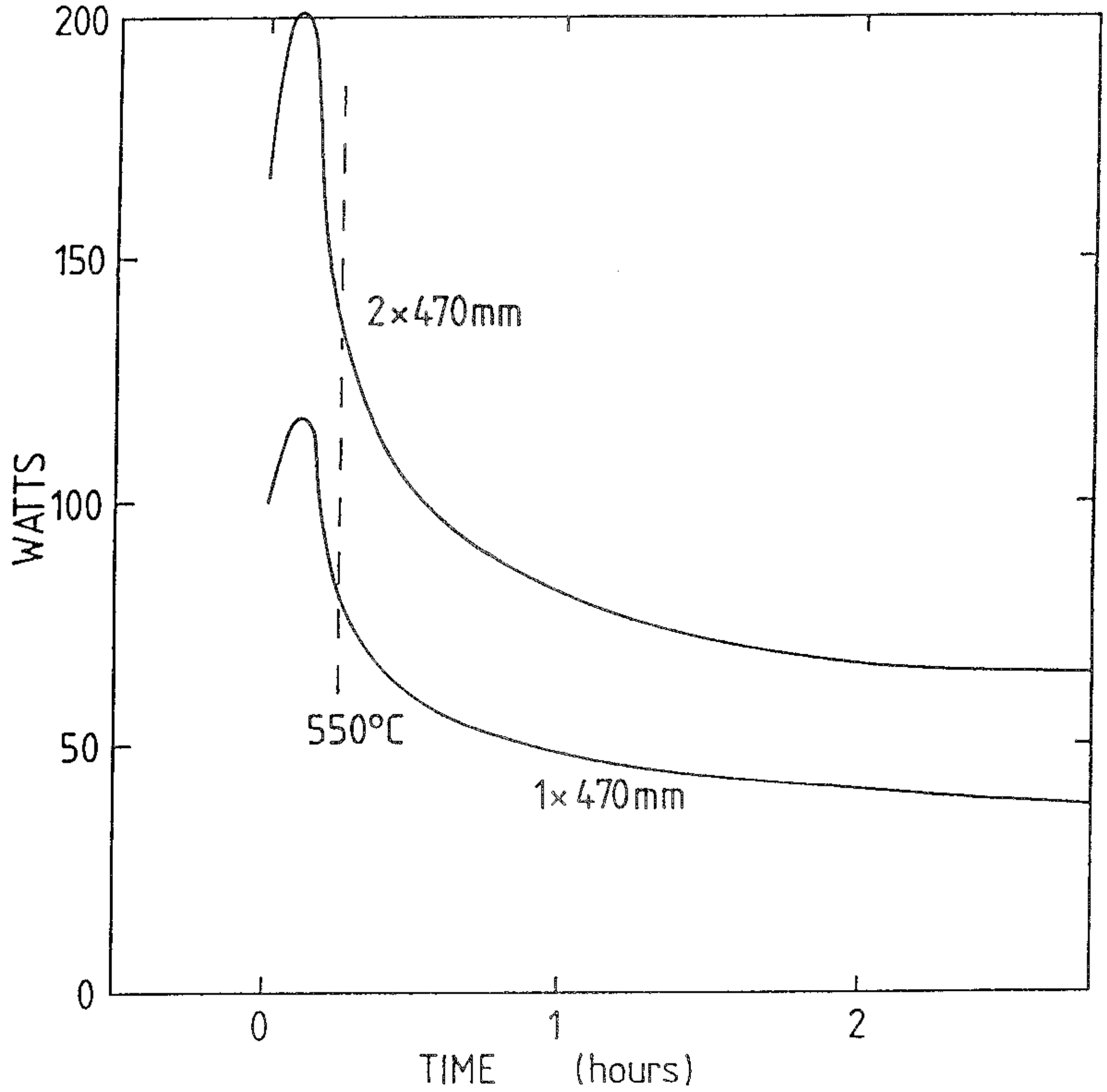


Figure 37(f) - Heat Soakage in Microtherm Dust Insulation Tube diameter 9.5mm, Microtherm thickness 50mm.

This arrangement was generally satisfactory for the Mark I and II units in the first months of operation but longer-term effects caused problems with deterioration of the central down tube conveying the steam. This tube traverses the region of highest solar flux density and it is difficult to maintain its integrity; originally it was surrounded by a thin-walled ceramic tube for protection, later by another stainless steel tube of larger diameter. Neither approach proved satisfactory in the longer term and it was decided to remove the central tube and replace this with a loop moving outside the very intense focal region, as illustrated in Figure 38(b). The light Mark II absorbers could still be adequately supported, but the larger Mark III–VII units could not; these required stand-off mountings clamped to the dish duct.

Overall the steam line connecting method for the absorbers proved mechanically satisfactory and connecting steam tubes no longer deteriorated. But the cost of this change was one of increased total losses; indeed, while the original central absorber straight-through connection resulted in very small loss only (less than 200 W/absorber or less than 3 kW for the array) the new arrangement, when taking account of convection, radiation and partial shielding effects, introduces more losses than occur in all the steam duct lines (ie over 10 kW total over the 14 absorbers, more in strong winds). While this greater than 10 kW loss could be reduced by insulating the connection tube from top of the absorber to the central dish duct, such insulation tends to be counter-productive because of the shading so produced.

Because well insulated ducts allow only very small losses, the preferred way to solve this problem is to support absorbers as illustrated in Figure 38(d), a configuration not originally chosen because of cost considerations. This would be a better cost-effective proposition for large dishes, which can then be shallower (ie of longer focal length).

In summary, the original absorber mounting and steam connection to the central duct was of high efficiency but of short life without major change. Conceptually, structures whether conveying fluids or not, should avoid the very intense solar flux region and our early attempt to solve this problem by protection proved inadequate. A more desirable approach is that illustrated in Figure 38(d) which is not, however, open to us conveniently on the present White Cliffs dish system. The solutions actually used [Figures 38(b) and 38(c)] are compromises which introduce significiant losses.

3.2.4 Conveying Feedwater and Steam from Moving Dish to Ground

Feedwater at over 7 MPa pressure has to be conveyed from the supply lines to the absorbers; steam at up to 550°C and 7 MPa pressure has to be fed from each absorber into station steam lines. Both fluids need to be conveyed via two rotating axes.

Solution of this problem has already been discussed in Section 3.1.4. The development of rotary joints which allow simultaneous passage of both fluids via the one joint for each axis essentially removes restrictions on the movement of dishes and permits higher efficiencies to be achieved in larger units [as the relative losses introduced by the rotating joints become less as dish size increases — Section 3.1.4(c)].

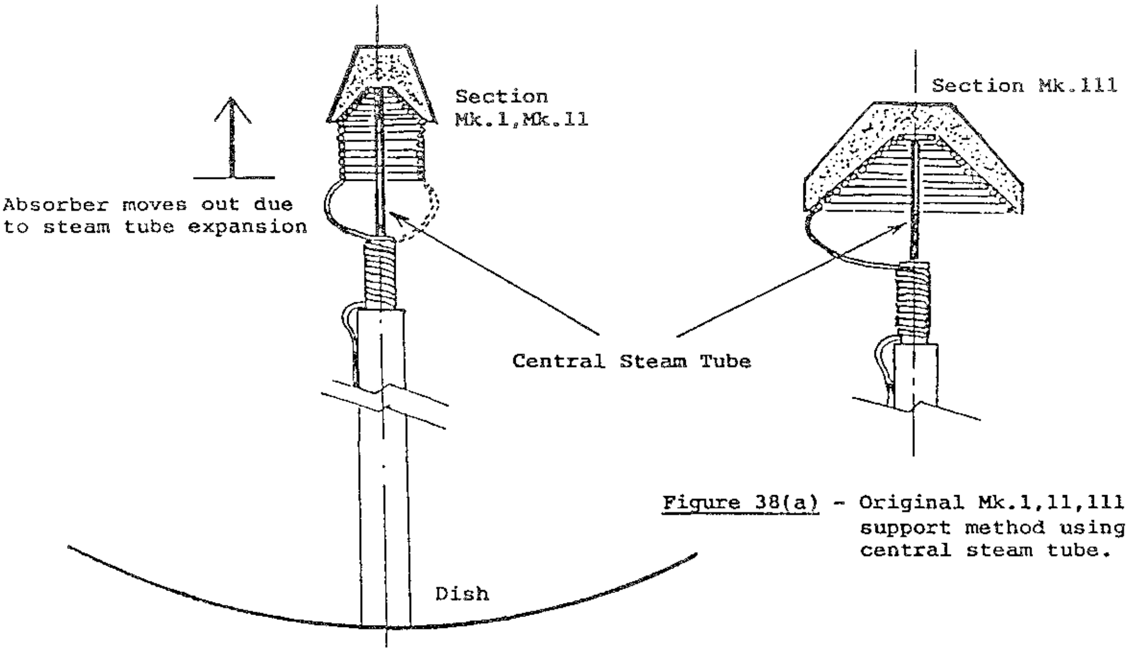


Figure 38(a) - Original Mk.1,11,111,1V, support method using central steam tube.

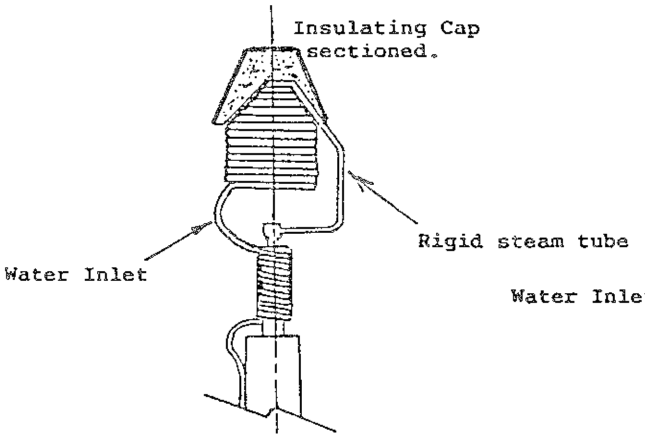


Figure 38(b) - Steam connection modified to reduce central tube heat stress problems (Mark 11)

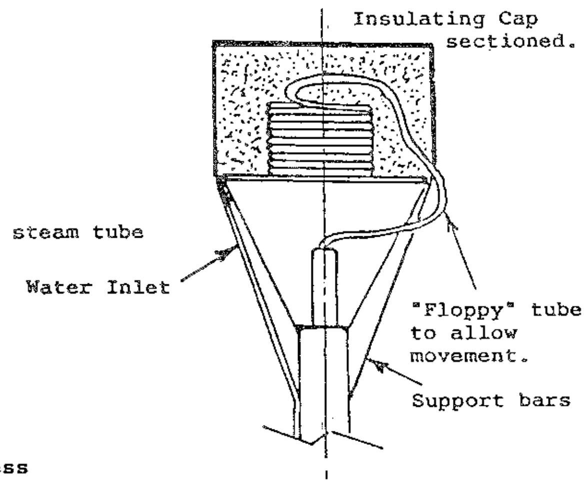
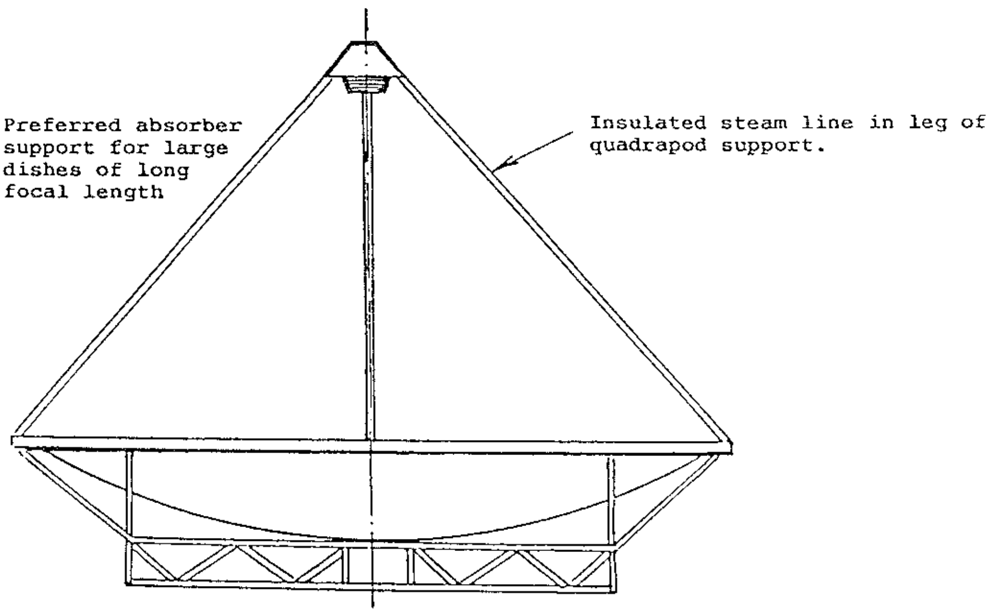


Figure 38(c) - Support of the larger Mk.V,V1,V11, etc. absorbers.

Figure 38(d) - Preferred absorber support for large dishes of long focal length



3.3 The Steam System and Components

Many considerations led to the use of steam as an energy transport medium, not the least being the large amount of conventional wisdom accumulated over the years. Water is a natural, accessible substance which does not pollute, unlike the various conducting oils which are sometimes used in conveying heat from solar and other collectors.

Heat-to-mechanical work conversion is achieved by a reciprocating expander, as discussed in Section 1.4(6), developed from concepts which have evolved from the work of steamcar enthusiasts over the years, resulting in technology which can be readily handled by those with some experience with motor vehicle engines. To attain cost-effectiveness, careful attention has been given to the use of standard and readily available diesel engine and other components and the minimizing of all practicable losses to achieve high conversion efficiency. Thus a vacuum pump is employed to faciliate steam expansion and water-cooled condensing is also used. The quality of steam which can be employed was determined by the same corisiderations of cost effectiveness as apply to the whole system particularly by the limitations set by material properties which can be conveniently used in constructing absorbers, steam lines, valves, 'hot' engine components (especially valves), and by the tradeoff between absorber conversion efficiency, array energy transport losses and engine conversion losses.

The steam system, shown diagramatically in Figure 2, operates as described in Section 1.1 and comprises:

3.3.1 A positive displacement 3-cylinder feedwater pump

with thyristor drive, able to deliver water at pressures over 9 MPa, in response to a signal voltage of about 0-5 V, pump speed being linearly dependent on input signal. This signal can be obtained either manually or from a feedwater control circuit.

3.3.2 Fourteen absorbers

fed in parallel via flow-equalizing capilliary tubes. Water changes to wet steam in the lower coils of each absorber, the steam gaining its final degree of superheat (up to 550°) in the cavity section, insulated by kaowool (calcium silicate) held in a stainless steel cap.

3.3.3 A thermocouple at the absorber

steam exit point to monitor tube temperature and indirectly, steam temperature — and operate, if necessary, the over-temperature offsteer circuit set at 580°C.

3.3.4 Two rotary joints,

allowing both feedwater and steam to traverse the two axes of dish rotation. In passing through the rotary joints, steam temperature drops to about 518°C after the first joint, then to 490°C after the second [the heat being transferred across to the incoming feedwater and not lost, as indicated in Section 3.1.4(1)].

3.3.5 The main ducts carrying steam

to the engine-room, where the steam enters at some 400°C, dropping a further few degrees before reaching the engine.

3.3.6 Pressure relief valve

set at 9.0 MPa.

3.3.7 Scale trap

to collect any particles and allow disposal by flushing.

3.3.8 A thermodynamic steam trap

which automatically bypasses to the condenser, any water but not steam, so reducing any delivery of water to the engine — especially when operating on wet steam.

3.3.9 The reciprocating expander,

3-cylinder engine with automatic motor-driven valves, for (i) bypassing steam to the condenser when quality is not adequate (before start); (ii) admitting or shutting off steam (throttle); and (iii) allowing draining of cylinders of water just at start up. The engine system is further described in Section 3.4.

3.3.10 Water-oil separation system

for treating the exhaust steam, to remove oil gathered in passage through the cylinders. This consists of a vortex column which retains oil droplets and condensed steam, and delivers these periodically to the feedwater tank for subsequent separation; a skimmer in the feedwater tank which removes surface oil for delivery to a centrifuge for separating the oil-water mixture collected. Because some of the oil forms an emulsion with the water, a filter pump and fine filter system are used for removing the colloidal suspension from the oil in the first compartment of the feedwater tank and a further filter to clear the water in moving from the second to the delivery (third) compartment of the feedwater tank. These two filters cause coagulation of the very fine oil droplets, resulting in their floating to the surface, falling over a weir, and being skimmed off in the first compartment. Figure 39 shows the skimmer, weir and filter bag in the feedwater tank.

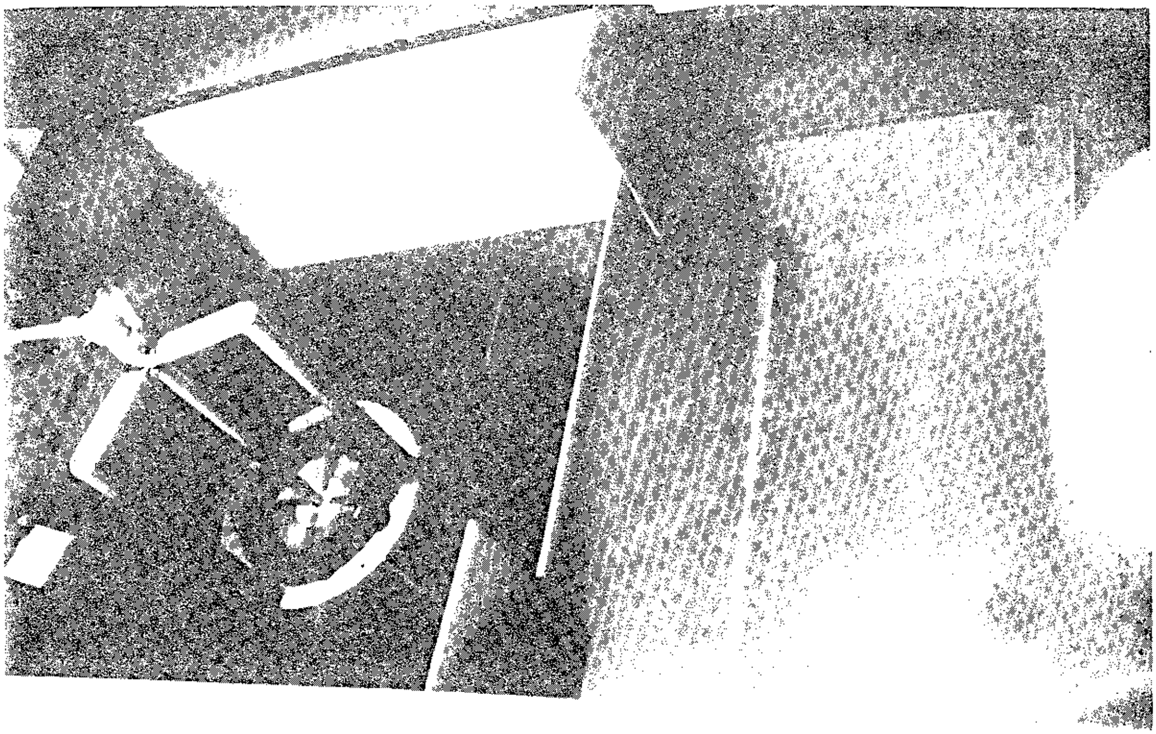


Figure 39(a) - View of Feedwater Tank Skimmer, Weir and Filter Bag (far right)

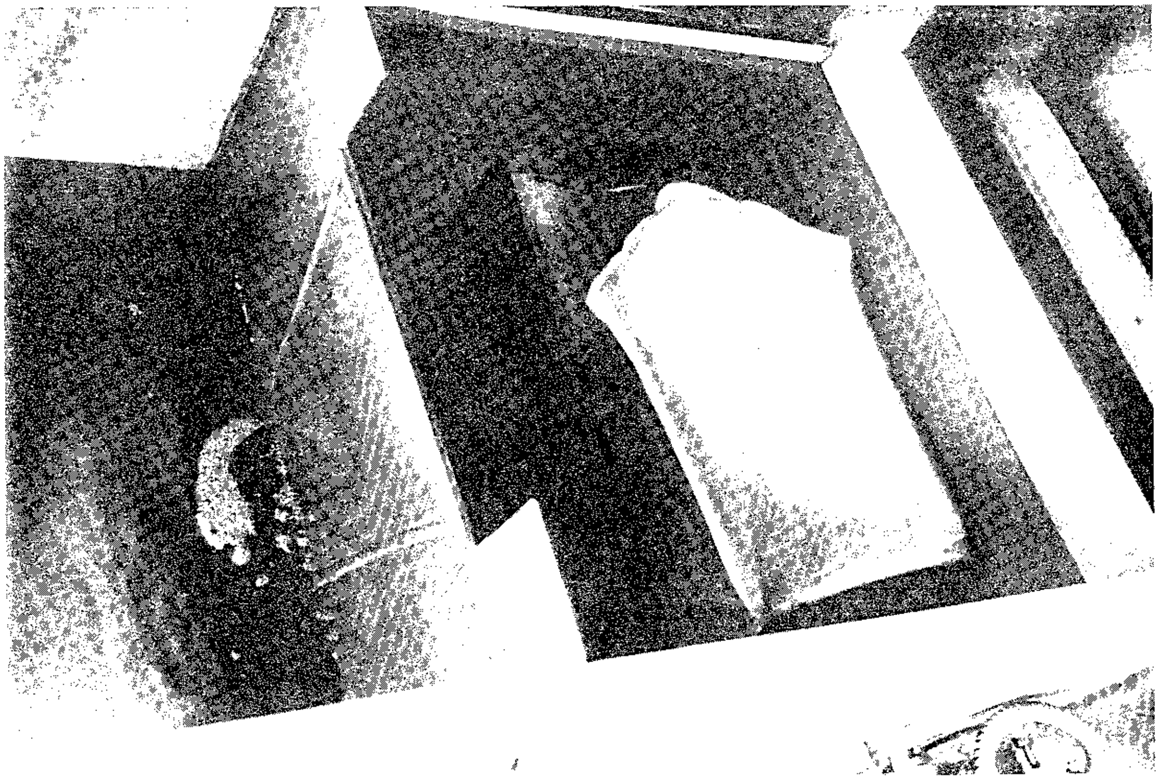


Figure 39(b) - Feedwater Tank Weir and Filter Bag. Below this bag can be seen the filter between the second and third feedwater tank compartments (Figure 2)

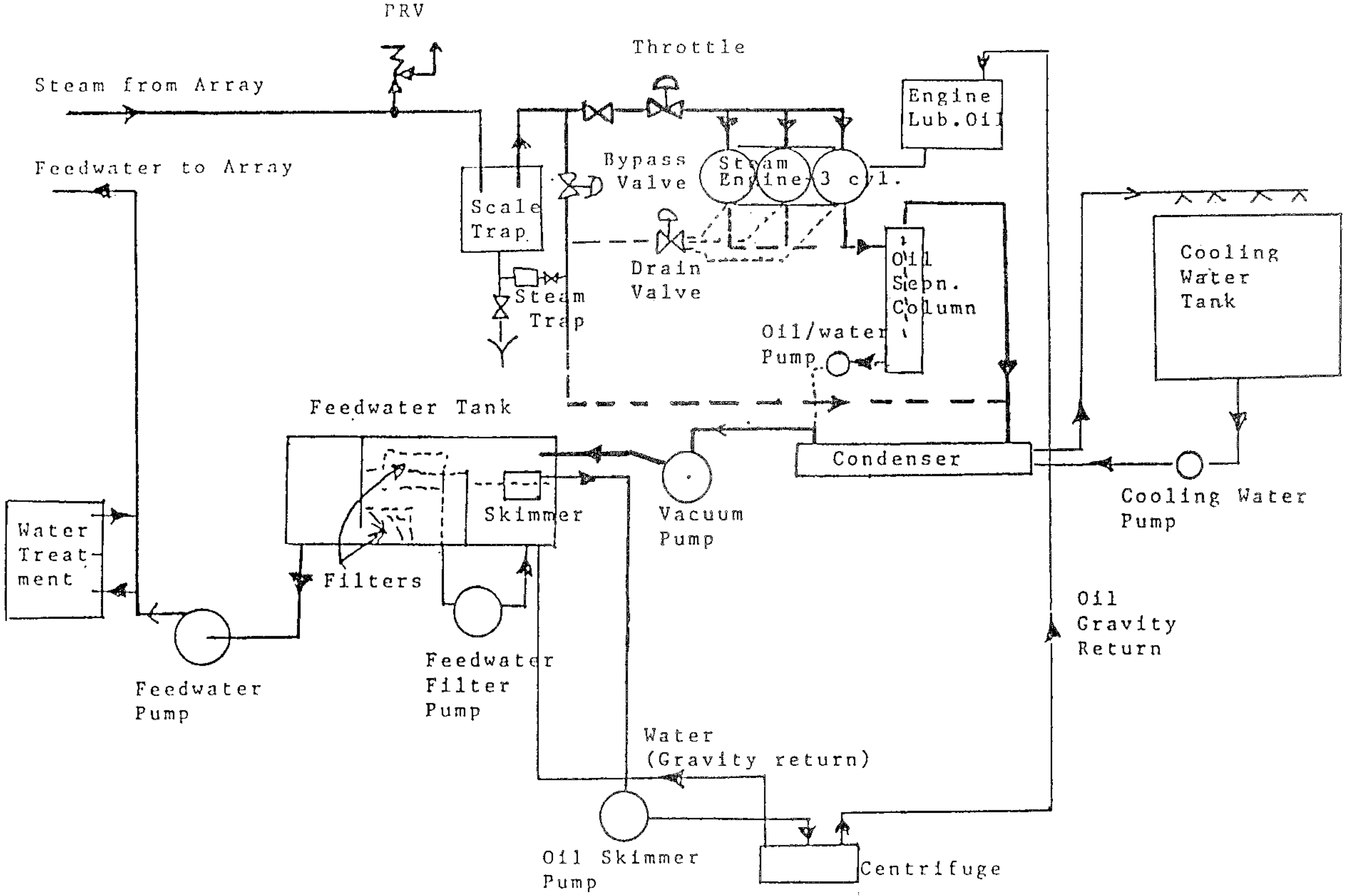


Figure 40 - First Steam/Water System for the White Cliffs Station

In a later simplified oil water treatment system, skimmer and centrifuge are removed to be replaced only by two stainless steel disks, rotating on a horizontal axis, dipping into the surface of the first compartment of the feedwater tank. Collected oil (containing very little water) is scraped off and delivered to the oil tank. An oil drier (standard commercial unit) removes water from the oil tank.

3.3.11 Vacuum pump — water cooled condenser system

for handling the exhaust steam and permitting more energy to be extracted from the steam by causing further expansion.

3.3.12 Condensate handling system.

In the system of Figure 2, condensate is handled through the vacuum pump, while condensate from the oil separation column is pumped to the centrifuge. In the later disk-skimming system, oil/water mixture from the latter is pumped to the feedwater tank.

An earlier version of the steam system is shown in Figure 40, in which the condensate is handled separately albeit in a more complex manner than in Figure 2. Because of advantages in this approach, our later designs (for example the Troy and Molokai engine systems — see Section 6) revert to separate condensate handling, but achieve simplification by employing the oil water pump of Figure 2 to handle both condenser and vortex chamber condensate, both being conveyed to the feedwater tank.

3.3.13 Cooling water system for steam condensing.

This employs a tank of 100 000 litre capacity to transfer the latent and sensible heat in the exhaust/condensate. Surface evaporation (day and night), ground conduction and radiation effects cause the water temperature to fall overnight in the tank.

3.3.14 Water treatment

was originally intended to maintain a pH value of about 9.0 but is not used since our experience has shown that untreated rainwater is very satisfactory following a few hours' running to rid the water of much of its dissolved air, resulting in better vacuum.

3.3.15 Steam system alarms.

Apart from the pressure relief value (PRV) on the incoming steam line to the engine room and a further PRV on the condenser (set at 1 MPa to avoid buildup of steam pressure in that unit), the following alarms close down the steam system and cause dish offsteer: engine oil pressure; oil tank level (high and low); feedwater flow; condenser cooling waterflow; vacuum system; certrifuge; oil water pump and liquid level in vortex chamber; engine overspeed (includes a backup system governor-actuacted); excess wind

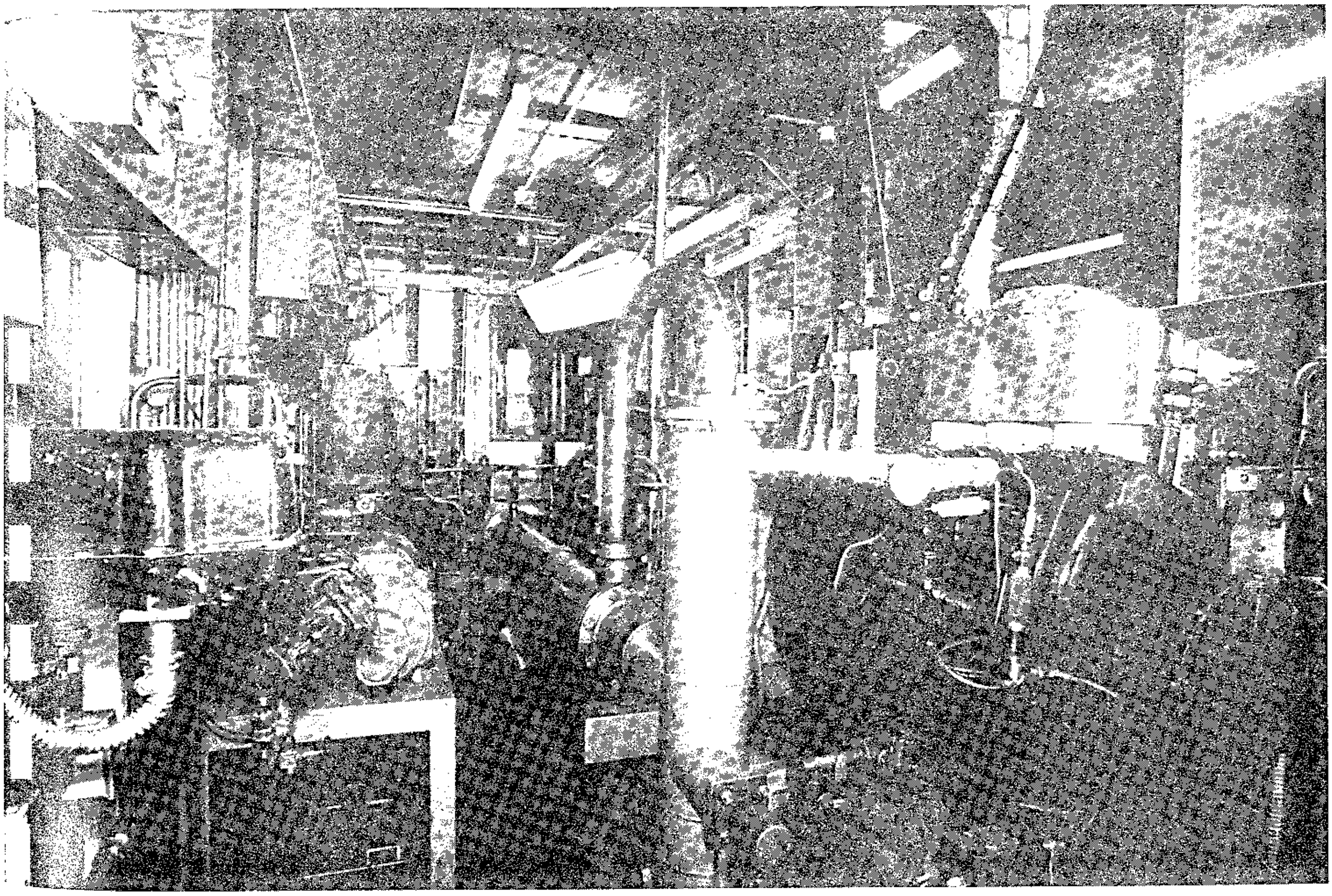


Figure 41(b) - White Cliffs Engine with Vortex Chamber and Condenser in view, Feedwater Pump (centre left) and Bypass Valve drive (far left)

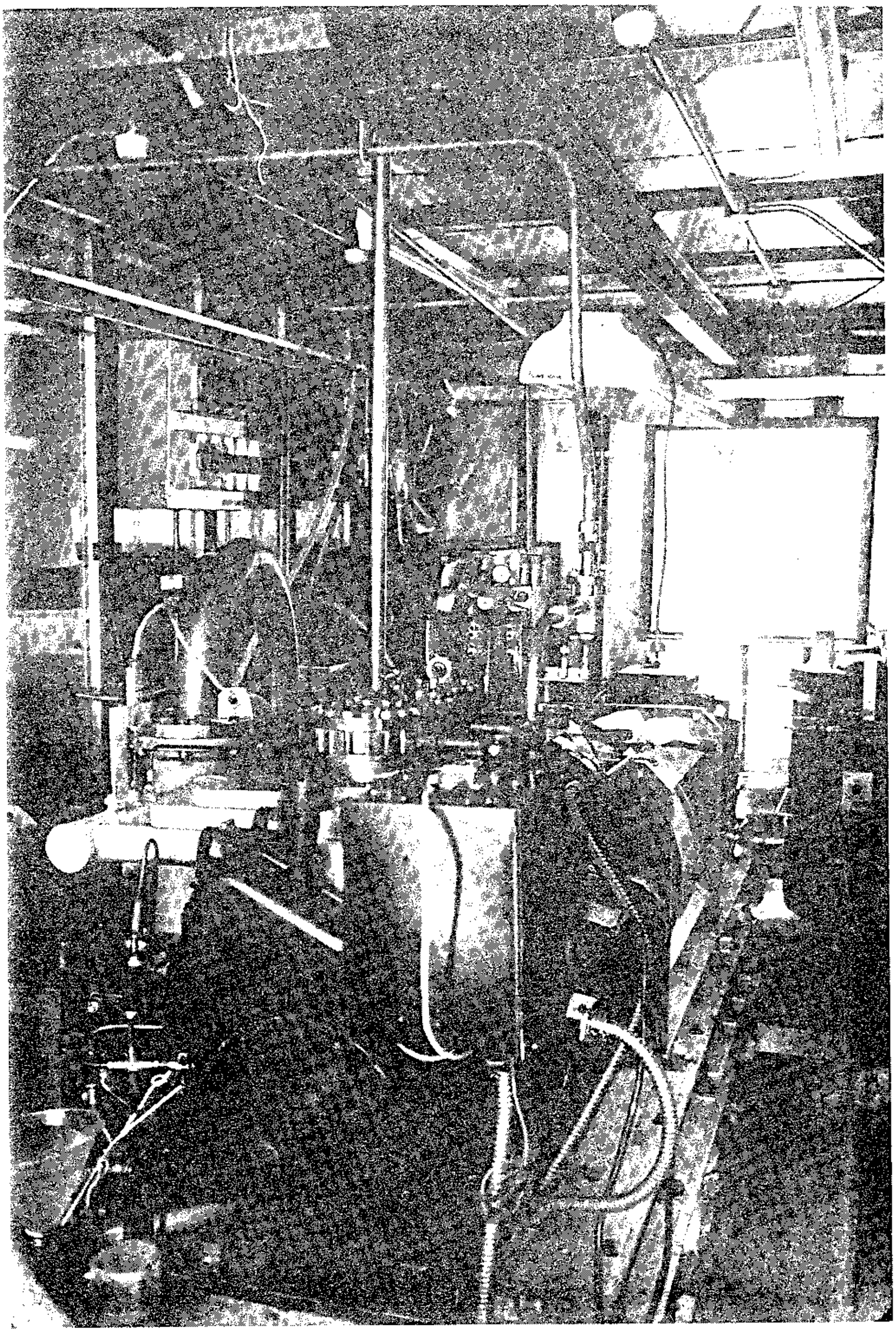


Figure 41(a) - White Cliffs Engine, alternator and dc machine (at rear) (above 80 km/h) on solar operation only. Figure 41(a) and (b) show components in the engine room.

3.4 The Steam Engine

In recent years much effort has been directed to developing, on the one hand, high efficiency heat engines (for example employing Stirling, Brayton and other cycles) for utilizing, very efficiently, the high quality heat from concentrating solar collectors; and on the other, to produce very inexpensive low efficiency steam and other engines which can be built in Third World workshops and supplied by energy from biomass. The former objectives have not as yet been realised because problems of performance, especially reliability and cost effectiveness, have not been adequately overcome; the latter also for various reasons have not resulted in that technology reaching significance.

But there is another approach, relevant to these application areas, which employs medium level technology and is based on mass-produced readily-available components, supplemented by some special items to produce steam engines with heat-to-mechanical work conversion efficiencies of over 20%, robust, reliable, able to be maintained by those with automotive and agricultural experience, and having the potential for cost-effectiveness for many applications.

Such engines have resulted from our development of the White Cliffs Solar Thermal Power Station [Kaneff 1983, 1987], where a unit has operated for many thousands of hours giving electricity supply reliably. Other units are currently working in the USA (in Troy NY, at Albuquerque NM and at the Sandia test facility, preparatory to operation on Molokai Hawaii); please see Appendix I. Further units are to be used for a rural village power supply in Fiji and for the utilisation of crop wastes in Australia. Figure 41 shows the White Cliffs engine.

3.4.1 Engine Details — Piston Operated Valves (POV)

For reasons already indicated, this unit employs a diesel engine converted to steam operation. The particular unit employed — a Lister 3-cylinder engine — is used in its thousands in Australia and has the advantage that each cylinder and head is removable.

Most of the engine is made from parts of two diesel engines (Lister and General Motors) which are on the market. The general form of the engine is shown in Figure 42. Steam is supplied to a chamber in the head of each cylinder; the engine is started by a standard electric motor. As a piston approaches top dead centre, the pins in its crown lift the three ball valves from their seats and steam enters the cylinder until the valves seat again past dead centre. The steam expands while applying pressure to the piston until the piston exposes the normal exhaust ports in the cylinder liner which was made for a 2-stroke diesel engine. The cylinders, cylinder heads, valve seats and steam chambers, that is, the conversion components, can be produced by relatively simple workshop techniques from cast iron, mild steel and stainless steel.

All parts of the engine are inexpensive, do not require special machine tools to fabricate, and two men could rebuild the engine with replacement parts between sunset and sunrise should that ever prove to be necessary.

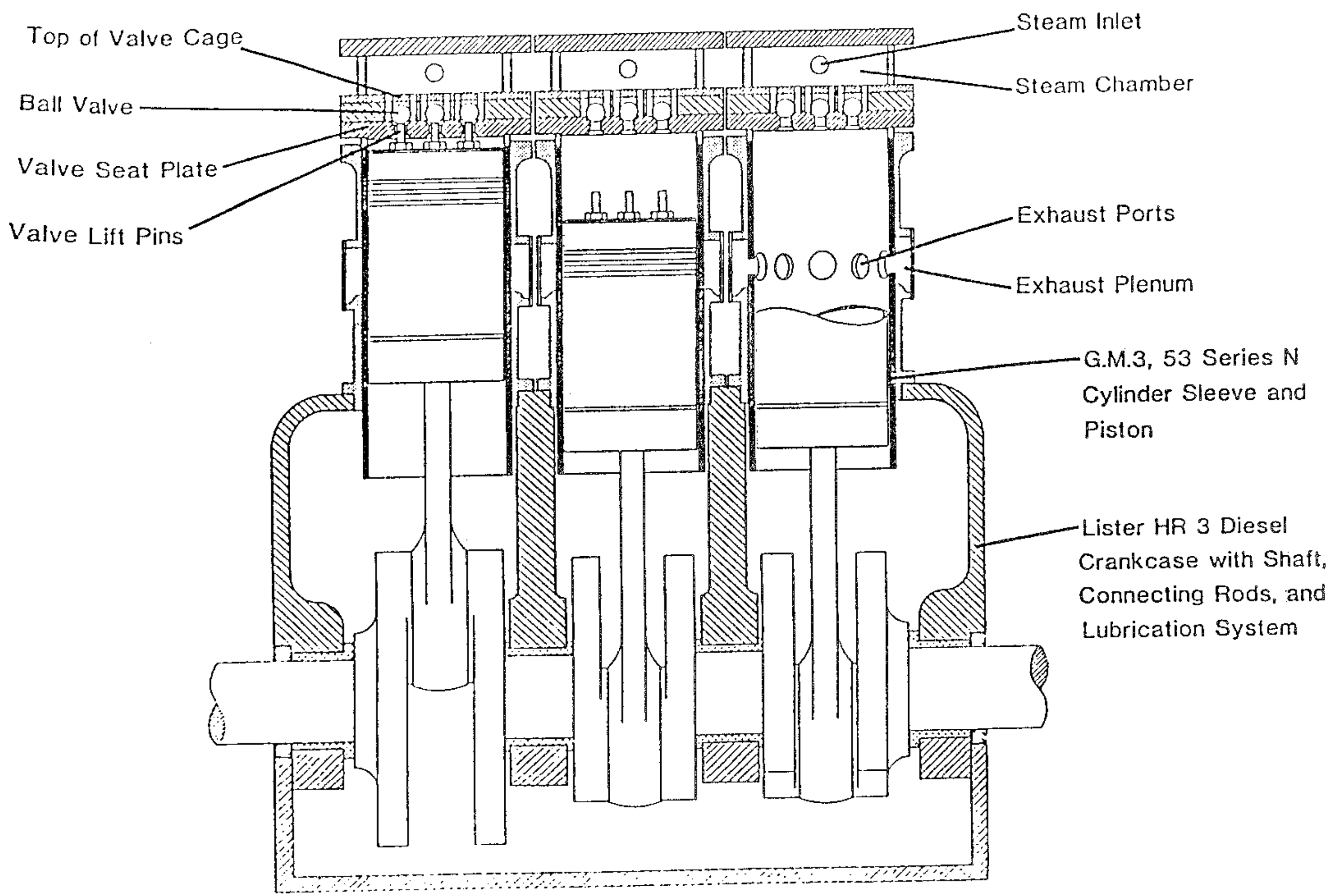


Figure 42 - Basic White Cliffs Engine Details showing piston operated valves, steam chambers, exhaust ports and engine block

Automated starting or stopping is facilitated by the 3 motor-driven valves — bypass, throttle (really an on/off valve only) and drain valve.

When the engine is stationary, a motorised bypass valve is open and water or steam from the solar collectors passes to the condenser until the steam conditions are correct for the engine to start. As water can collect in the steam line to the engine, on start when the throttle opens, water and steam arrive at the engine. With water in the cylinders, the starter motor cannot crank the engine if the water can escape only via the inlet valves. Consequently, a motor-operated drain valve is fitted with a port to each cylinder. Interlocks prevent the starter functioning until the drain valve is open. In configurations which do not allow water buildup in lines, this drain valve is not necessary. When it is, the water can flow to the evacuated exhaust line to the condenser, through ports which limit the amount of steam lost. As soon as the engine starts the drain valve is closed by a signal from a speed measuring instrument. When the engine is running, any water in the steam from the solar collectors is diverted via a steam trap into exhaust lines.

Two major areas of development were necessary:

1. The Valve Mechanism

   Extended reliable operation was achieved only after much attention to geometric configuration and dimensions, satisfactory valve constraints and especially achievement of a satisfactory materials and hardness matching between all appropriate components[8].

2. Oil-Water Treatment

   The engine exhausts into an evacuated condenser via a vortex chamber which collects most of the engine lubricant and water droplets. However, the steam carries some oil droplets which must be removed before the water is recirculated through the solar collectors.

   A process using little power was devised to do this and return as much as possible of the oil to the engine. This is already described in Section 3.3.10, but in more detail, the exhaust steam line enters tangentially the upper end of a cylindrical vortex chamber. Oil and water droplets are stopped by a gauze sleeve on the inner surface and drain to the bottom of the chamber; the steam passes up through stainless steel wool held in a cylinder, which is attached to the top plate of the vortex chamber. The smallest oil drops pass into the condenser with the steam and the condensate carries these as a very fine suspension to compartment 1 of the feedwater tank via the casuum pump. This dispersion of oil in the condensate cannot be removed by conventional filters or the centrifuge, and special fine filters must be employed.

   Some 2 ml/s of oil is recovered from the engine exhaust with the complete condensate treatment — the oil is washed and cleaned by this process, leaving solids in the various filters.

   The White Cliffs engine configuration is:

[8]Please refer to Section 5.8.2 for component lifetime and maintenance requirements.

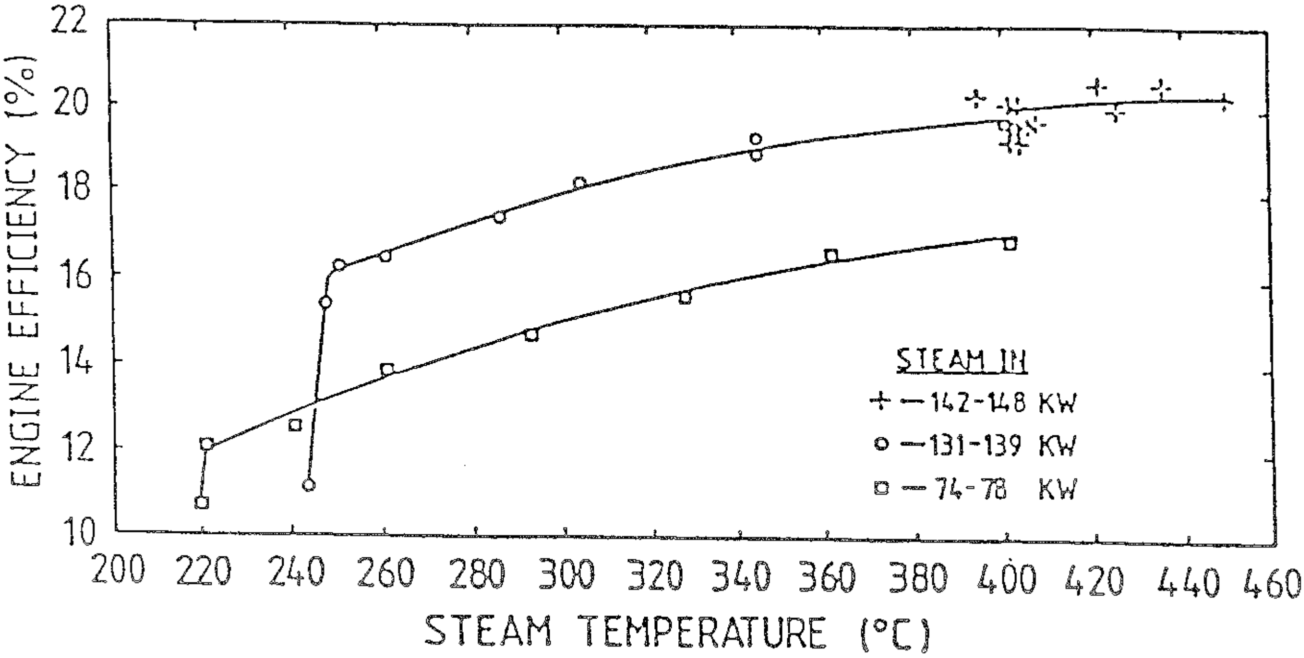


Figure 43 - White Cliffs Steam Engine Performance

Steam supplied from auxiliary boiler

(Measurements made by P. Holligan and M. Williams, Energy Authority of NSW, August 1983)

(Note: Improved efficiency occurs at higher steam energy input).

TABLE VII — STEAM ENGINE PERFORMANCE

Tests 6 June 1982 Engine + Boiler

After tapered pins were introduced
Valve lift = 0.090" nominal
Cylinder Clearance = 2.6mm (0.104") nominal

FW Pump Setting	7.0	6.75	6.5	6.25	6.0	5.75
FW Flow ml/s	50.4	49.0	47.6	46.0	44.0	41.5
FW Back Pressure psi	760	780	780	800	820	840
ER Temperature °C	244	249	280	310	380	427
ER Steam Pressure psi	520	550	550	580	620	630
Engine Temperature °C	240	242	273	302	369	415
Engine Steam Pressure psi	480	500	510	540	590	600
Engine Temperature Out °C	73	74	73	74	74	73
Exhaust Pressure kPa	−79	−76	−81	−79	−80	−81
Engine Oil Pressure psi	39	39	40	39	39	38
Boiler Enthalpy $kW_{thermal}$	135	131	132	131	133	129
	42×335	46.3×335	48.3× 335	49.8×339	54.3× 344	56.3× 347
Electricity Output dc + ac kW	+4.7 =18.8	+4.7 =20.2	+4.7 =20.9	+4.7 =21.6	+4.7 =23.4	+4.7 =24.2
Engine Mechanical Output kW*	22.3	23.9	24.6	25.4	27.4	28.3
Engine Efficiency (η)	16.5	18.2	18.6	19.4	20.6	21.9

$$* \quad \left(\frac{\text{Elec Output dc}}{\eta\ \text{dc}} + \frac{\text{Elec Output ac}}{\eta\ \text{ac}} + 1.4\ \text{kW (no load losses)}\right)$$

Rated flow for system = 50.4 ml/s.

Efficiency > 22% at higher steam quality.

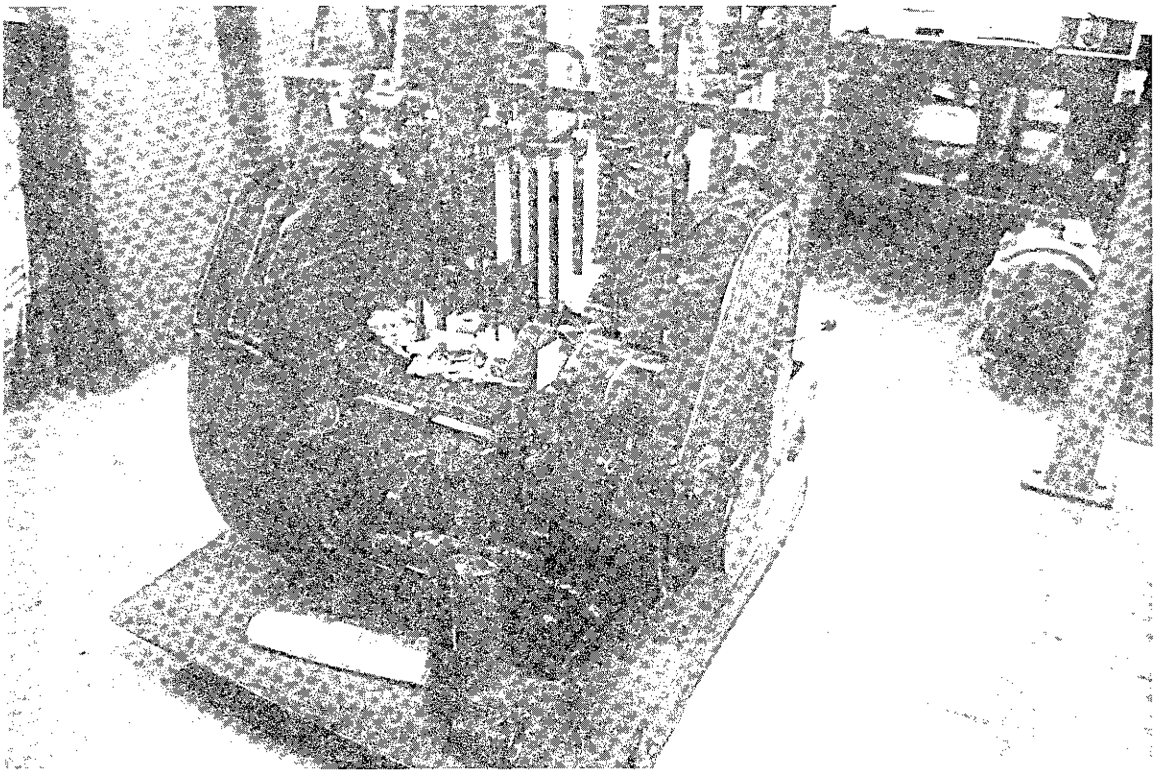


Figure 44(c) - A 3 Cylinder Engine Block before Conversion (as many of the original components as possible are used).

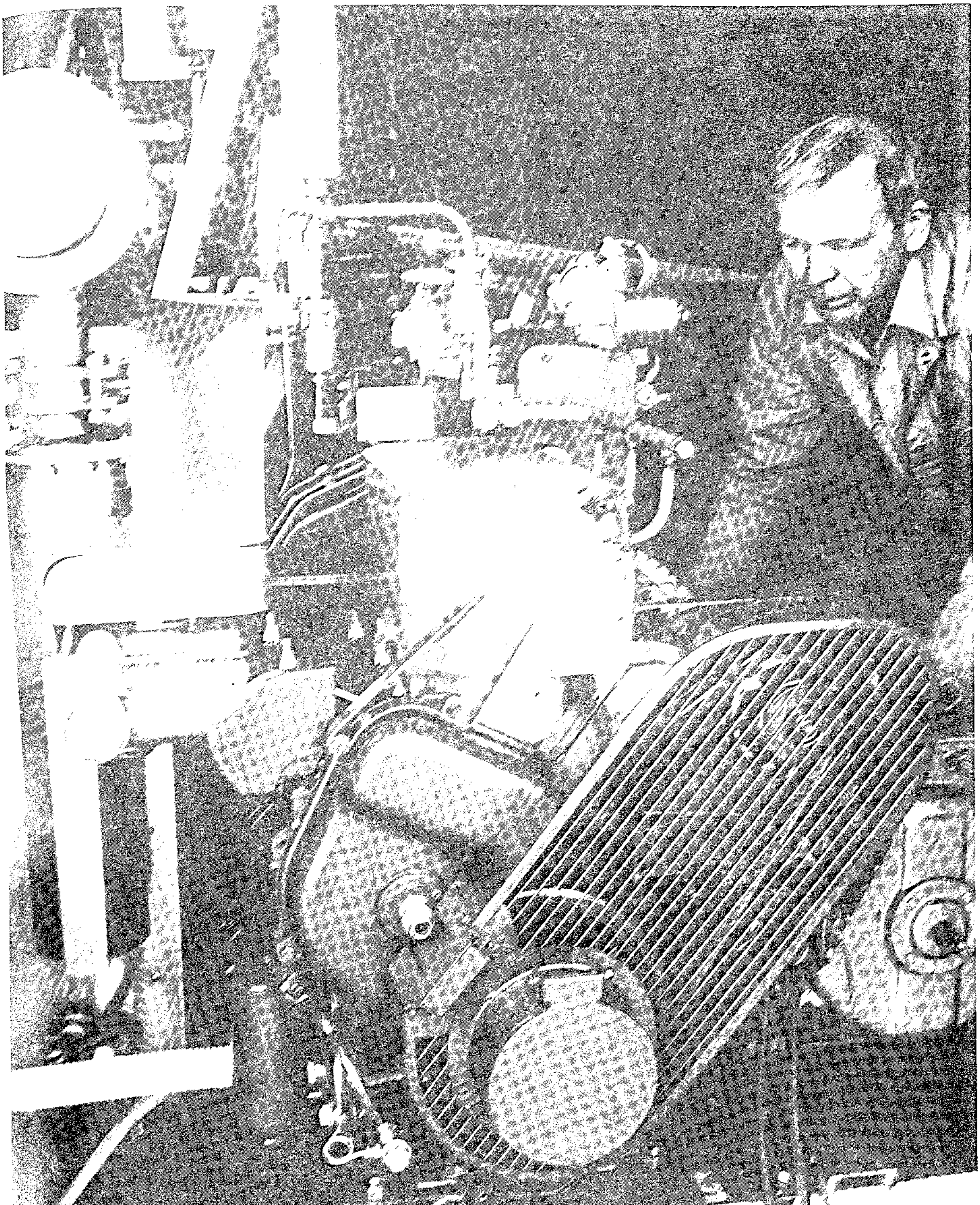


Figure 44(b) - The Engine of Figure 44(a) in working order
(Note Vortex Chamber to the left, and condenser above vortex chamber).

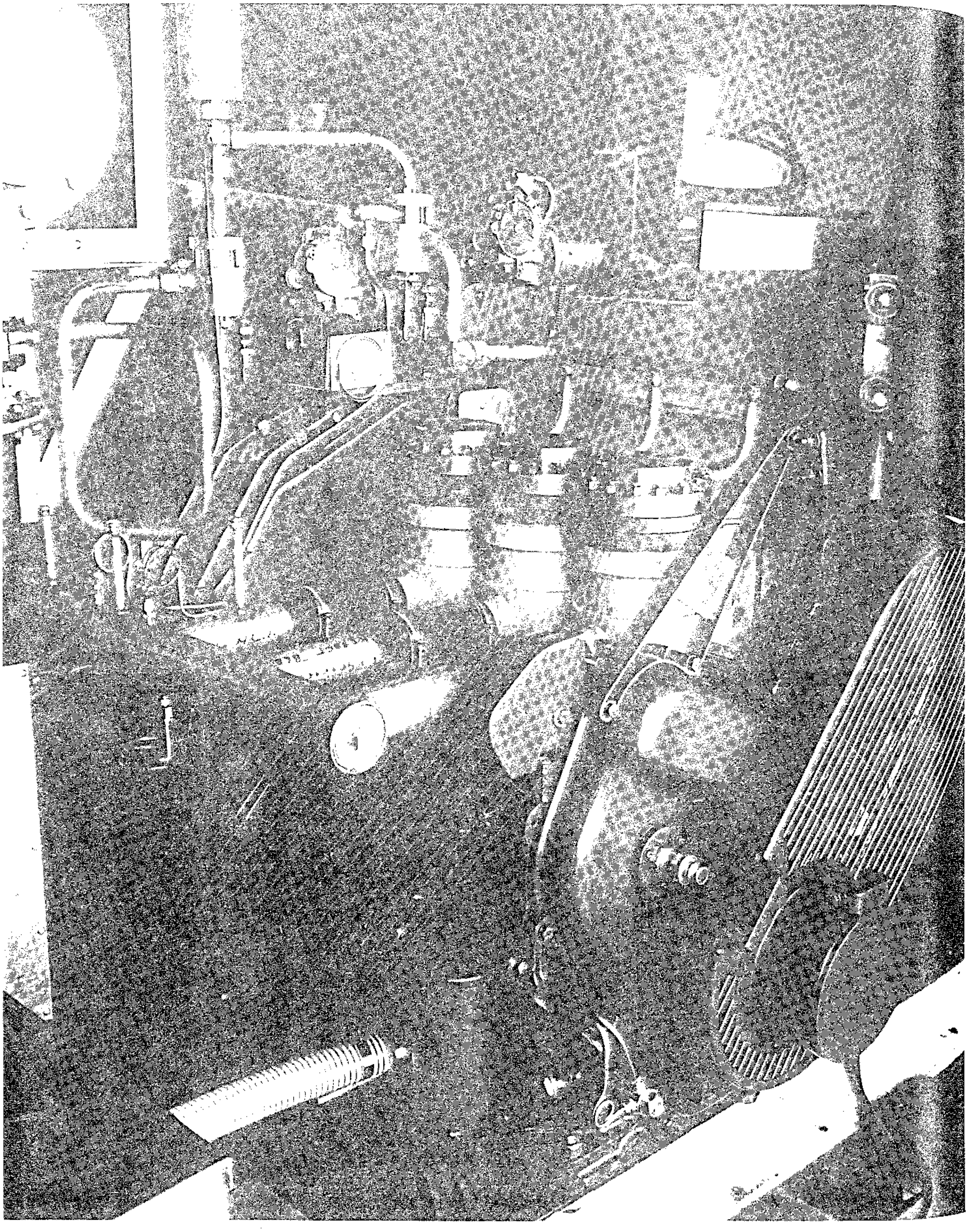


Figure 44(a) - 3 Cylinder Engine Conversion, a later development than the engine of Figure 41. Insulation has been removed to show cylinders be noted that engine speed (and system frequency) is set by the reference V_R and no other speed control is required.

Whenever there is no solar steam contribution, the steam engine stops (or it may be supplied from its auxiliary boiler). The coupling between steam engine and alternator allows the AC/DC set to continue to turn while the steam engine is stationary (with an energy loss in the freewheel coupling of about 140 watts); the coupling automatically accepts energy input from the steam engine whenever the latter's speed has reached N and can contribute energy as a result of adequate steam supply.

With the steam engine stationary, the AC/DC set can continue to supply the load until the battery has been discharged or preferably (to maintain a reasonable battery life) has been 80% discharged (ie battery voltage on load has dropped to about 1.8 volts per cell).

When the battery can no longer maintain the load, the diesel generating set is brought into service automatically.

3.5.1 Battery Operating Modes

A daily load cycle for White Cliffs was not known initially and could be obtained only by experience. Notionally the cycle was considered as in Figure 46, for a summer's day[9].

Because of conversion losses, AC load energy available from the DC machine/battery storage unit is about 52% of the excess steam engine output energy available for storage; or AC load energy available via storage is about 57% of that which would have been available directly from the alternator with the same engine output[10].

AC output via storage = mechanical power from engine $\times$ DC generator efficiency (0.90) $\times$ battery storage efficiency (0.7) $\times$ DC motor efficiency (0.90) $\times$ AC generator efficiency (0.92) = 52% $\times$ mechanical power from engine.

Direct (no storage) AC power output = mechanical power from engine $\times$ AC generator efficiency (0.92) = 92% $\times$ mechanical power from engine.

$$\text{Ratio} \; \frac{\text{AC power output via storage}}{\text{direct (no storage) AC power output}} = \frac{52\%}{92\%} = 57\%$$

[These values apply for significant load flows and are higher than could be achieved using rectifier-inverter systems which also involved greater capital cost when this system was developed.]

The DC machine/battery system permits a relatively simple means for providing not only storage but, very importantly, a way of coping dynamically with the problems of load and insolation variations and a means for utilising all available solar energy. Size of the DC machine has been chosen to provide 25 kWe AC output and to be able to inject 25 kWe DC input to the battery (this is all that can be available because AC and DC generator efficiencies are comparable). Capacity of the battery storage has been chosen (for want of a better criterion in the absence of load demand

[9]Over the years it has turned out that this concept of a daily load cycle was far from reality. As indicated in Section 5.4, the actual load can vary from almost flat to the occurrence of peaks at various times of day; sometimes these peaks occur at normally expected times, but often at other times (see Figures 71 and 72 for example). Battery energy flows from all sources [Bare considered in Section 5.5.3.

[10]Nearly one-half the generated energy is lost if it needs to flow through the battery system. Losses are relatively smaller at high charge and withdrawal rates.

Bore	98.4mm
Stroke	114.3mm
Number of Cylinders	3
Maximum Steam Pressure	70 kg/cm^2 (abs) (6.9 MPa)
Maximum Steam Temperature	450°C
Condenser Pressure	0.25 kg/cm^2 (abs) (24.5 KPa)
Expansion Ratio (Adjustable)	1.25 (used)
Lubrication	as in Lister engine
Lubricant	specially selected
Measured Efficiency — (Steam Press 42 kg/cm^2, Temperature 415°C)	21.9%

3.4.2 Auxiliary Boiler

An auxiliary monotube boiler is available for testing the engine and to act as a backup if the diesel unit is out of service.

3.4.3 Performance

Table VII shows representative performance characteristics and Figure 43 indicates efficiency varitions at different steam temperatures for four different thermal power inputs — these measurements were made by P. Holligan and M. Williams, NSW Energy Authority, in August 1983. It is apparent that efficiency drops slowly with reduction of superheat until saturated steam results, after which operation on wet steam causes a rapid reduction in efficiency as degree of 'wetness' increases.

Figure 41 shows the engine at White Cliffs; a later version is indicated in Figures 44(a) and (b); a block before conversion is shown in Figure 44(c). Engine operation is described in Section 1.1. We consider this engine technology has good potential and scope for considerable further improvement.

3.5 The Electrical System — Energy Storage

The overall philosophy employed held that maximum practicable efficiencies should be attained in all units while collection costs are high, even at the penalty of considerable extra cost, as the extra energy gained can be traded off with the requirement of less collector area.

The mechanical-to-electrical conversion and storage sections of Figure 2 are identified in Figure 45, which also illustrates the machine shaft torque-balance and frequency control functions [Kaneff 1980(b)].

The coupled AC and DC machines are in turn mechanically coupled to the engine via a freewheel coupling, allowing continuous electrical machine rotation and intermittent steam engine operation — in line with the availability of solar energy. The arrangement allows all available useful solar energy to be gathered and used directly and/or stored.

Digression from 50 Hz causes the DC machine field to adjust operation to restore set frequency (signal V_R) in accordance with excess or deficit of energy from the engine in relation to load demands. At night or in cloudy periods, the AC load is supplied by the battery via the DC machine (the engine being stationary). It will

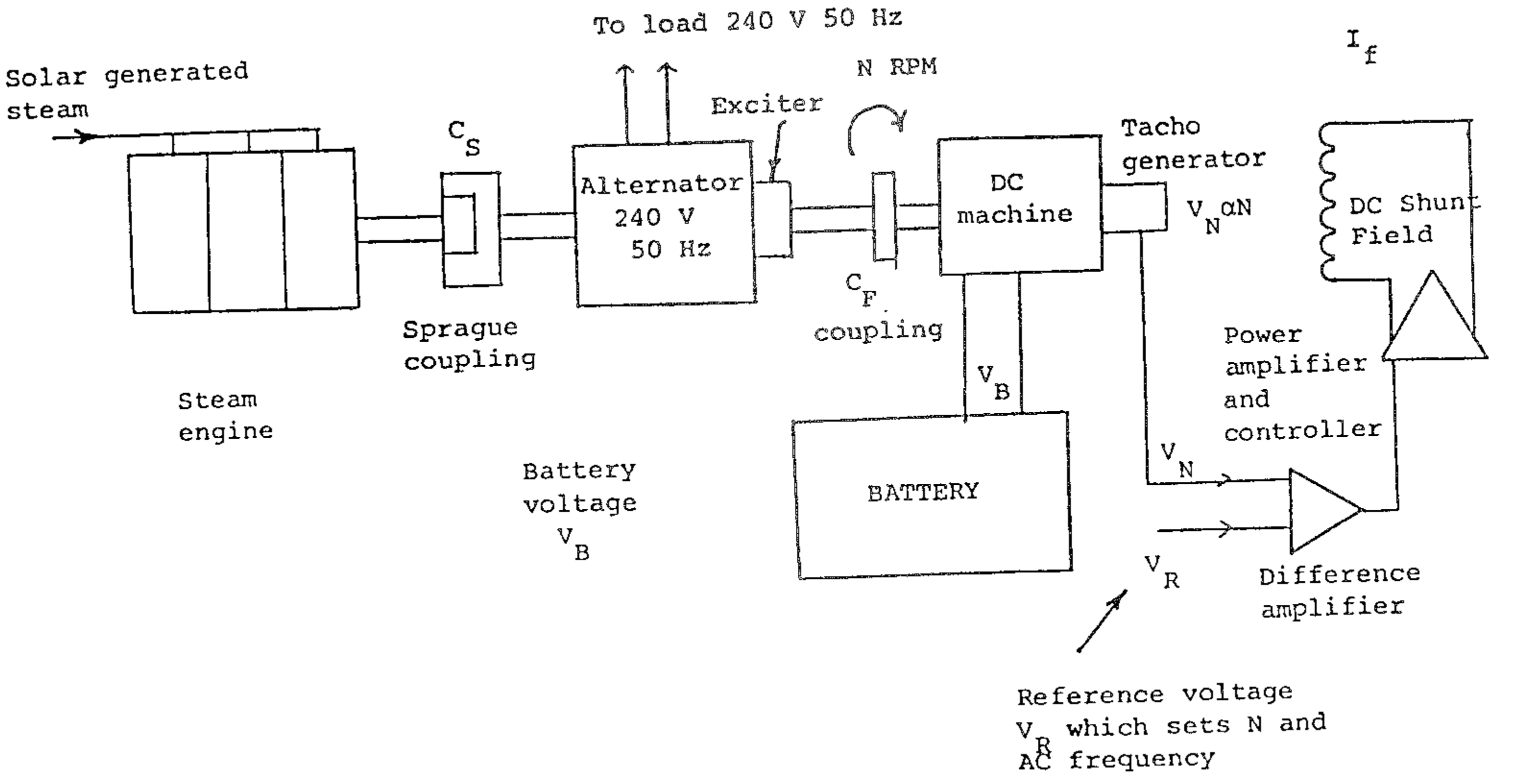


Figure 45(a). The ac/dc Machine/Battery Store/Torque/Frequency Control Systems.

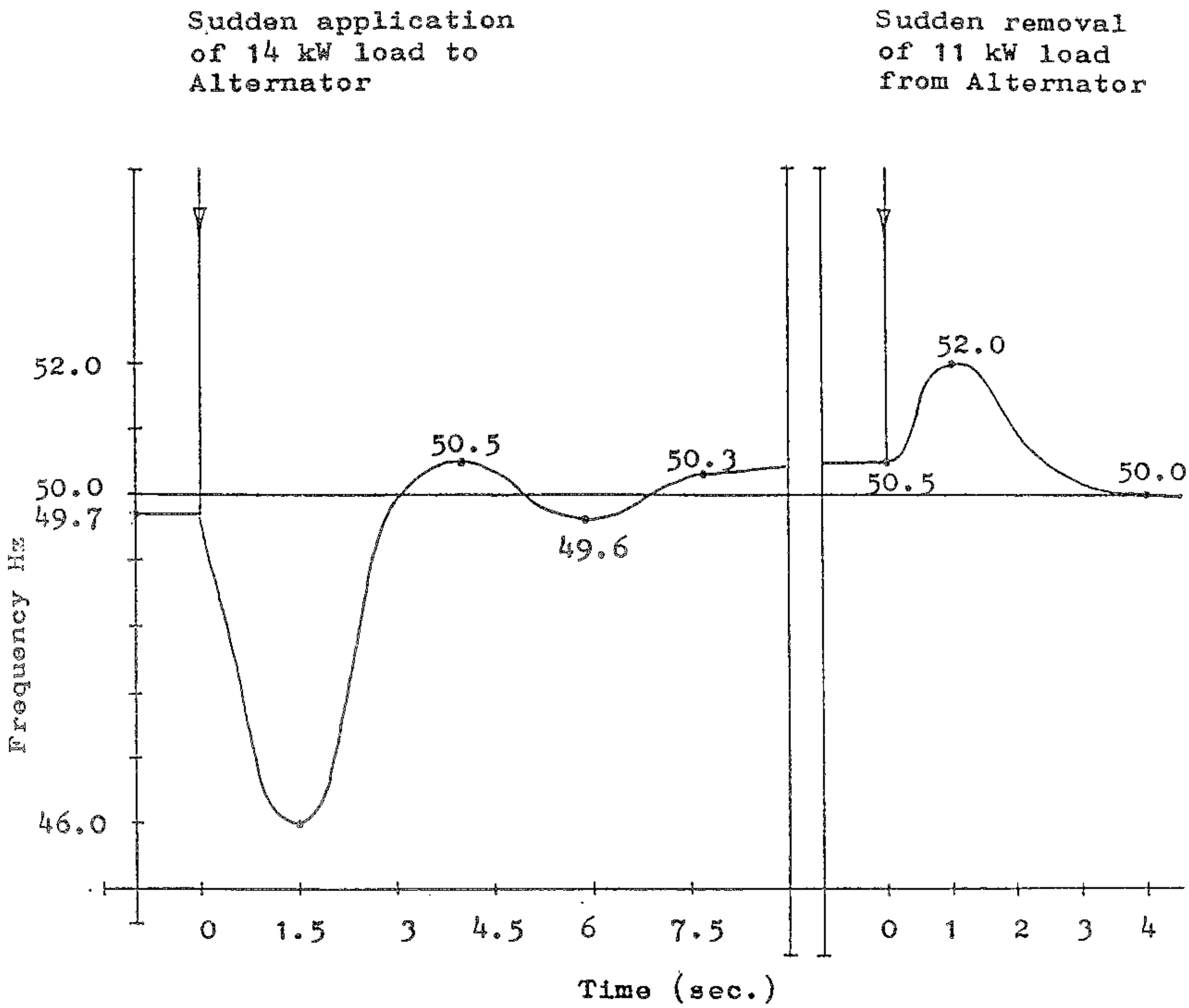


Figure 45(b) - Typical Transient Response/Recovery times of the ac/dc machine/battery store/torque/frequency control system of Figure 45(a)

Note: The binary field control system operates at approx. 2-3 steps/second. Transient responses set by field control characteristics as a compromise between amount of overshoot and duration of the transient. Steady state frquency is normally 50 Hz ± 0.5 Hz.

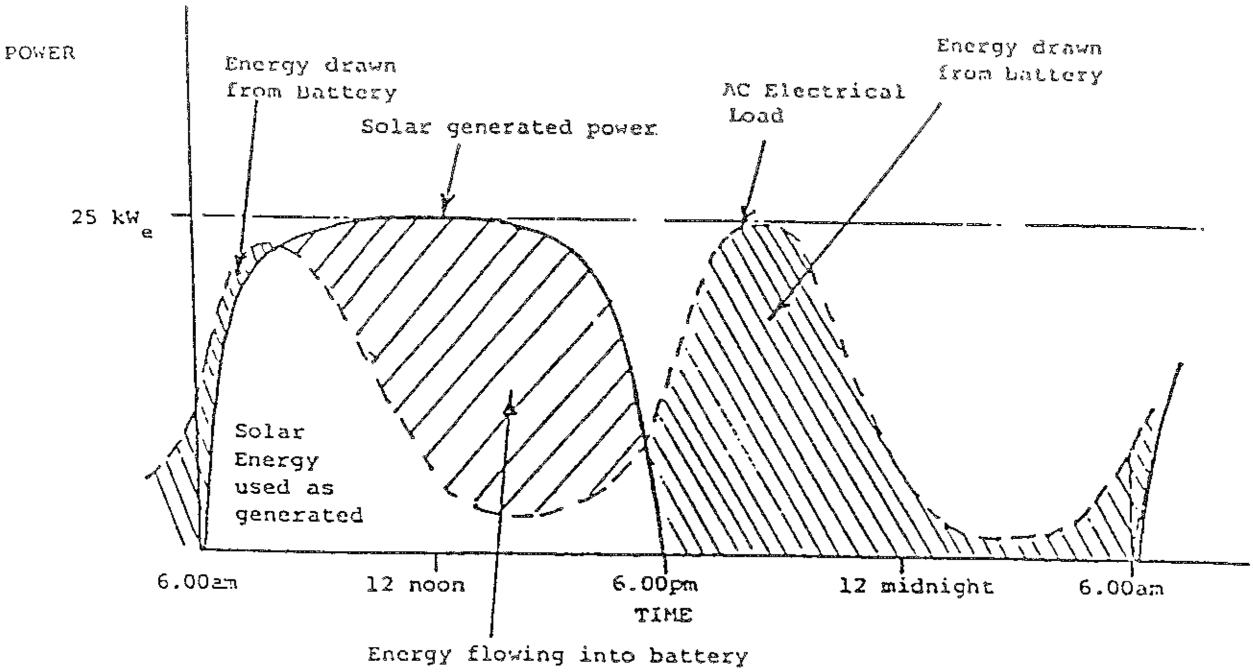


Figure 46 - Notional White Cliffs Load Curve

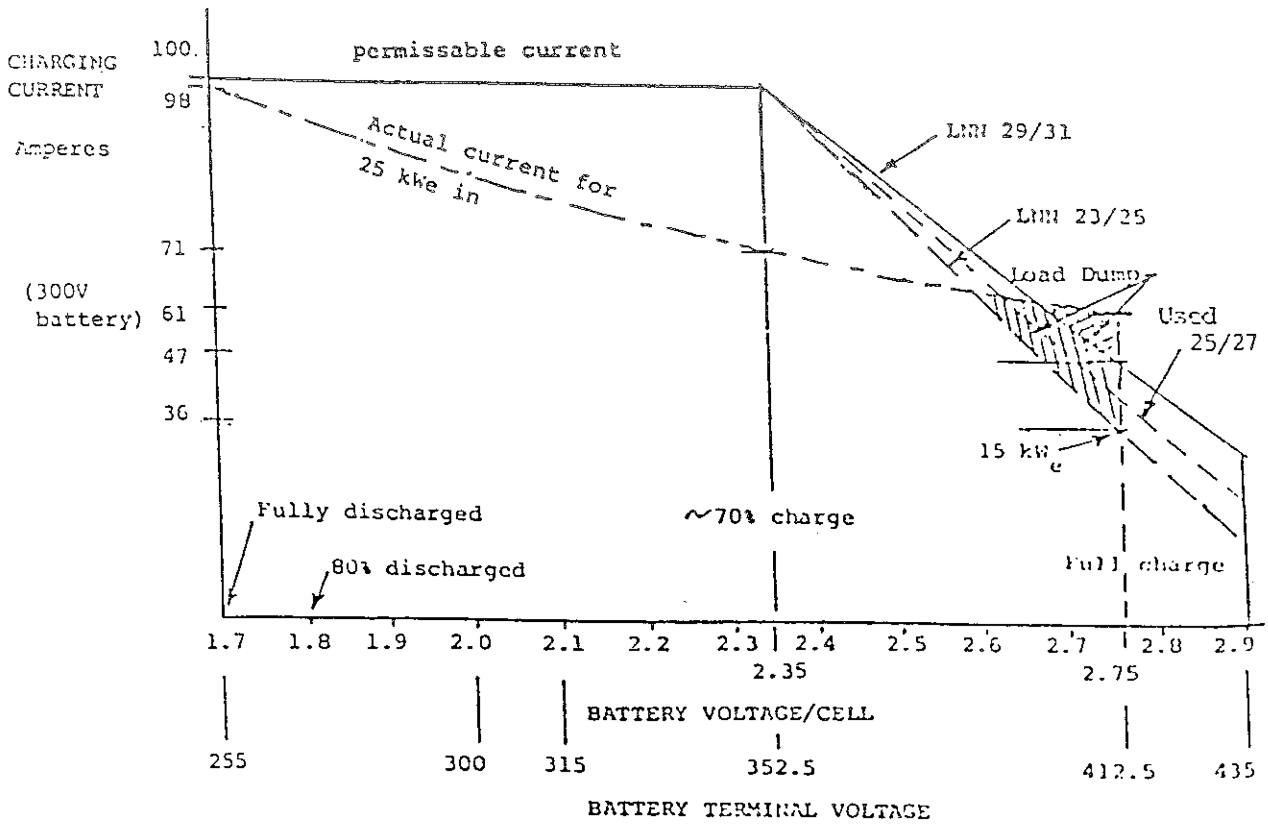


Figure 47 - Battery Parameters and Operating Zones

information) such that a full day's power station output can be injected into an empty store.

In the event, the actual load characteristics have turned out to be so variable that the above considerations were almost a fiction. As indicated in Section 5.1, load characteristics may vary at times from almost constant 24-hour load to the appearance of several peaks each 24 hours, as is more normal with such load curves.

To ensure proper operation of the system and/or long battery life:

(a) When on-load battery terminal voltage drops to 1.8 volts/cell (270 V), the auxiliary power source (diesel unit) is brought into service (1.8 V/cell represents about 80% discharge of the battery — if absolutely necessary, further energy may be taken to 1.7 V/cell but at the cost of reduced battery life).

(b) The battey will accept up to 25 kWe input until the charge condition has well exceeded the gassing voltage of 2.35 V/cell (352.5 V) or about 70%+ charge.

For Lucas-type LNN 23/25 heavy-duty traction cells, forming a battery of 300 V nominal voltage, a charging rate of 25 kWe input can be maintained until voltage/cell has reached nearly 2.6 V. For Lucas-type LNN 29/31 cells, a charging rate of 25 kWe can be maintained almost up to full battery charge. In practice it is not expected that load would need to be dumped since some energy from the system would always be used during the day and total load demand per 24 hours is likely to be greater than solar energy available from the system (so that a carryover of battery charge from one day to another would appear unlikely — this has been borne out in practice).

The battery operating zones are illustrated in Figure 47. Figure 48 shows the basic DC system.

3.5.2 Protection

A DC circuit breaker connects the battery to the motor armature and starter, the DC field has a suitable discharge resistor and field control, and the DC machine/battery unit is electrically isolated from the rest of the system, and the batteries are housed in a separate container.

V_R (Figure 45) sets the speed and frequency of the system and the associated control holds the frequency within limits. The alternator control takes care of AC voltage and regulation. When speed (frequency) rises above tolerance, the steam throttle (held wide open in normal operation) is closed, steam is bypassed to the condenser and the collectors are offsteered to reduce solar input to Bzero.

The DC machine has an internal temperature sensing circuit which, when energised, indicates high temperatures are being generated — the signal is employed to switch on the external cooling fan. If the temperature still increases, the DC circuit breaker is tripped to protect the machine from overheating. Tripping of the circuit breaker is most likely to occur while the machine is motoring (since the current flow is then higher than for generating) or an electrical fault may have occurred. In any event, because of the central role played by this DC machine in operation of the system, the auxiliary supply is switched on and the solar systems closed down until the problem has been cleared. This protection has never been called on to operate.

Battery temperature: High battery temperatures reduce working life of the battery; 70°C working temperature should not be normally exceeded. Temperature sensors are provided for each bank of batteries and operation of the system will be discontinued if the temperature exceeds 70°C on any bank.

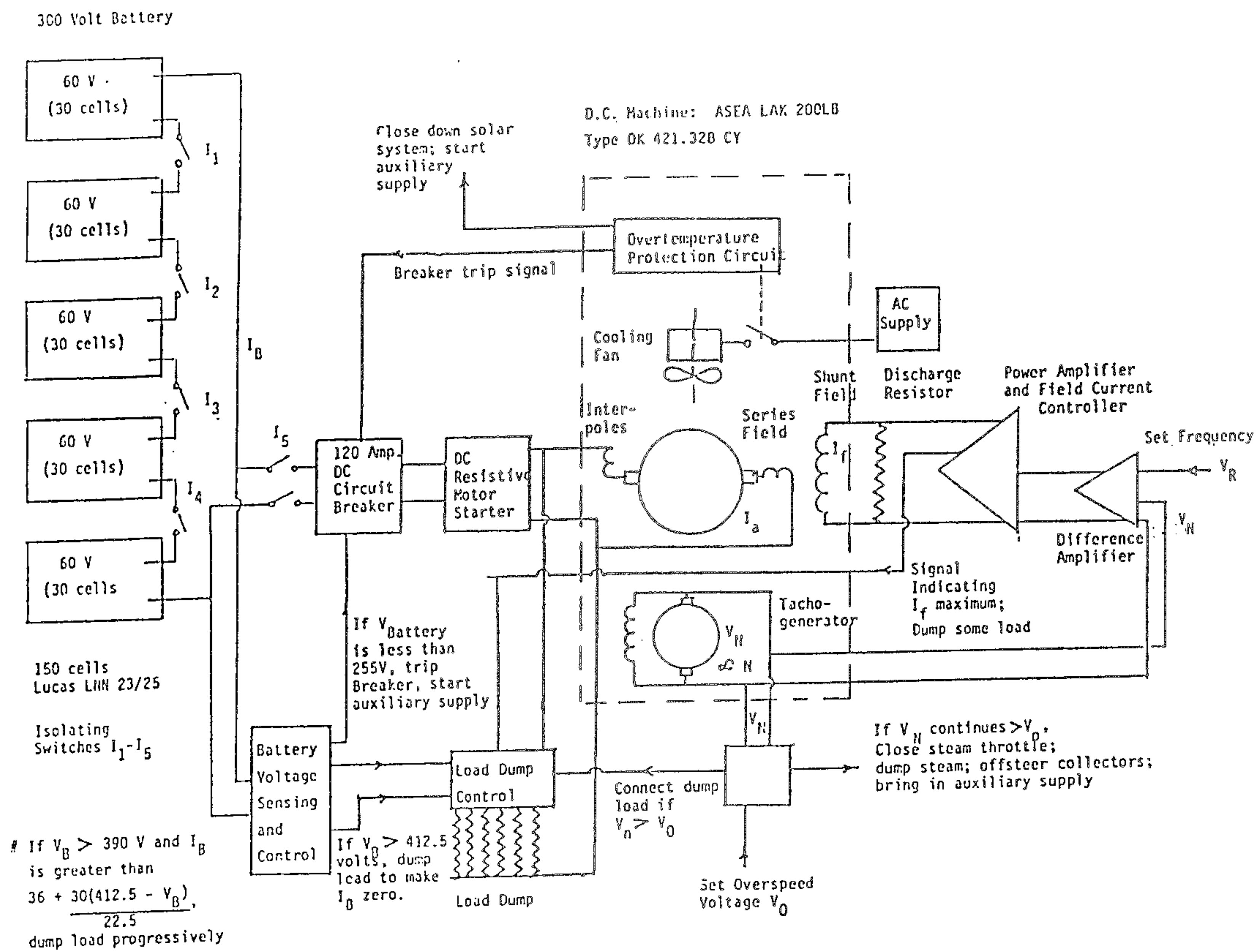


Figure 48. The Basic dc/Battery System.

3.5.3 Specifying DC Machine and Battery

The DC machine and battery must be considered together because of their close interrelationship.

While nickel cadmium batteries are likely to have a longer life, their cost disadvantage of about a factor of four times led naturally to the selection of lead acid batteries. Fortunately, Lucas Industries had developed a range of heavy-duty traction batteries specially for the demanding conditions experienced in Mount Isa mines, and these were selected as the best balance between first cost, durability, capacity and effectiveness.

Lead acid cells have terminal voltages which vary widely depending on conditions. A 2 V nominal cell may reach as high as 2.9 V on full charge then, if disconnected, its voltage will drop to 2.1 V within 8–12 hours, depending on temperature and other factors. On the other hand, a 2 V cell having been charged to 2.9 V may drop to 2.1 V in very few seconds in heavier discharge. On discharge, to all intents and purposes therefore, the voltage per cell (on load) may be considered to range from 2.1 V (fully charged) down to 1.8 V (80% discharge) and 1.7 V (fully discharged — an undesirable condition).

On charge, a fully discharged cell starts at 2.0 V and, as charge accumulates, its voltage rises slowly to 2.35 V (gassing voltage) when about 70% charged. Thereafter, voltage rises more rapidly to 2.75 V on full charge and, at certain conditions such as high temperatures, even to 2.9 V. To conserve life of the battery, however, volts per cell should not be allowed to exceed 2.75.

An obvious characteristic of a battery subject to varying amounts of charge and discharge is the wide excursions in terminal voltage which are encountered, as illustrated in Figure 49.

Because of the consequent varying iron, eddy current and copper losses, care is needed in selecting a suitable DC machine. Unfortunately, because of an almost complete lack of information of the probable daily consumer load variations, it was not practicable to design an installation which can be assured to be optimum. In the event, it was taken that the DC machine would operate more or less in all possible load zones. Consequently, selection of a machine with relatively low losses at both low and high generating and motoring loads was made.

Parameters of the DC machine selected are given in Table VIII; Figure 50 shows the DC machine characteristics at various operating conditions; on balance, it operates best with a 300 V nominal battery, using Lucas-type LNN 25/27 cells, the units selected [Kaneff 1980(b)]. Consistent with our general policy on high efficiency electrical components, an ASEA servomotor was used in this application, running at carefully defined lower speed, lower voltage, and lower current than rated values to achieve higher efficiencies [Kaneff 1980(c)].

3.5.4 The AC Machine

The Energy Authority of New South Wales specified a single phase alternator operating at 240 V. Commercial versions of such machines tend to rather low efficiency, typically less than 88% on full load. Jones and Rickard of Sydney were able to supply a custom-built machine, rated at 37 kVA, 240 V, 155 A, 50 Hz with an efficiency of 92% from full load down to about one-quarter load. Even though this unit was considerably more expensive than normal commercial machines, the 4–5% higher efficiency effectively saves 1 collector in 20 or so; consequently the extra cost was

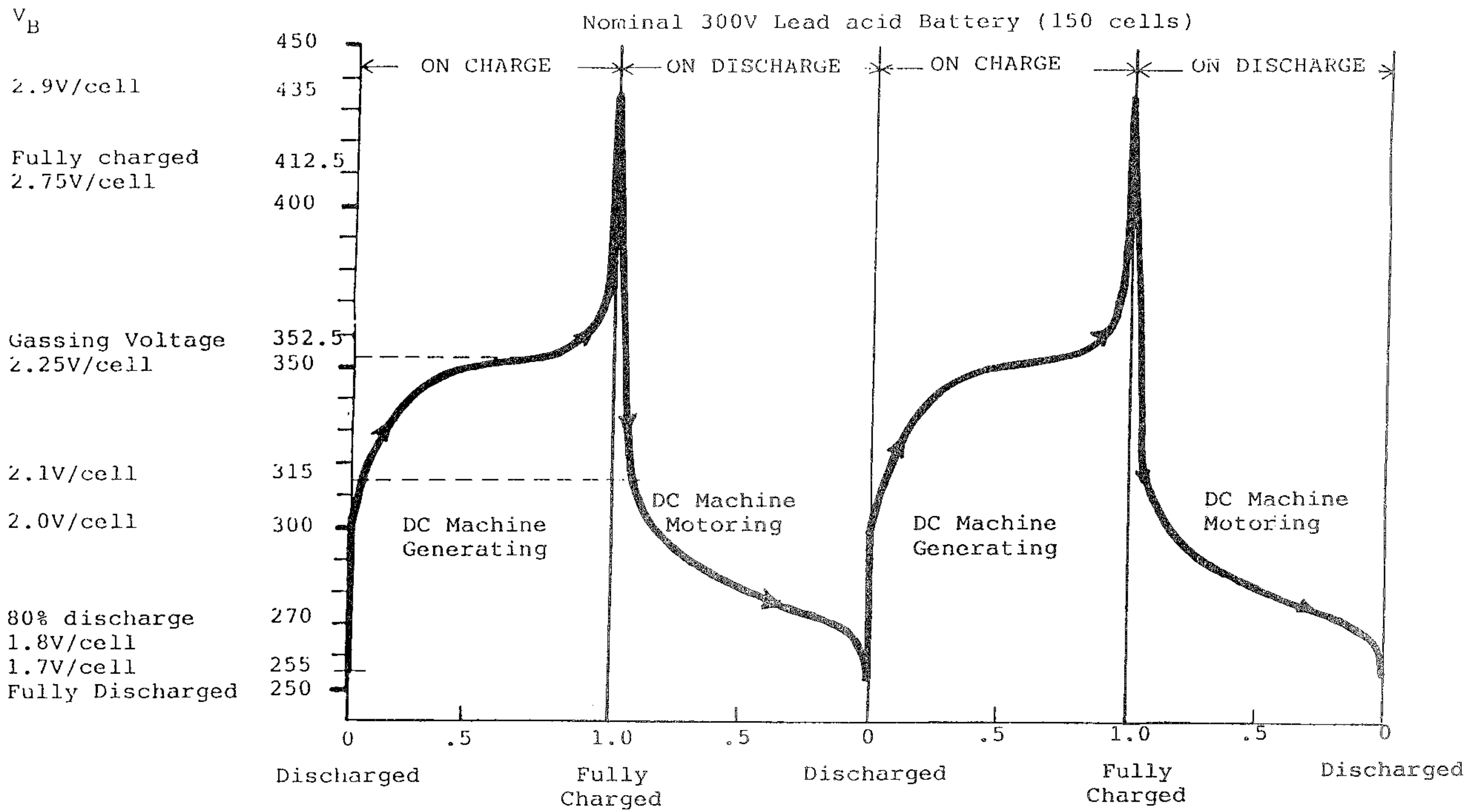


Figure 49 - Battery Voltage Variations at Different Charge/Discharge Conditions

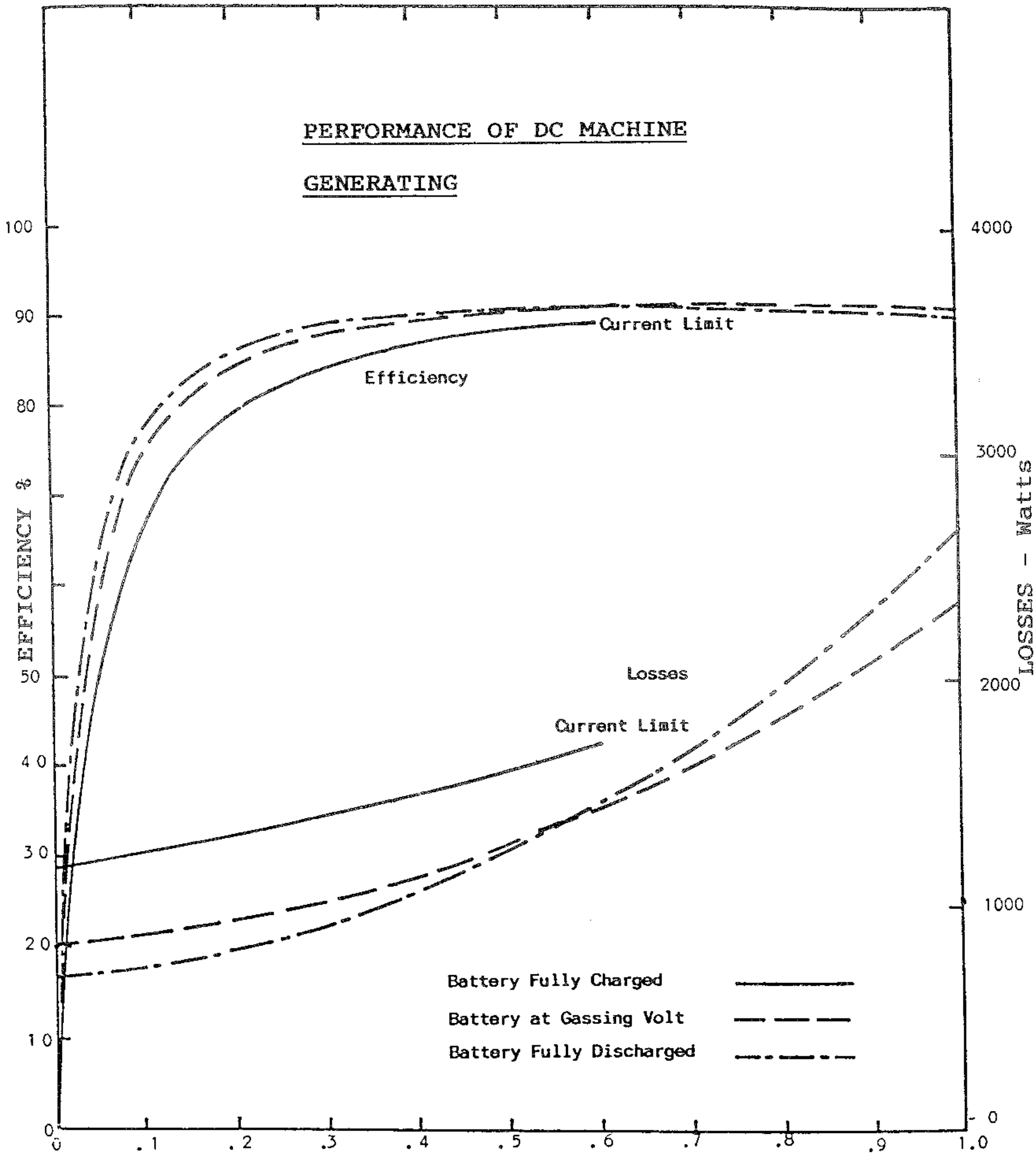


Figure 50(a) - OUTPUT POWER Per Unit (to give 25kW input to Battery at 1.0 pu.)

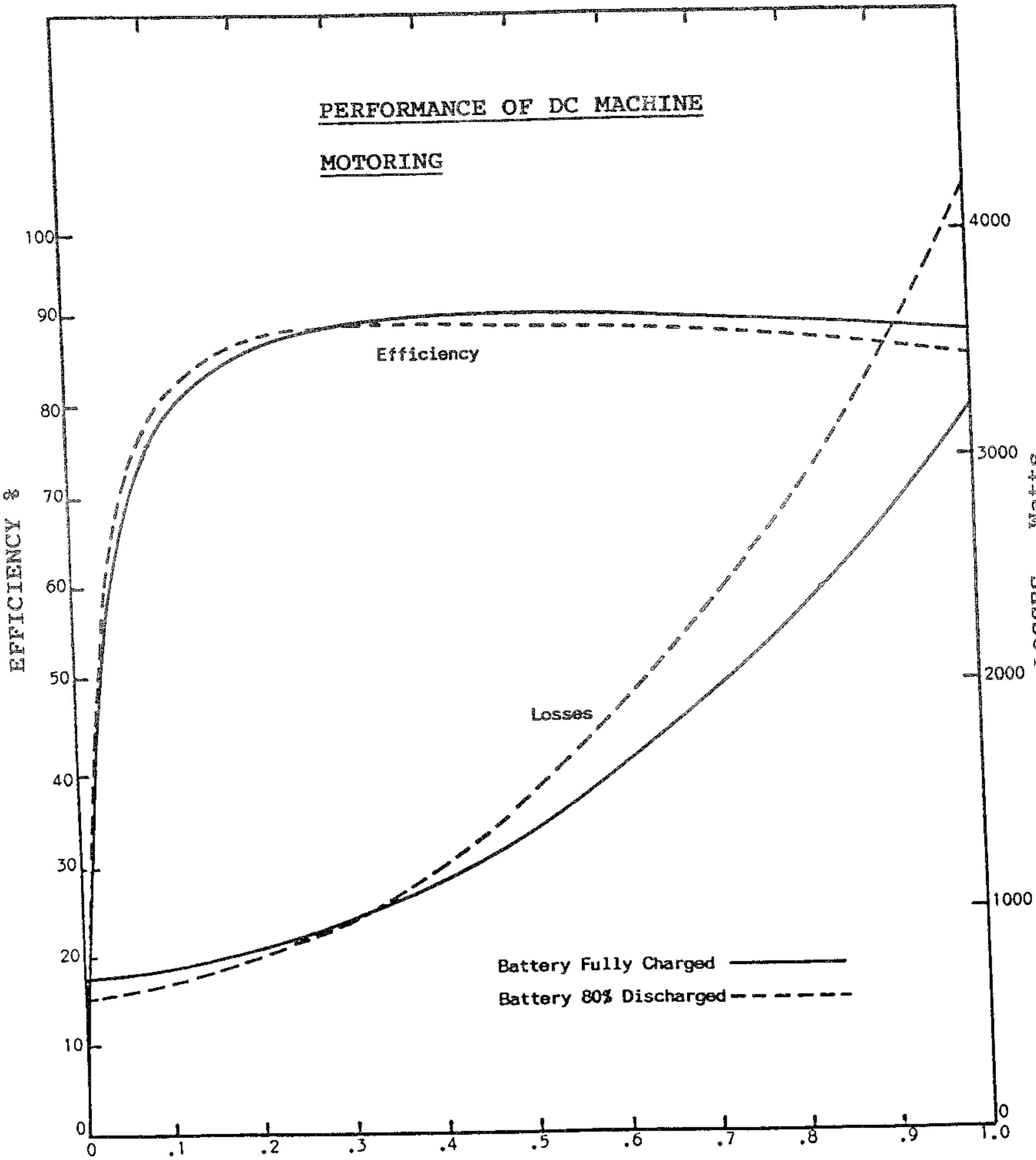


Figure 50(b) - OUTPUT POWER Per Unit (to give 25kWe AC from Alternator at 1.0 pu.)

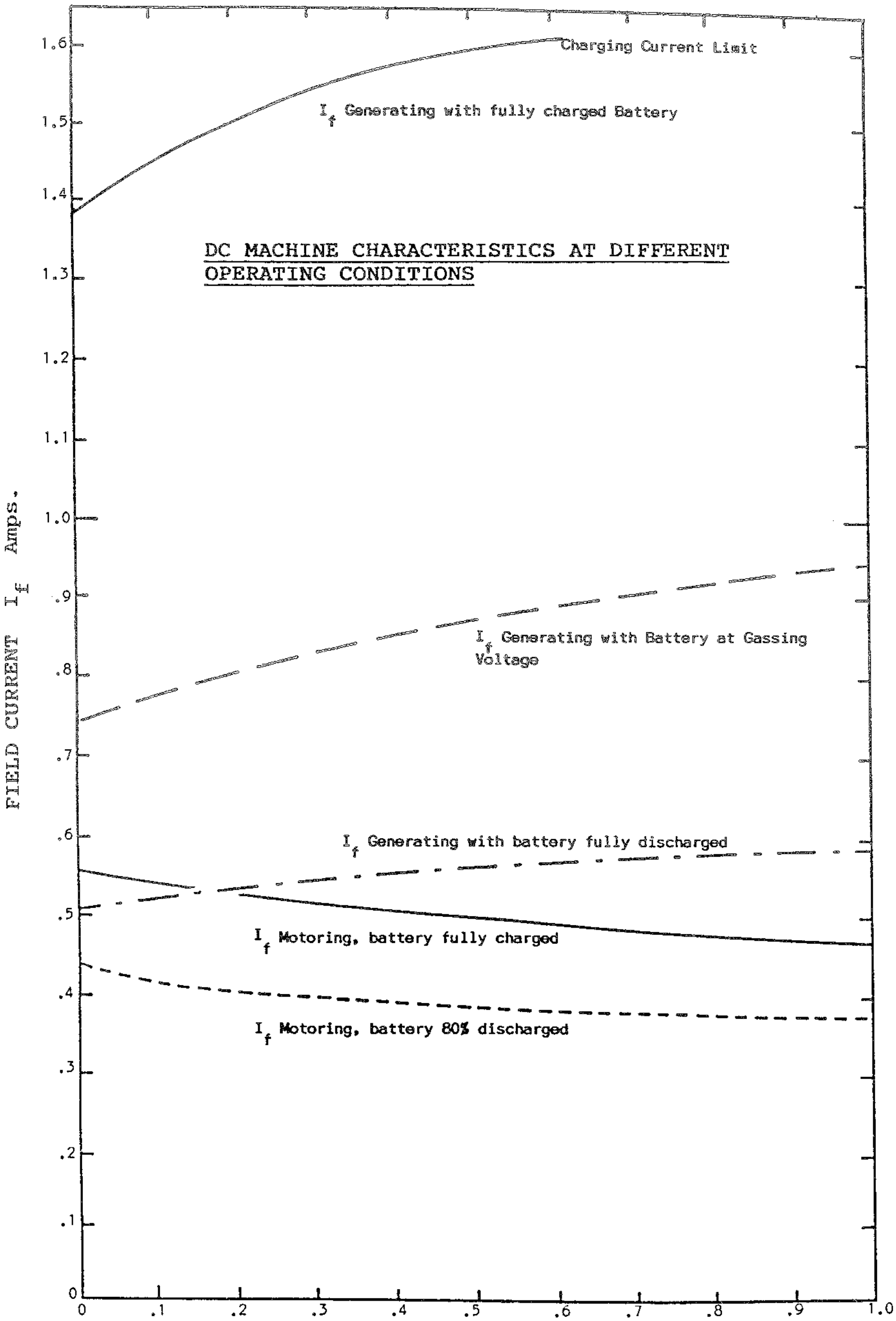


Figure 50(c) - OUTPUT POWER Per Unit (Motoring: to give 25kW AC from Alternator at 1.0 pu.; Generating; to give 25kW into Battery at 1.0 pu.)

TABLE VIII — DETAILS OF DC MACHINE

ASEA Type LAK 200 LB Laminated Frame DC Motor YY 441.8740; OK 421.328 CY Compound Wound, 42.0 kW, 1 600 PRM, Continuous Duty, Armature 470 V, 98.0 Amps, Field Voltage 200 V with Blower 3 x 415 V, 50 Hz, 1.5 Amps, OK 421, 024-A and Tachometer Generator OK 421.017-A, T GBB 1-5 A and Klixon X 114 (temperature protection).

Efficiency at Full Load	91.2%
R_a at 20°C	0.128 Ω
$R_{\text{interpoles}}$ at 20°C	0.079 Ω
R_{series} Winding at 20°C	0.017 Ω
$R_{\text{shunt field}}$ at 20°C	135.0 Ω
L_a (150 Hz)	7.2 mH
L_f	143.0 H
Potential Drop, including Brushes at Full Current	32.0 V
I_f at 1600 PRM	1.37 A
I_f at 2400 PRM	0.044 A
Insulation	Class F

This machine runs at 1500 rpm for 50 Hz supply.

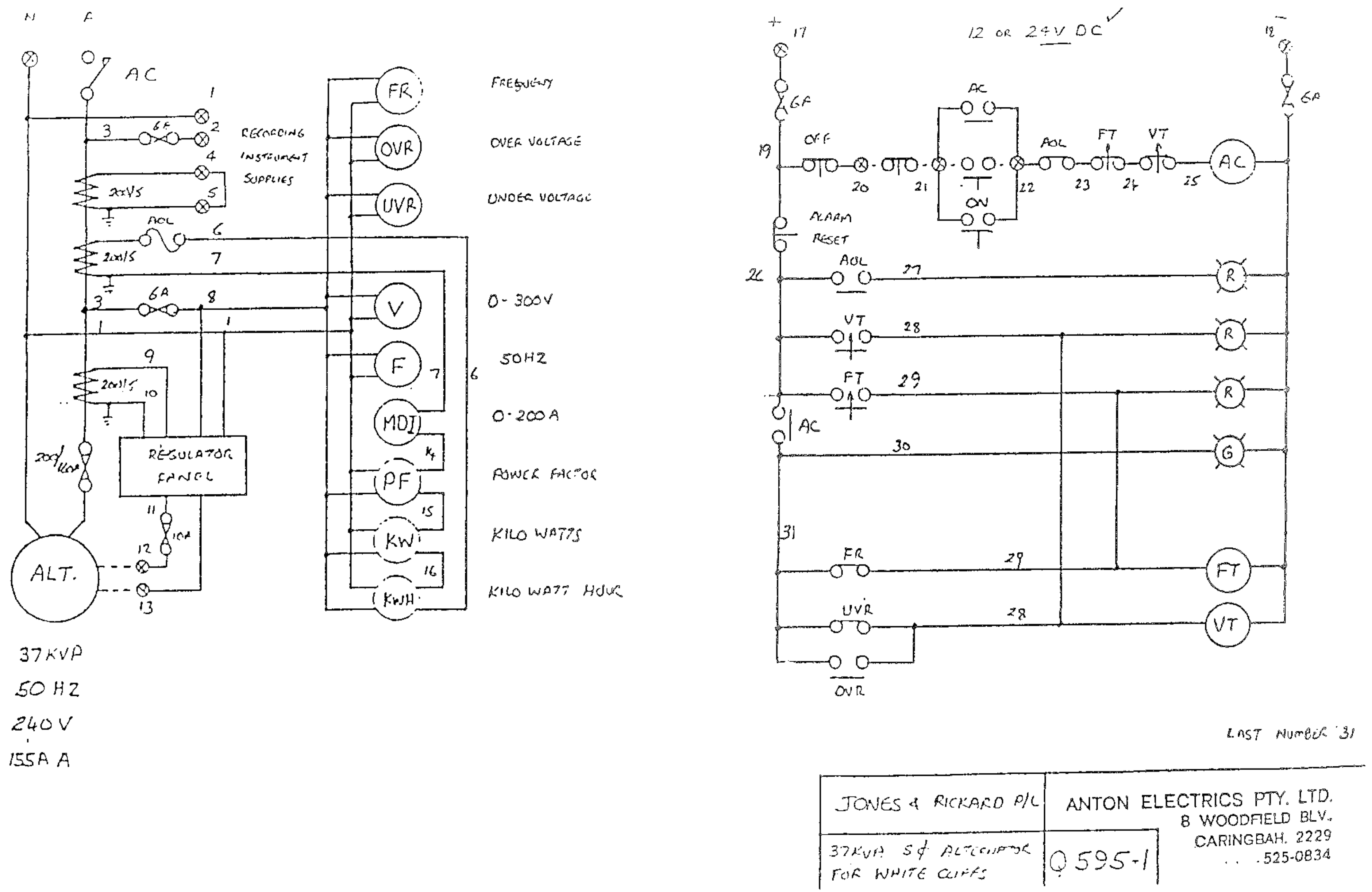


Figure 51a - The ac System - General Connection Arrangement

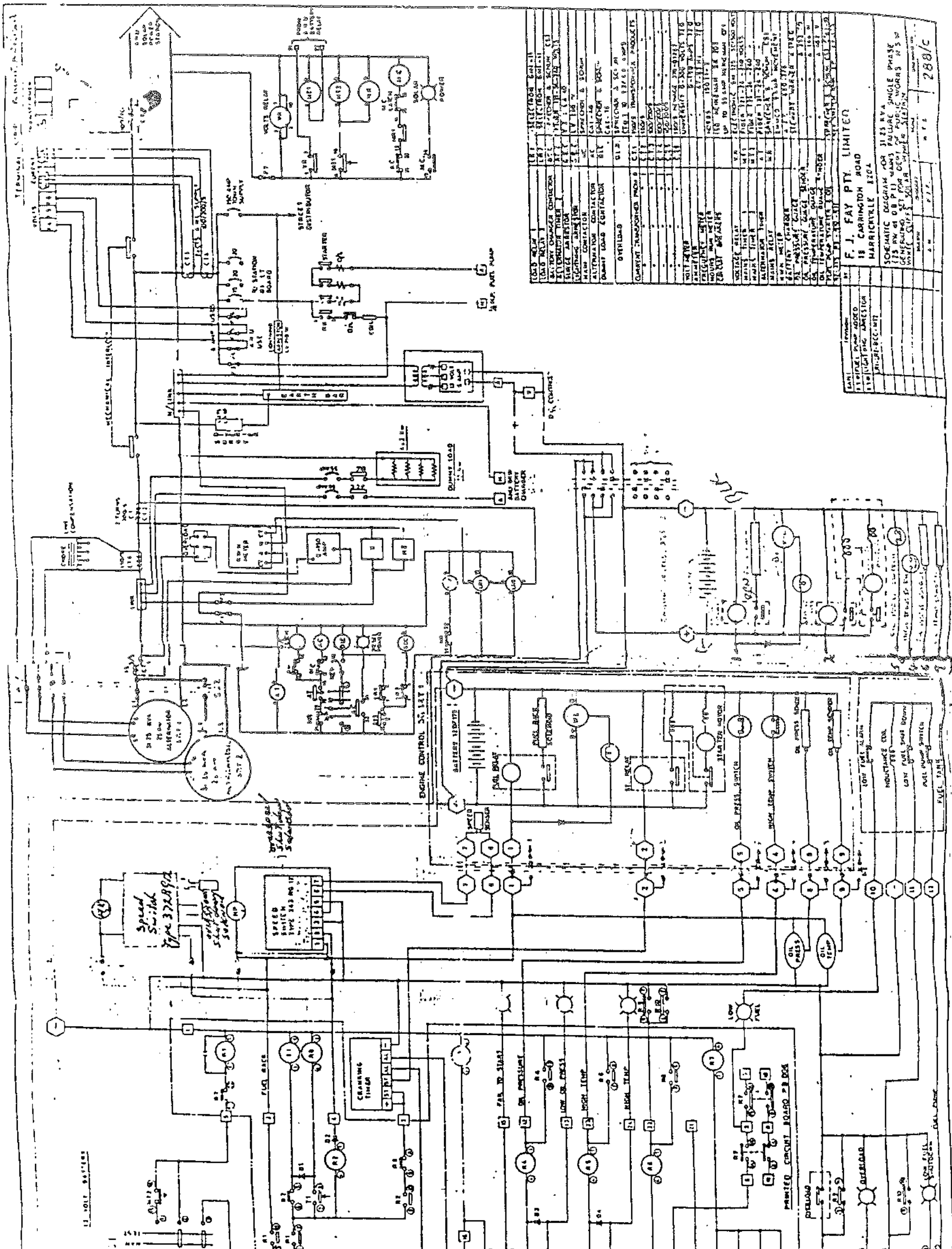


Figure 5b. - Diesel Generator Wiring

warranted, particularly since a batch of machines would cost much less per unit, improving potential cost-effectiveness futher.

Figure 51 gives the general connection arrangement for the AC system, including regulator and instrumentation, as well as indicating the DC control and display connections. A mechanically-linked interlock prevents simultaneous connection to the load of the solar AC supply and that of the backup diesel supply (see Section 3.7)

3.5.5 Electrical — Storage System Protection

The following features are included in the solar section:

AC Machine: Overcurrent, over- and under-frequency protection; operation of any of which drops the AC machine out and switches automatically to diesel supply, which can come into service within a few seconds. So long as no solar alarms have triggered, solar energy is fed to the battery via the DC machine (so long as battery voltage is less than 400 V). If battery voltage is more than 400 V, the solar array offsteers, the steam engine stops and the auxiliaries close down in 10 minutes. Load must then be taken from the battery.

DC Machine: Overcurrent and overheat protection, either of which disconnects machine armature from the battery. A temperature sensor brings in a cooling fan before overheat is reached, but this and overheat protection have never had need to operate.

Battery System: Battery operating temperature limit is 70°C after which the battery is dropped out of service and the solar station has to close down. [This has never operated; electrolyte temperature is usually less and 50°C.] Operating voltage of the battery is set between 270 V and 400 V. The diesel is arranged to take over at a battery voltage of 270 V. If battery voltage were to fall to 260 V (100% discharge), the battery would be disconnected and the solar station would close down (dishes offsteer and steam system auxiliaries stop after 10 minutes). If battery voltage rises above 400 V, dishes offsteer and steam system stops after 10 minutes, but station continues to run on the battery supply. If the diesel system is online and battery voltage is below 327 V, solar station cannot go online but supplies the battery only until 327 V is exceeded, when the solar supply is automatically switched online and the diesel set is stopped. This operating condition happens early morning and is arranged to allow the battery to attain a significant charge in case cloud appears and closes down the solar system, necessitating restarting the diesel, which might happen frequently in intermittent cloud, and would be undersirable.

3.6 Auxiliary Boiler and Superheater

The steam system of the station is arranged to operate in either of two modes: from solar-generated steam and fuel-fired-boiler generated steam. In the latter situation the solar array is not operational and the feedwater pump is manually valved to feed a small monotube boiler with diesel oil fired burner, able to supply up to 148 $kW_{thermal}$ energy into the steam (two separate burners allow essentially two levels of power) whose quality is readily adjustable to produce up to 500°C and pressures of up to 7 MPa. The system is efficient, converting fuel energy into fluid heat energy at an efficiency of about 85%.

The auxiliary boiler is used for engine tests and to serve as an emergency supply when the battery is discharged and the backup diesel system is out of service — this has happened frequently.

Boiler construction is extremely simple and economical: the three monotube energy-absorbing sections comprising preheater (a tube coil adjacent to the flue), main heater (a tube coil next to the burner), and a superheater (a pancake winding between the two tube coils) which are all wound from 19mmOD, 1.6mm wall thickness stainless steel steamless tube with welded connections within the heating zone. The structure of tubes is insulated by 50 mm durablanket (calcium silicate) and encased in a stainless steel cover. A small 6 mm diameter tube can bleed off steam from the main line to clean the monotubes regularly and so prevent any build up of material on the outside of the tubes.

This unit is integrated into the station control and protection system, the only manual function required being the valving on of the boiler input and output and the valving off of the solar array.

Superheater: With similar construction to the boiler, a sup[erheater, arranged to fire while steam of whatever dryness is generated, was tested for effectiveness over a year or so in 1985/86 with the object of adding energy during low insolation levels. However, because of the inadequacy of the water flow equalizing means in each abasorber, on most occasions of low insolation the superheater was unable to produce dry steam and its operation was terminated, pending the implimentation of better feedwater flow control.

3.7 Backup Diesel Electric System

Because White Cliffs Solar Power Station is required to supply power on a continuous stand-alone basis, the Energy Authority of New South Wales provided a 25 kWe diesel backup power system which is integrated with the solar station to the extent that town load can be supplied interchangeably from either system, a mechanical linkage on the respective circuit brakes preventing the two being closed (or open) together.

Both solar and diesel systems can charge the station battery (singly or together) and the diesel set can supply the solar station auxiliaries when the latter is not connected to the load — this was a valuable feature during early development work on the solar system.

A 25 000 litre oil tank holds diesel fuel, which is also used for powering the boiler.

3.8 Power Distribution

Single phase 50 Hz power is supplied to the township through heavy aluminium conductors (to ensure relatively small losses and volt drop), generation voltage being set to provide 240 V to the users and protected by a station circuit breaker set to operate when load exceeds 25 kWe. Responsibility for distrubution and load connection has been by CWR Ltd of Wilcannia until March 1988, after which it was taken over by the Broken Hill County Council.

3.9 Environmental Monitoring and Operational Data Acquisition

Instrumentation provided on the station was intended to satisfy two purposes:

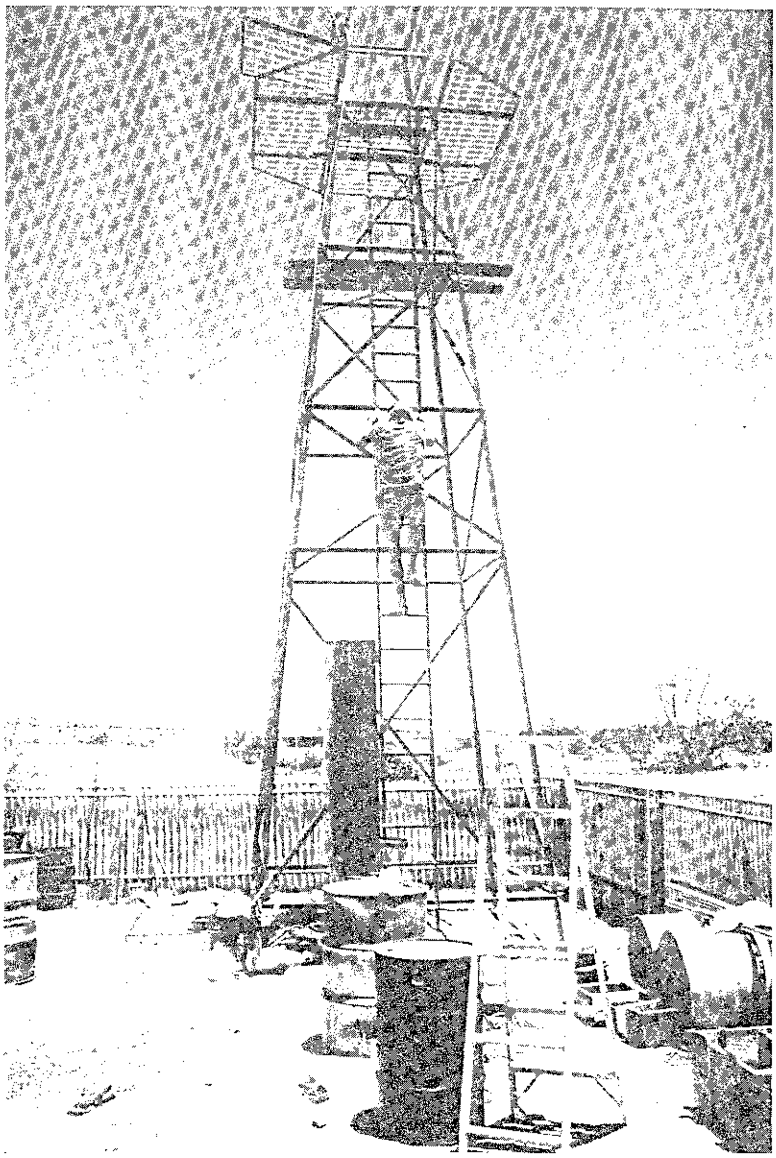


Figure 52 - Seven metre Tower for mounting sun and wind monitoring instruments (December 1979) in the yard of the White Cliffs Hotel (Subsequently relocated at the Station site

(a) Until the station was connected to the town load, the experimental system required measurements in a readily accessible rapid way which could be scanned visually alomost instantaneously from moment to moment; the quantities so required varied from time to time, depending on the task being addressed. At the same time other records were required of an integrated nature with profile variations in time, being available. These requirements were consistent with normal electricity system demands, so indicating and integrating instruments and chart recorders were installed. We have often experienced much frustration with sampled systems which do not give rapid access to instantaneous variations, unless simplicity and cost are sacrificed; so the decision was made to employ a largely manual and traditional metering approach for the experimental phase of the development, then to tailor a data acquisition system for opertional purposes when the real needs were known.

(b) Indication and recording of quantities normally expected of electricity generating systems ie:

- Integrating watt meters for energy generated (solar and diesel); energy to load; losses; energy to auxiliaries; energy to and from storage.
- Instruments indicating voltages; current; power; power factor.
- Running hour meters for solar and diesel units.
- Chart recorders for power generated and power to load.
- Diesel and boiler fuel used.

These measurement systems were compatible with the needs of (1) above and required in addition:

- Continuous chart recording of insolation and of wind velocity at the top of the array. Figure 52 shows the tower set up in the White Cliffs Hotel grounds in December 1979 to monitor sun and wind. This was shifted to the station site (some 400 m away) in 1982.
- Steam conditions — pressure and temperature (both from dial gauges and from transducers for suppling indicating or recording instruments) of steam into engine room, at engine inlet and at engine exhaust.
- Feedwater flow.
- Cooling water temperature (inlet and outlet).
- Engine oil pressure.
- Absorber maximum temperatures.

Table IX summarizes the general attributes of the monitoring and integrating instruments.

Additional to the above, an anemometer and direction indicator on a 30 m tower above the array measured wind speed and direction at this higher level, while a further anemometer and direction indicator measured the conditions on the top of Turley's Hill, some 1 km to the north-east, at a height of a few metres above the instruments on the 30 m tower. Sun and wind monitoring instruments have confirmed, over the years, that White Cliffs is not only an excellent solar site but is also a good wind energy area; curiously the wind resources seem considerably less even 100 km away at Wilcannia (south) and to the north.

We have comprehensive continuous instantaneous solar and wind chart records for White Cliffs from December 1979 and operational data (intermittent) from January 1982 to November 1983; then daily operational data records since November 1983 to the present. There are also comprehensive wind velocity

TABLE IX — MONITORING AND RECORDING INSTRUMENTS — GENERAL INFORMATION

MEASUREMENT RATES AND SCANNING INFORMATION

Scanning Intervals	:	According to need — for example to examine array performance on a clear day, sensing at 15-minute intervals is adequate; but on a rapidly varying cloud pattern, readings need to be made at 1-minute intervals or less.
Normal Accumulation and Averaging Period	:	15 minutes.
Evaluation Summary	:	Daily, monthly and quarterly.
Evaluation Period	:	Environmental, December 1979–present; Experimental, January 1982–June 1983; Operational, November 1983-present.

MONITORING INSTRUMENTATION

Insolation	:	Eppley pyrheliometer on 2-axis tracker recording on Watanabe chart recorder. Accuracy ±2%.
Wind Speed	:	Rotating cup anemometer recording on Watanabe chart recorder. Accuracy±3%.
Wind Direction	:	0–360°, no calibration, recording on cassette recorder every 20 minutes.
Temperature	:	Absorber temperature by calibrated thermocouple, ±5% accuracy overall. Steam temperatures by compensated thermocouple, digital readout, accuracy±1%.
Pressure	:	Water and steam, by dial gauges and pressure transducers, calibrated. Accuracy±2%.
Feedwater Flow Rate	:	Three-cylinder positive displacement pump driven by linear thyristor-driven servo motor of calibrated performance. Flow range, 0–80 ml/s (near linear calibration) setting and measuring accuracy better than 0.5% when flow is greater than 1 ml/s.
Material Properties	:	Mirror reflectance masured by Eppley pyrheliometer.
Powers	:	By integrating kilowatt hour meters, kW meters.
Solar Power to Town	:	By Watanabe chart recorder.

and direction records on computer-compatible tape from records on the 30 m tower and from Turley's Hill, over the period 1980 to 1986.

Quarterly progress reports (1983–1987) record various direct and derived solar data, and various derived operational data as follows:

- General account of operational highlights, problems and results of operation over the quarterly period.
- Availability of the solar system.
- Daily and monthly direct beam kWh solar energy incident on the collectors.
- Daily and monthly direct beam kWh solar energy incident on the collectors for instantaneous levels greater than 700 W/m^2.
- Daily peak insolation W/m^2.
- Subjective assessment of the weather and sky conditions (fine, slight cloud, cloud, haze, etc).
- Monthly kWhe generated by solar system and supply hours.
- Monthly kWhe generated by the diesel.
- Monthly kWhe generated using the auxiliary boiler.
- Monthly energy supplied to battery from each source.
- Monthly energy supplied from battery to town load.
- Monthly kWhe supplied to station auxiliaries from each source.
- Monthly fuel and water used by each system.
- Monthly nett electrical output from the station.
- Monthly hours of operation of each power source and outputs.
- Total solar energy generated by the station and overall efficiency of conversion of solar energy to electricity.

With the metering and recording approach employed, it proved possible to gain rapidly an appreciation of the sensitivity of the system to various parameters, especially with the aid of additional temporary metering of particular components identified as particularly interesting or important. Essentially a first approximation model of the system was obtained in this way and used for further refinement.

3.10 The Operating System

The overall solar power station is organized on the basis of a number of autonomous systems, as already outlined, their arrangement for operation and control purposes being illustrated in Figure 53[11]. Features of the operating system include:

i. Station operation is affected by 3 external factors:
   A. The town load which places, within the limits set by each user circuit breaker, an essentially uncontrollable load demand, up to a maximum of 25 kWe, after which the main circuit breaker will operate and disconnect the load. On solar operation, excess energy not taken by the load is stored in the battery. On diesel operation, output depends on town load with a small amount of energy (currently varing from 0 to 6 kW) going to charge the battery so long as town load is less than about 15 kWe.

[11] Figure 53(a) gives the functional arrangement of the original system which operated until November 1990, when the freewheel clutch was removed and the operating system necessarily changed to the arrangement in Figure 53(b).

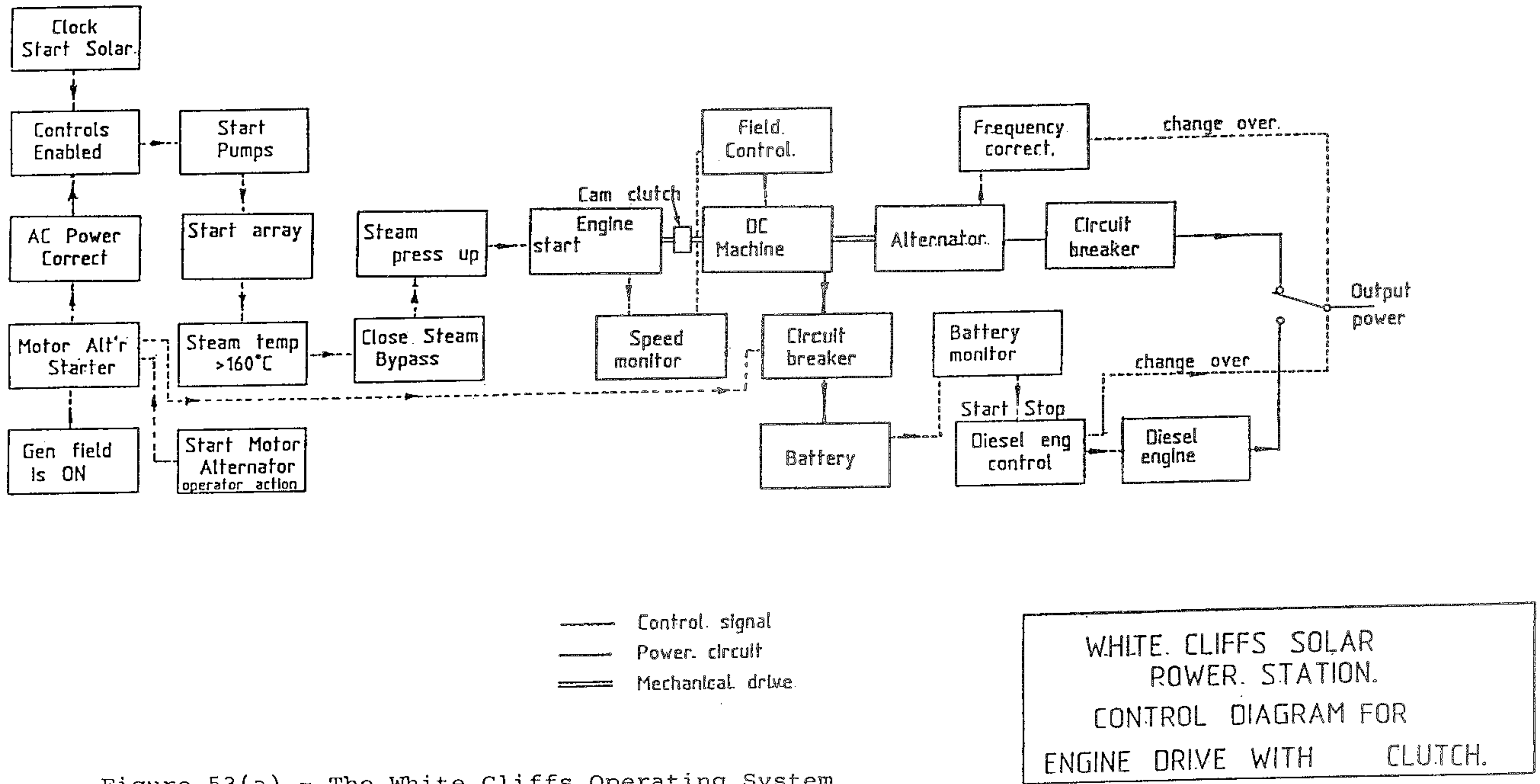
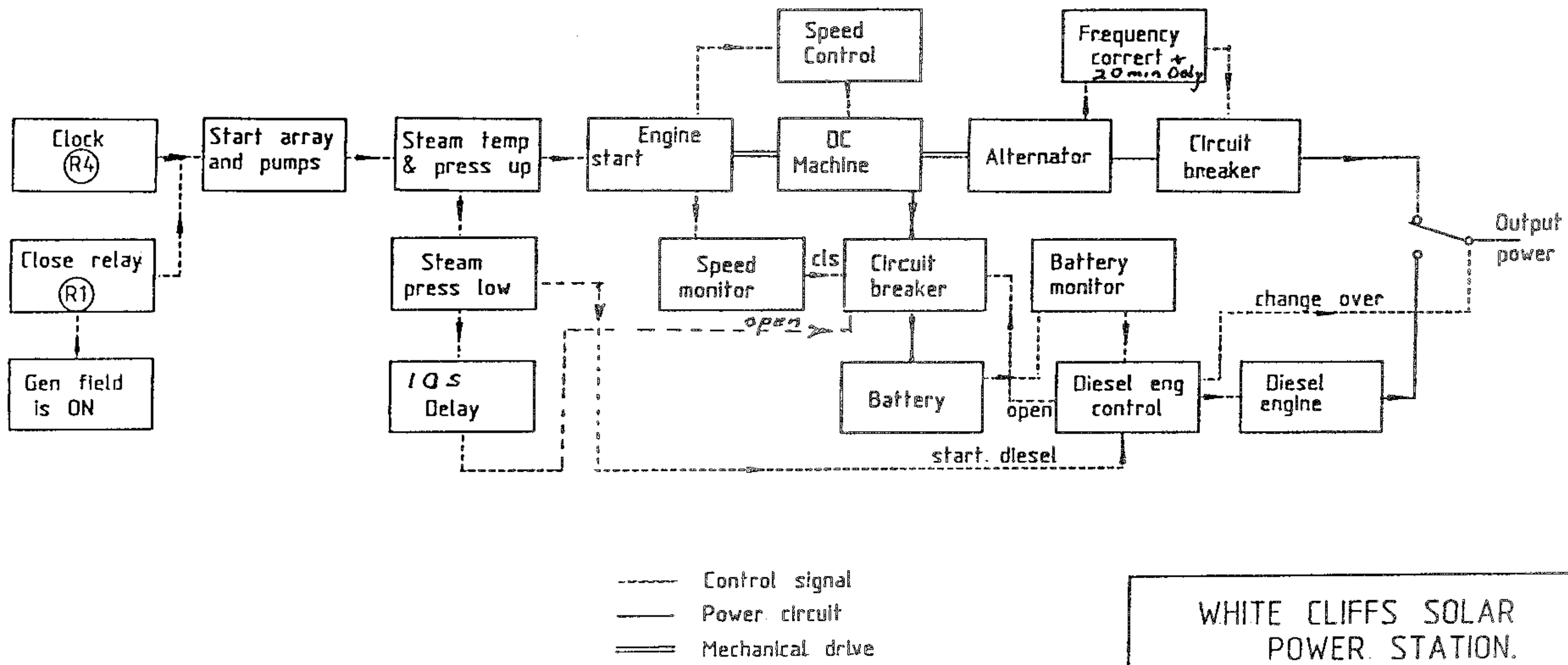


Figure 53(a) - The White Cliffs Operating System with Freewheel Clutch (original system).



WHITE CLIFFS SOLAR
POWER STATION.
CONTROL DIAGRAM FOR
ENGINE DRIVE WITHOUT CLUTCH.

Figure 53 (b) - The White Cliffs Operating System without Freewheel Clutch (Implimented November 1990).

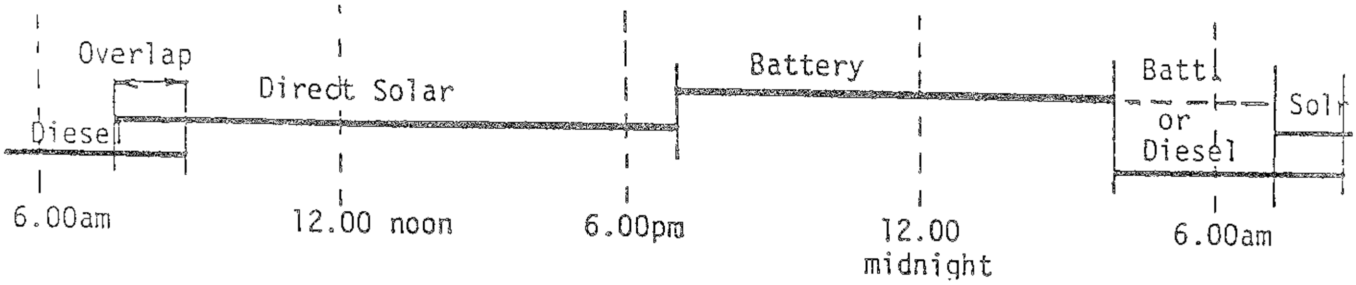


Figure 54 - Overlapping Solar/Diesel Operation

The above is a typical cycle over 24 hours. If solar output on a given day is adequate, the battery continues to supply the load until the solar system starts the next day: otherwise the diesel starts at some time during the night.

B. Wind Velocity which sets an upper limit of 80 km/h to solar operation. Below this velocity, the dishes can track; above 80 km/h, the solar array is automatically parked in the vertically-facing position and the steam system closed down so long as the excess velocity persists for more than a few seconds; nor can the steam system or array be started at wind velocities above 80 km/h.

C. Insolation: A unit (currently not in place) has been developed to control feedwater flow to achieve maximum solar-electric output in accordance with insolation. This also acts to prevent a master-clock-start in the presence of cloud which causes direct beam radiation to be less than 100 W/m^2.

ii. So long as (B) and (C) above are favourable, the solar system starts some 20 minutes after sunrise each day in response to a master-clock signal which first switches on the auxiliaries [feedwater, vacuum, cooling water and oil-water treatment pumps, and centrifuge (when used)], then raises the dishes from a south-east horizantially-facing position to face vertically upwards for about 7 minutes, to ensure that all absorbers have filled with feedwater with no trapped air. The array then moves towards the east and down for about 3 minutes by which time each dish has acquired the sun and tracks thereafter, so long as no counter-commands (as the result of alarms for example) arrive from the central controller or so long as individual absorbers do not overheat, offsteer and stop.

iii. Depending on insolation level, steam quality may be adequate for an automatic engine start within 5 minutes or less after the dishes have tracked. [At low insolation, this time could extend to 10 minutes or more.] The engine attains synchronous speed (the speed of the continuously-rotating AC/DC set) within a further 2 or 3 minutes (or longer depending again on insolation). Thereafter, solar energy is supplied to the system until station close-down is signalled by the master clock at some 20 minutes or so before sunset, when the dishes automatically move back to the south-east horizontally-facing position.

iv. Operation during the day in the presence of intermittent cloud causes the engine to continue operation, sometimes stopping, sometimes coasting on stored energy in the heat gathering and transport system, sometimes providing useful power. The array maintains approximate sun pointing during the cloudy periods as a consequence of receiving pulses generated by the dish control units. [These pulses are overridden by sun sensor signals, when these are above a small threshold level.]

v. If the station supplies the load from the battery whose voltage has not dropped to 270 V when the solar system is ready to start (ie with diesel not operating), the solar system supplies the town immediately it can generate (with battery assistance initally), then supplies load + battery, depending on available energy. On the other hand, if the diesel is already operating due to prior dropping of battery voltage to 270 V, the solar system charges the battery only (with the diesel suppling the town load) until battery voltage exceeds 327 V, when the diesel cuts out, transfering the AC load to the solar system. Operation is in accordance with that outlined in Section 3.5.5. Charging of the battery to 400 V has never occurred in operation.

The cutting in or out of the diesel system in relation to the solar unit is illustrated in Figure 54. If total energy stored during the day is not used during the night, the diesel does not cut in before solar operation resumes the next day.

vi. Engine start is managed by 3 automated valves as previously described; the freewheel coupling allows intermittent engine operation and coasting down to a speed (in intermittent cloud) of some tens of revolutions per minute. If speed falls below 30 rpm, the automatic stop sequence is initiated and restart will occur only when steam quality has attained its threshold value. Two levels of overspeed protection are provided; the first for speeds above 1 650 rpm, bringing in a normal stop sequence with offsteer of dishes and close of throttle, opening of drain and bypass valves. If the speed has reached 1800 rpm (due to possible failure of the first system), the mechanical governor (or a further speed indicator) acts to close down the engine. Auxiliaries run on for about 10 minutes before stopping. The station continues to supply the load on battery supply.

vii. Any battery-based protective operations which involve switching off the battery automatically bring in the diesel supply, offsteer the dishes and close down the steam system.

viii. The steam system close-down sequence involves first turning off the energy source (offsteer of dishes or cutting of burner flame if on boiler operation) and simultaneously closing engine throttle, opening bypass and drain valves; and allowing the station auxiliaries to operate for a further 10 minutes before stopping. Any of the alarms mentioned in Section 3.3.15 can initiate close-down, or pressing the 'emergency stop' also has the same effect.

ix. Operation of a pressure relief valve does not, of itself, cause any shutdown but the consequences of this action can lead to shutdown.

x. Each solar collector has its own power supply and mirror control system as already discussed in Section 3.1, being largely autonomous. Nevertheless the functions "stop"; "start"; slew "forward", "reverse", "up", "down"; "offsteer"; "park"; can be communicated from the station controller or by manual control from the control desk. One of the interlocks handled by the station controller prevents dishes tracking unless feedwater flow has been established. Thermocouples on each absorber cause offsteer on overheating, as indicated in Section 3.1. Signals from these thermocouples are multiplexed to the central control desk to provide indications of temperatures on the respective absorbers (one meter per absorber), a valuable diagnostic indicator on the state of the solar array.

xi. The station battery plays an essential role in the electrical system for the utilization of all available solar energy. Due to resource limitations, only a rudimentary battery charger was provided for the diesel (in fact this charger was intended as a means for placing an initial charge on the station battery from a small petrol set in case no other means were available to start the solar station). As a consequence, only a relatively small contribution from the diesel set can be made to the battery; since no control is provided on the charger, energy enters only if the diesel voltage exceeds a voltage dependent on the actual battery voltage, unless manual adjustments are made, up to a maximum of 6 kW.

xii. The station controller, apart from playing a part in the foregoing operations, ensures that all actions follow in the correct sequence and that prohibited functions do not occur.

xiii. Manual overrides are provided on all systems, facilitating experimentation.

An optimization unit has been developed (but is not currently connected) to control feedwater in the array, a function which depends on insolation profile

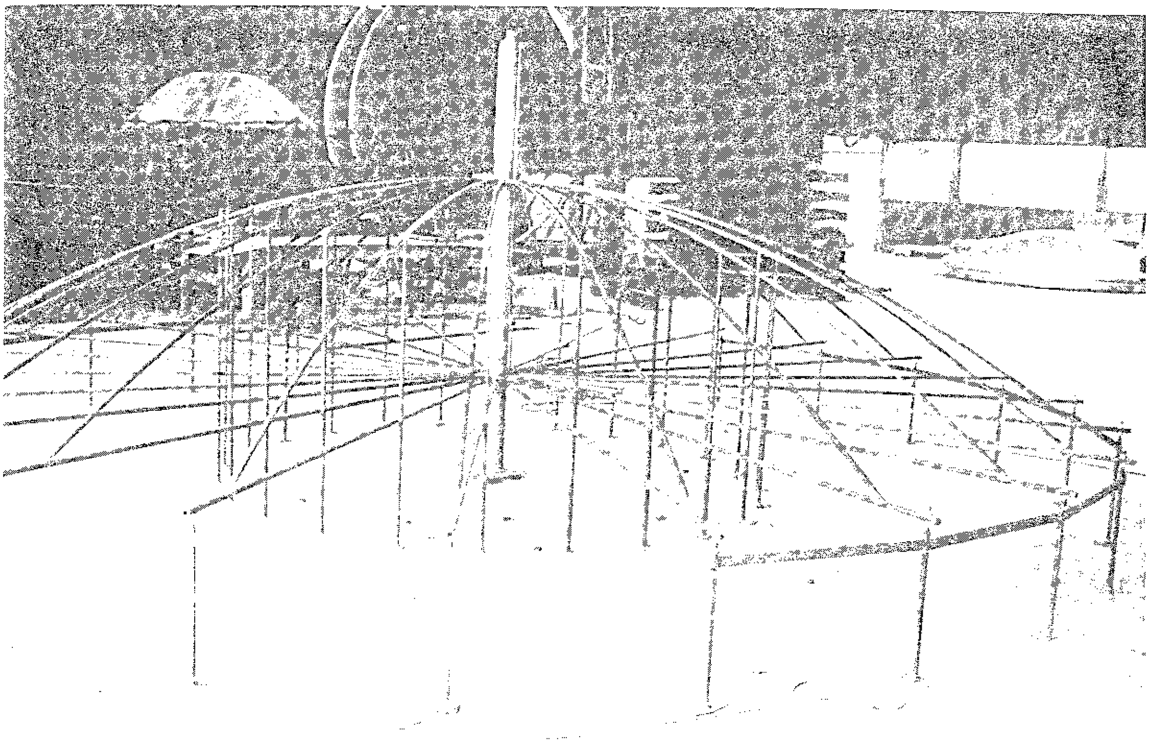


Figure 55 - Dish mould structure before covering with thin sheet steel sectors, chicken wire and rendering

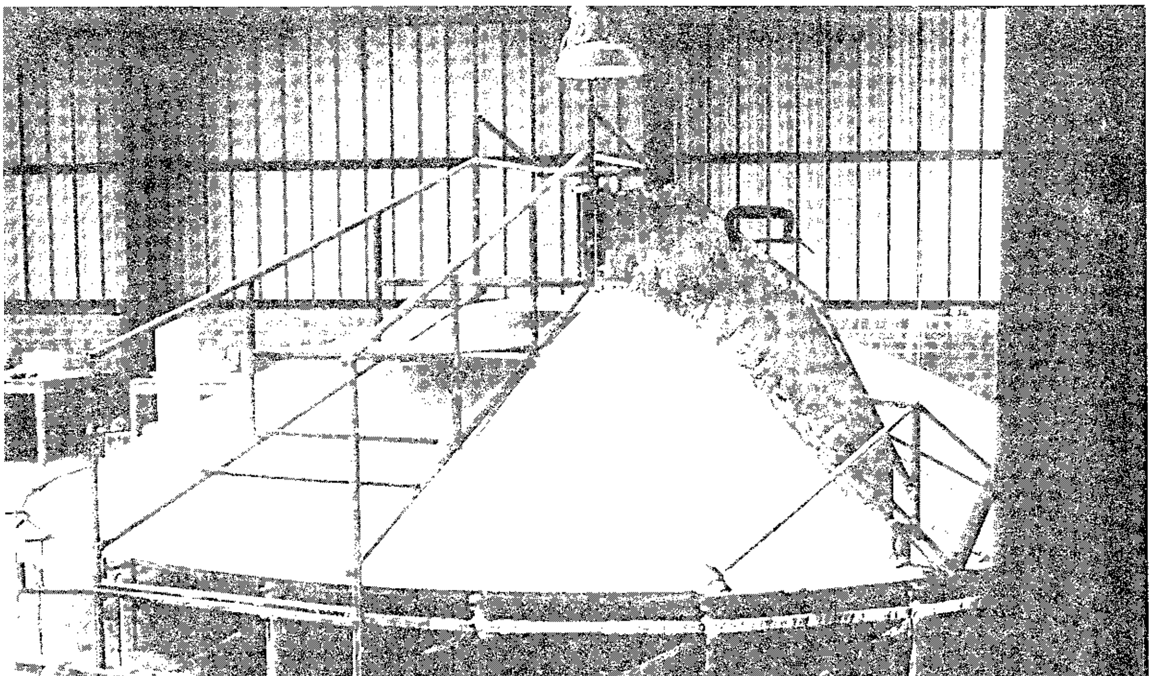


Figure 56 - The completed frame, rendered and finished in plaster of Paris

during the day but is not straightforward, requiring a model which relates mass flow, insolation, absorber characteristics, dish characteristics, duct heat loss characteristics, engine characteristics, cooling water and vacuum conditions, together with actual parameters in the system and the several key response times involved. The function involves an optimization of electrical energy output over a day's operation, including energy used in auxiliaries. Incorporation of this unit as a normal system function awaits improvement of the flow control for each absorber to achieve effectiveness.

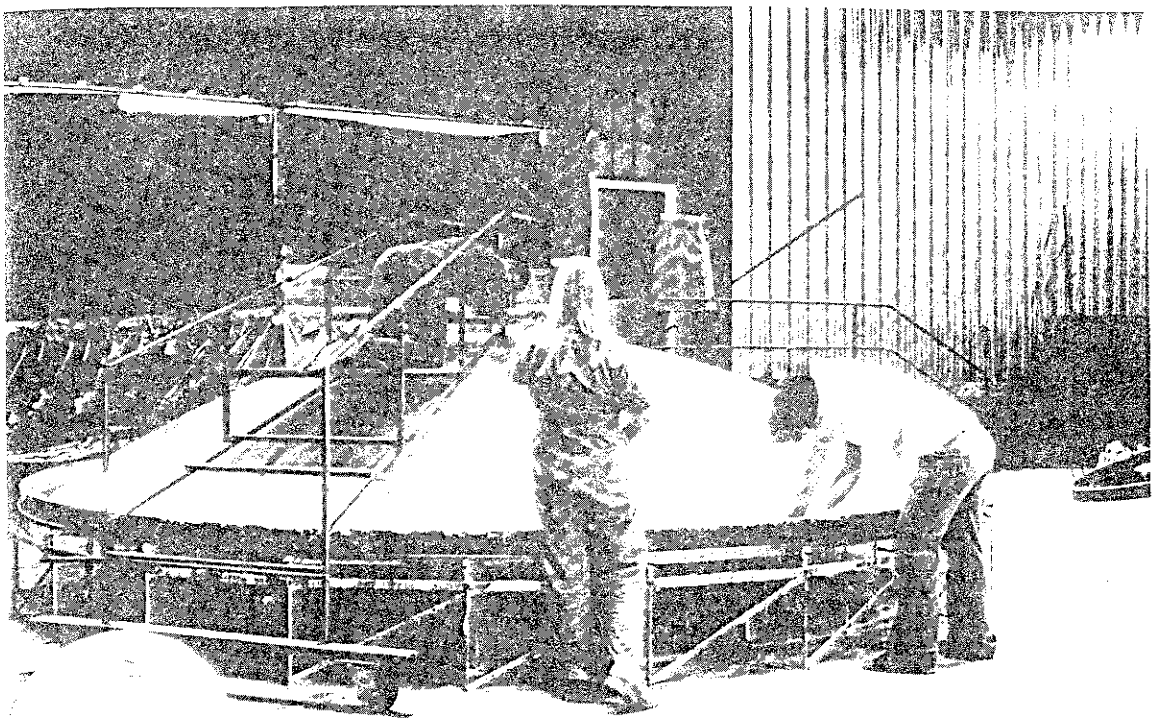


Figure 57 - Dish mould with a coating of material to prevent adhesion of the fibreglass mastermould copy to be made from it

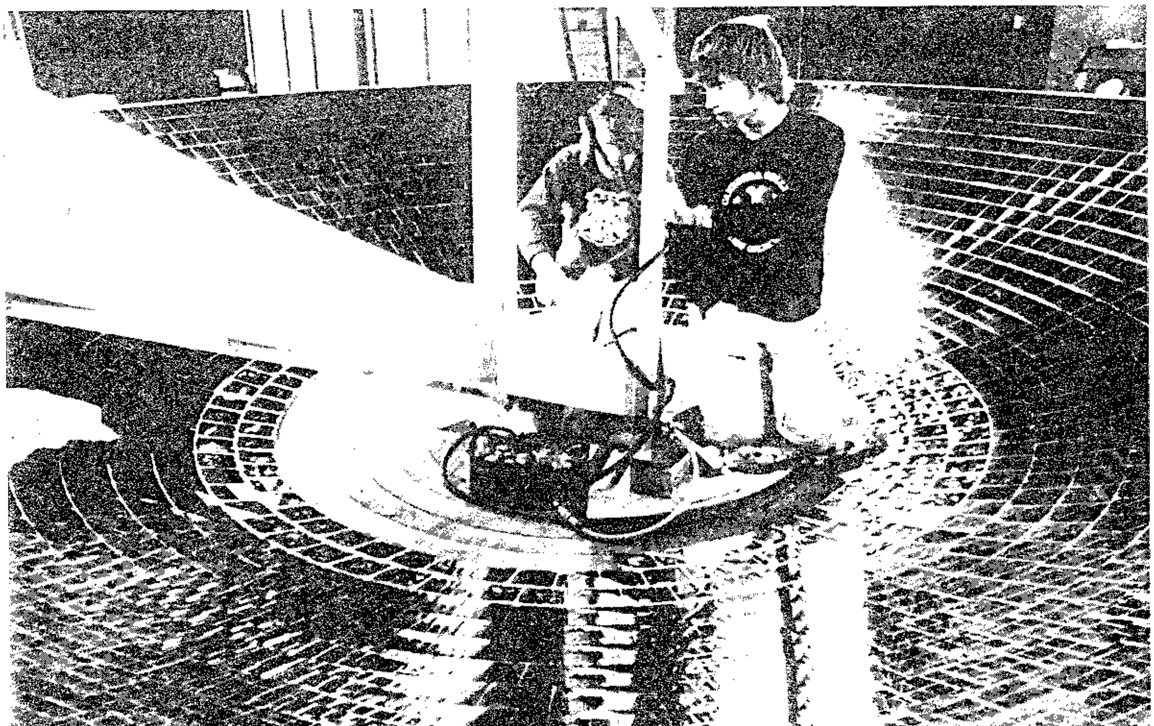


Figure 58 - Tile laying of a dish almost complete

4 CONSTRUCTION AND INSTALLATION

The overall project involved research and development, design, fabrication, transport, installation, commissioning and operation and evaluation. Assistance from several groups was obtained. All conception, research and development, design and much of the construction was carried out 'in house' with assistance from hired professional and technical staff. Consultants' views were obtained on the steam system and on possible rotary joint designs but eventually we had to rely largely on our own resources in these respects. Of help was the experience of steam car enthusiast commander G. Vagg (who selected the basic engine concepts and supplied a Mark I version engine). Subcontractors were used to construct the frames holding the dishes, the sheetmetal ducts and the fibreglass shells for the dishes (from a master mould produced by us). A professional firm of project managers was employed to provide scheduling guidance and financial control.

The nature of the logistic problems in establishing the power station needed to be experienced to be appreciated; care was essential to ensure that absolutely everything necessary — literally down to the last nut and bolt — was brought in (even drinking water). In the process a well setup field station was established, allowing other activities to be initiated in the area later.

All components were constructed in Canberra (1 100 km away) allowing the very minumum of installation effect onsite by our staff, with occasional assistance from locals. Work onsite was performed by small groups of 2–3, except during installation of the ducting when a larger team was brought in for the purpose.

Leaving aside sophistication in design, actual construction and installation were developed to be straight forward — all construction tasks were within the competence of relatively small mechanical, electrical and electronic jobbing shops.

4.1 Collector Array

Section 3.1 outlines various aspects of the solar array, including information on configuration. The collectors required good manufacturing accuracy to achieve a uniform set of dish parameters enabling components for each dish to be identical. Dish accuracy required care in mould design and construction, good fibreglass expertise to avoid shrinking, and frequent inspection of the glass tile-laying procedures to make certain that the rules developed to produce accurate reflective surface were being followed. The basic mould with accurate shape was produced by our own staff and, with the assistance of an expert fibreglass contractor, we produced a mould from which the fibreglas contractor made 14 paraboloidal shells with steel-rim mounting ring incorporated.

The glass tiles were cut in a simple jig (of our design) from 2.5 mm thick rear-silvered motor car windscreen glass by an expert glasscutter, the sides of each tile being radial (and straight) on a radius calculated for the circumference of each circle of tiles; the top and bottom of the tiles being cut to this curvature. The process was simple, rapid and cost effective, all tiles for one dish being cut and packed in some 10–12 hours.

A team of enthusiastic high school and university students was given the task of mounting the 2 300 plane glass mirror tiles onto each dish substrate, using GE 2000 series silicone adhesive (4 mounting blobs per tile with a bead of adhesive on each edge to seal against

Figure 59(a) Winding a Mark III absorber

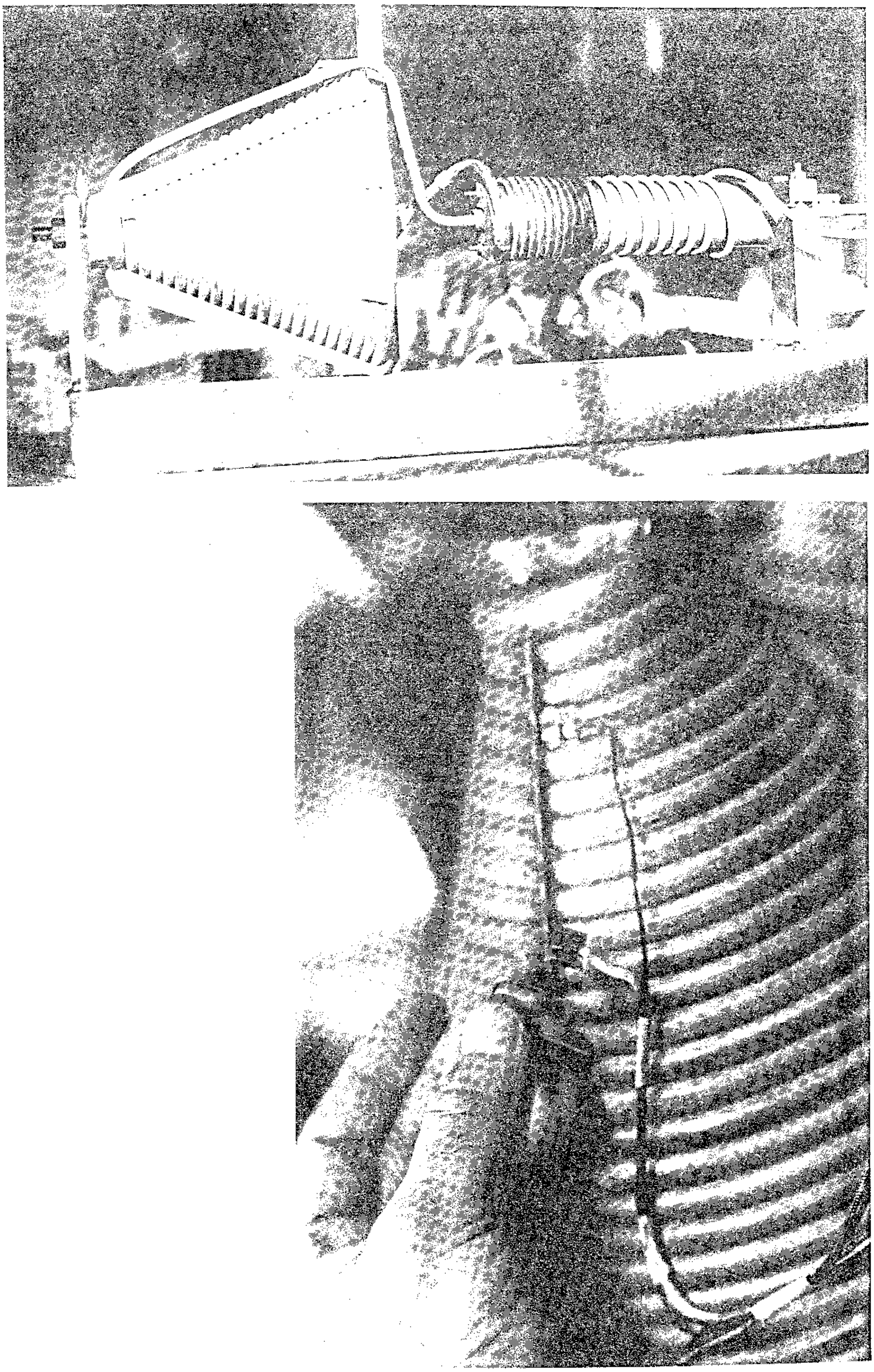


Figure 59(b) Mark IV absorber with text instrumentation

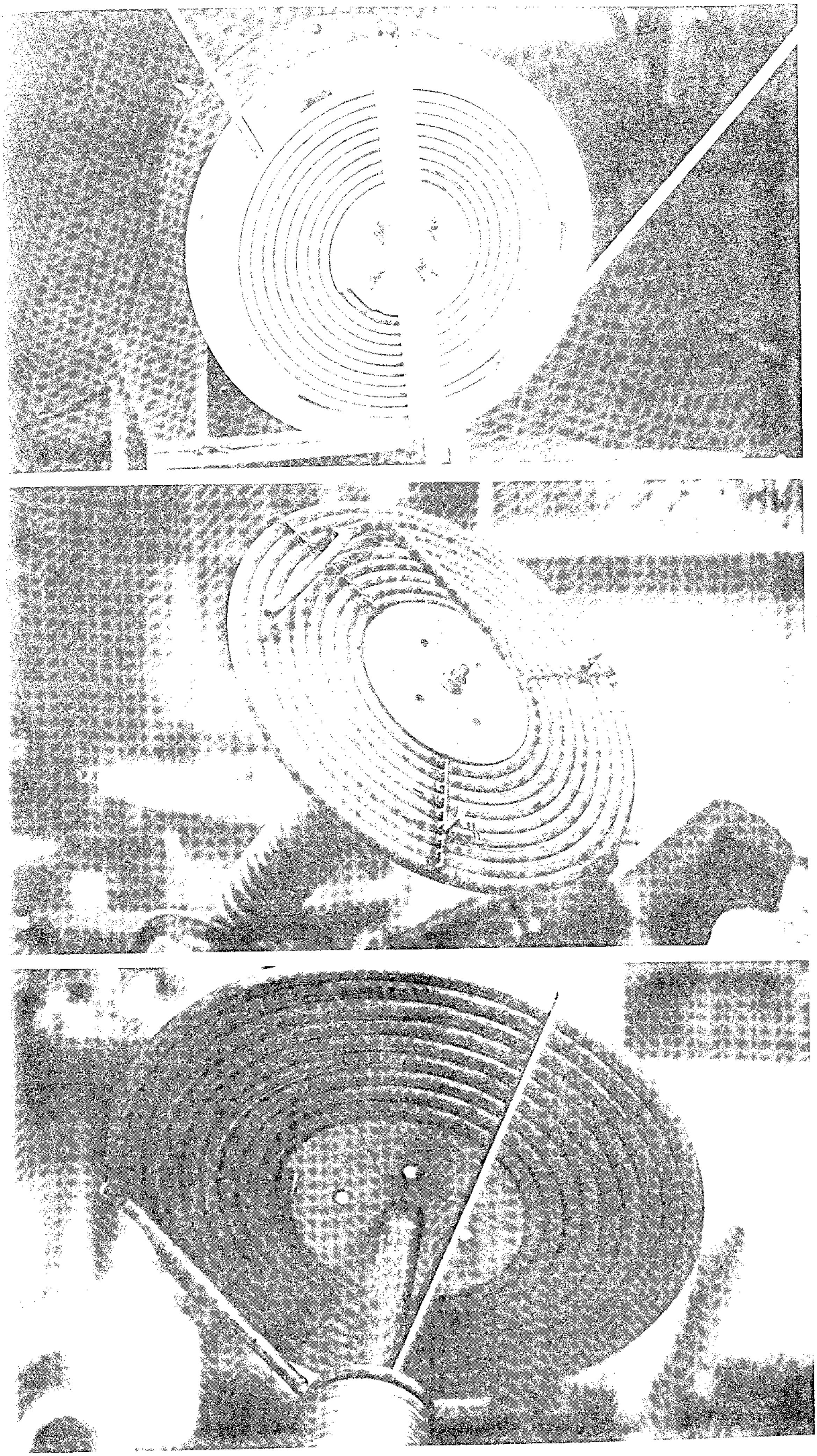


Figure 59(c) Pancake winding used in Mark V - VIII absorbers moisture intrusion). The adhesive was compatible with the mirror backing reflective and protective coat. With careful inspection the tile-laying team soon gained an effective competence; tiles were laid in rapid time very professionally in January/February 1981. These tiles are still in excellent condition both as regards fixing and reflectivity. The very similar focal region characteristics for each dish attested to the success of the moulding, dish manufacturing and tile laying practices.

Figure 55 shows the mould basic structure which was covered in very thin steel sheet sectors, chicken wire attached, then rendered with sand/cement render, shaped approximately by a rotating parabolic vane, then given some 3 mm thick coating of plaster of Paris — this stage is shown in Figure 56.

Figure 57 shows the dish mould with a coating of material to prevent adhesion of the fibreglass master mould (copy) to be made from this mould.

Around the (inverted) dish rim was mounted a deep rail levelled to within 0.1–0.2 mm all round; a slipper on the end of the parabolic vane (which pivots on the dish centre), together with the very accurate parabolic vane, ensured that the final shape was accurate.

Dish substrates taken from the master mould turned out to have not changed their dimensions during manufacture by more than 1 mm or so on 5 m diameter — they could readily be placed back in the mould.

Figure 58 shows the final stages of completing tile laying. The timber ladder pivots at the dish center and runs on wheels around the outside. Not shown, because they have been removed, are the terraced forms which were placed inside the dish to allow tile-laying to begin at the dish rim and to proceed towards the centre, this method being considered the most potentially accurate and convenient, the first row of tiles being laid to a line scribed around the rim and each row of tiles being checked with other lines scribed to locate the position of each row of tiles. The last tile in each row usually had to be cut to fit.

During the laying process, beads of silicone adhesive squeezed from each joint and were most readily and cleanly removed by pulling off at the correct time (some 20 or more minutes after laying, this time being determined very much by atmospheric temperature). Figure 58 shows some beads still in place. Any adhesive adhering to the mirror surface could be readily removed by a rag soaked in methylated spirits.

We were very pleased with the results of these processes which produced excellent glazed dishes.

Dish frames were manufactured by a subcontractor to a sample frame which we supplied. The pedestal pipes and rotating pedestal heads and azimuth drive ring were constructed in the Research School of Physical Sciences Workshop. Actuator components were subcontracted.

4.2 Absorbers (Receivers)

Absorber construction was simplified down to the winding of 9.6 mm diameter stainless steel tube on a shaped former, terminating with swagelock fittings and providing an insulated stainless steel cap to reduce losses.

Several different designs of absorber were built as already noted (Section 3.1.3 and Figures 24-28).

Figure 59 indicates different aspects of absorber winding and heat treatment.

Different means have been employed to keep the absorber tubes to their desired shape, ranging from welding turns together at 3 or 4 points around the circumference, to the provision of a frame and clipping system; each approach has advantages and disadvantages. The current designs favour frames to which the tubes are clipped.

Heat treatment was initially employed to anneal tubes after winding, but we decided that this was probably, on balance, an unnecessary process with no clear advantage. The traumatic conditions under which absorber windings have to operate seem to transcend matters of annealing, use of Pyromark paint for better absorbtivity, and methods of constraining winding shape. We address these problems in our new generation designs.

4.3 Station Plant

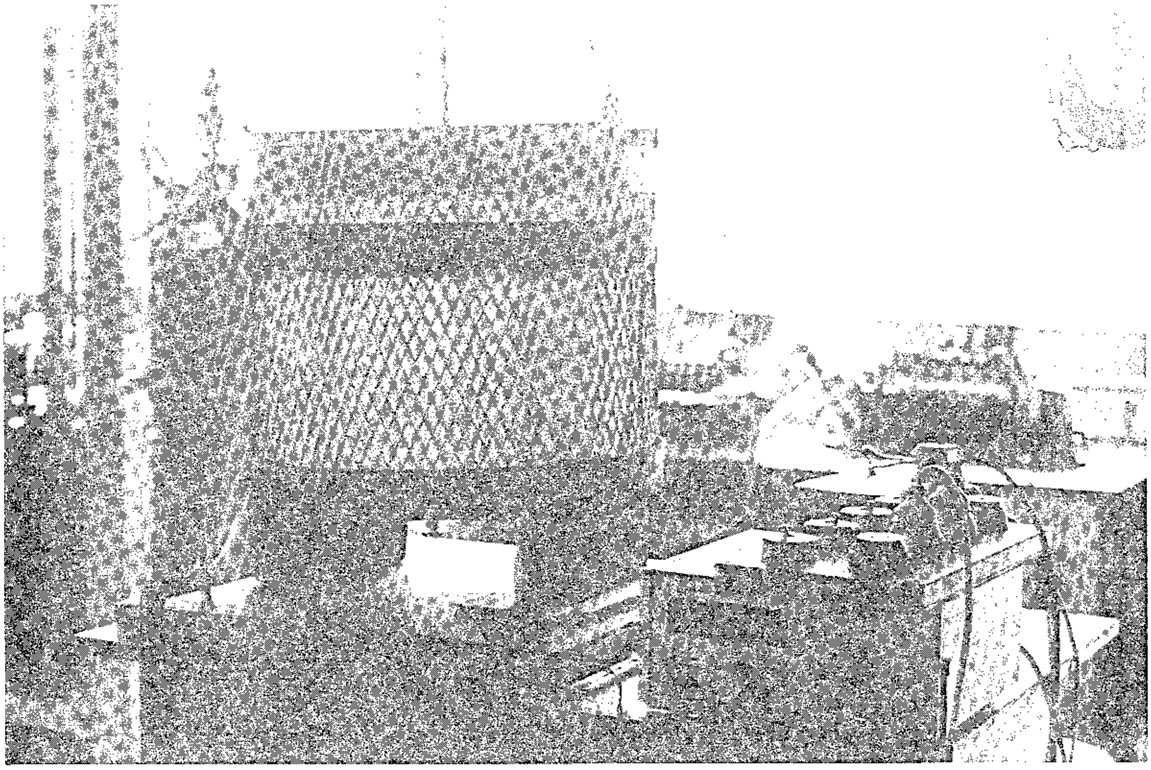
All constructed engine system components and electrical machines and auxiliaries were mounted in Canberra within a 6m x 2.4m shipping container; electrical switchboards, station controller, electrical controller, array controller and operator's console were mounted in a futher container; the 760 ampere-hour battery was mounted, with protective devices, in a third container. These containers were transported complete to White Cliffs and there were installed as shown in the plant layout indicated in Figure 60.

The auxiliary boiler was mounted in an adjacent room constructed onsite, as indicated.

A further container was added to house a display room for tourists and visitors to the station by the Energy Authority of New South Wales, who fitted out an excellent display including slide/voice presentation and a small dish model which can move on two axes and point to a light source. This is located as shown in Figure 60; windows provide good views into the engine, control and battery rooms.

4.4 Transport and Installation

The 14 dishes, dish frames, pedestals, actuators and other components for the collectors were transported on two trucks, the dishes being nested in two stacks on a frame built for the purpose. The ducts and insulation were carried later inside the shipping containers which housed the engine-room, control and battery rooms. Transport posed no problems, except tight bridge clearance (dishes).



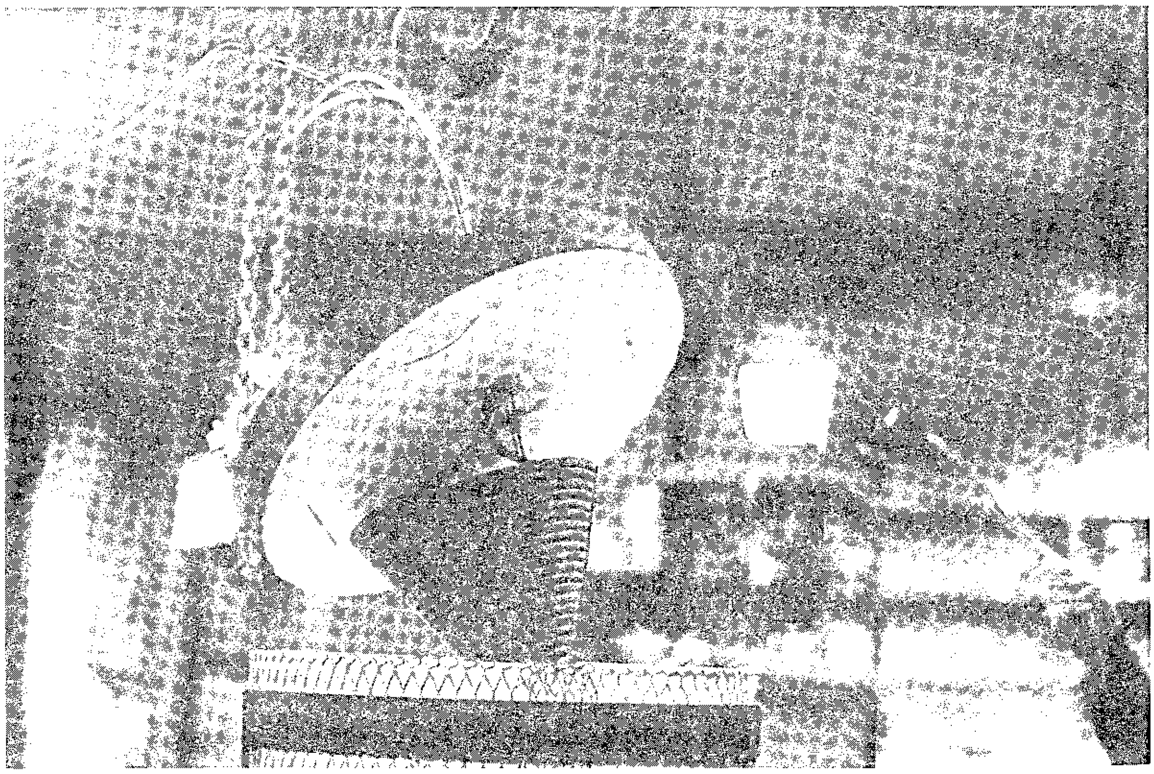


Figure 59(d) Top - Heat Treatment Oven
Bottom - Remover and Mark IV absorber after Heating

Note: Experience has shown that heat treatment after winding absorbers produces no obvious advantages

Figures 61 and 62 show dish transportation; Figure 63 gives a view of the construction site.

4.4.1 Site Philosophy

The array site slopes down to the north, with a fall of nearly 1 m in 80 m, a favourable orientation allowing the collectors to be spaced somewhat closer than would be the case on level ground. The region (average rainfall about 20 cm per annum) had been in the grip of a drought for several years and most of the naturally sparse (at best of times) ground cover of small plants had all but dried up and disappeared, leaving the gibbers (assorted rounded small stones and rocks extending down a metre or so and forming perhaps 10-20% of the soil) in view and allowing the winds to more readily raise the characteristic red dust. Working this ground with hand tools was difficult and it was fortunate that opal drilling machines were in the area to help. Lifting of heavy items was performed by a crane purchased for the purpose and later sold.

Figure 64 indicates the area enclosed to house the station.

Our philosophy concerning ground preparation was "...if at all practicable, leave the ground as it is and create the minimum distrubance ...", thereby taking advantage of one of the features of our paraboloidal dish design which requires only a hole in the ground for foundations. Accordingly, no levelling, smoothing or other preparation was carried out.

On architectial advice, the New South Wales Energy Authority decided to heap soil around the station buildings to allow this area to blend in more appropriately with the surrounding opal mining diggings, buildings and hills. This feature is evident from Figure 60 and from Figure 1[12].

4.4.2 Installation

The four shipping containers (housing respectively the engine, electrical and other plant, the control and protection equipment and operator's console, the battery room, and public display area) needed for foundations 12 concrete pillars (500mm x 500mm) set 500 mm into the ground. The containers were simply lifted off their transporter and lowered onto their pillars, resting just above ground level.

The foundations for each collector required drilling a 700 mm hole 3 metres deep — employing a local opal drilling rig — then dropping in the 300 mm diameter pedestal support pipe and setting in about 1 cubic metre of concrete (mixed on the spot using gravel from a local creek bed and a petrol-driven mixer — the cement was the only item brought in). Figure 65 gives a view of the dish pedestal support pipes set in the ground.

The dishes were mounted on their pedestals, and actuators, drive motors and control units fitted. Each dish unit was then connected, via opto-isolators and underground wires sheathed in copper tube (to reduce effects of lightning surges which, in our experience,

[12]Architectural advice was provided to the Energy Authority by Associate Professor J. Ballinger, Director Solarch, School of Architecture, University of NSW. Earth berming was also used as a means of controlling the internal temperature of the building.

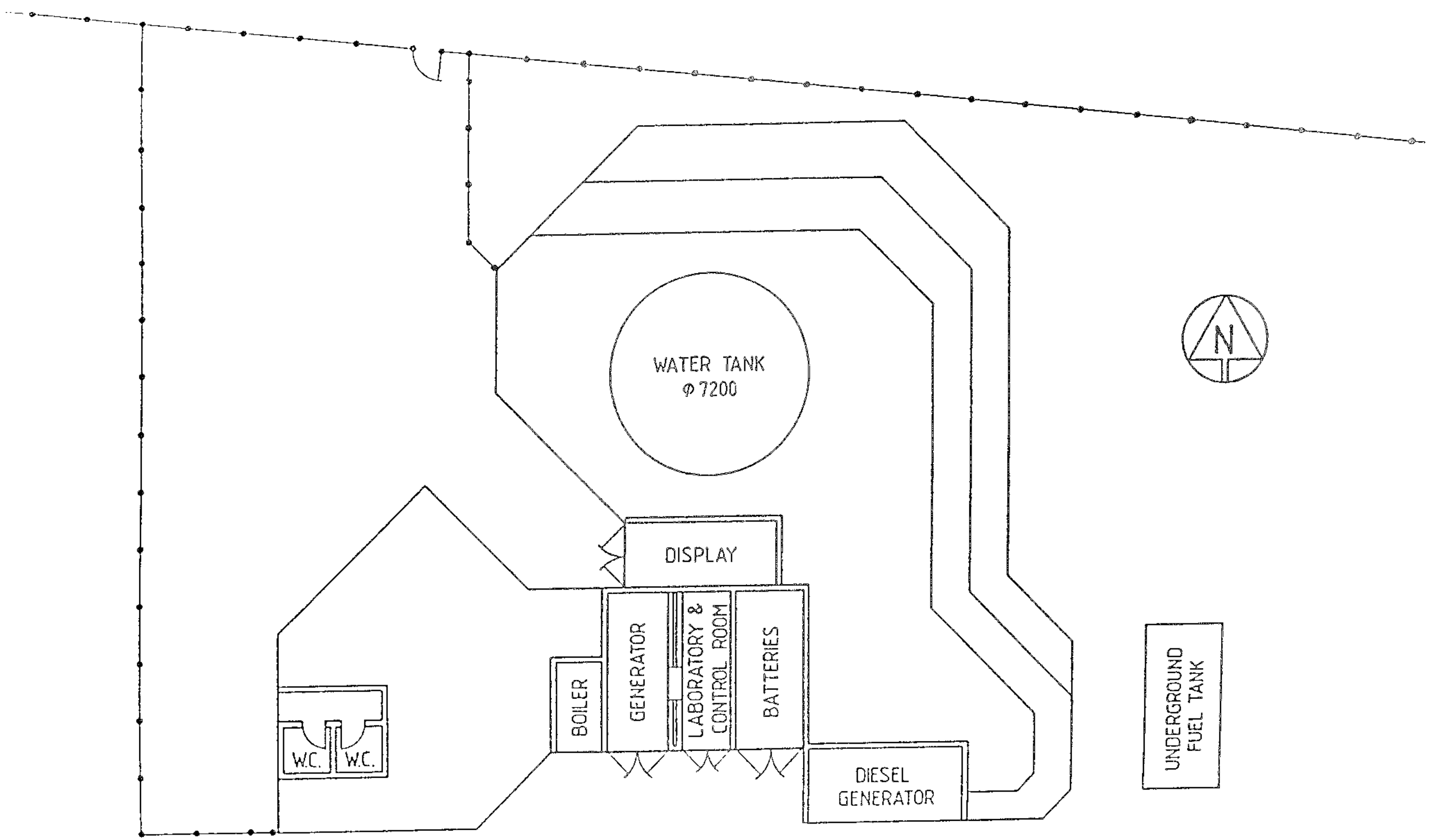


Figure 60. Layout of Station Plant and Earthworks.

Figure 61 - Transporting the 14 Dishes

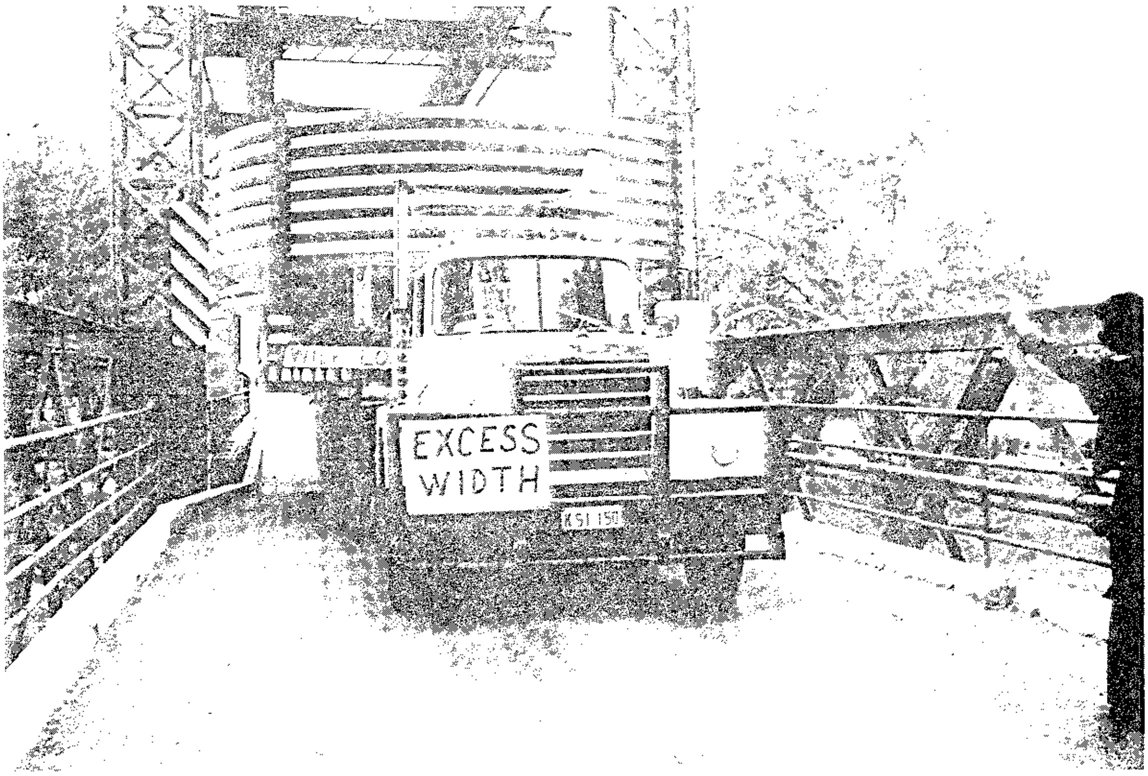


Figure 62 - The main dish transport problem - clearance of only centimetres on the Wilcannia bridge

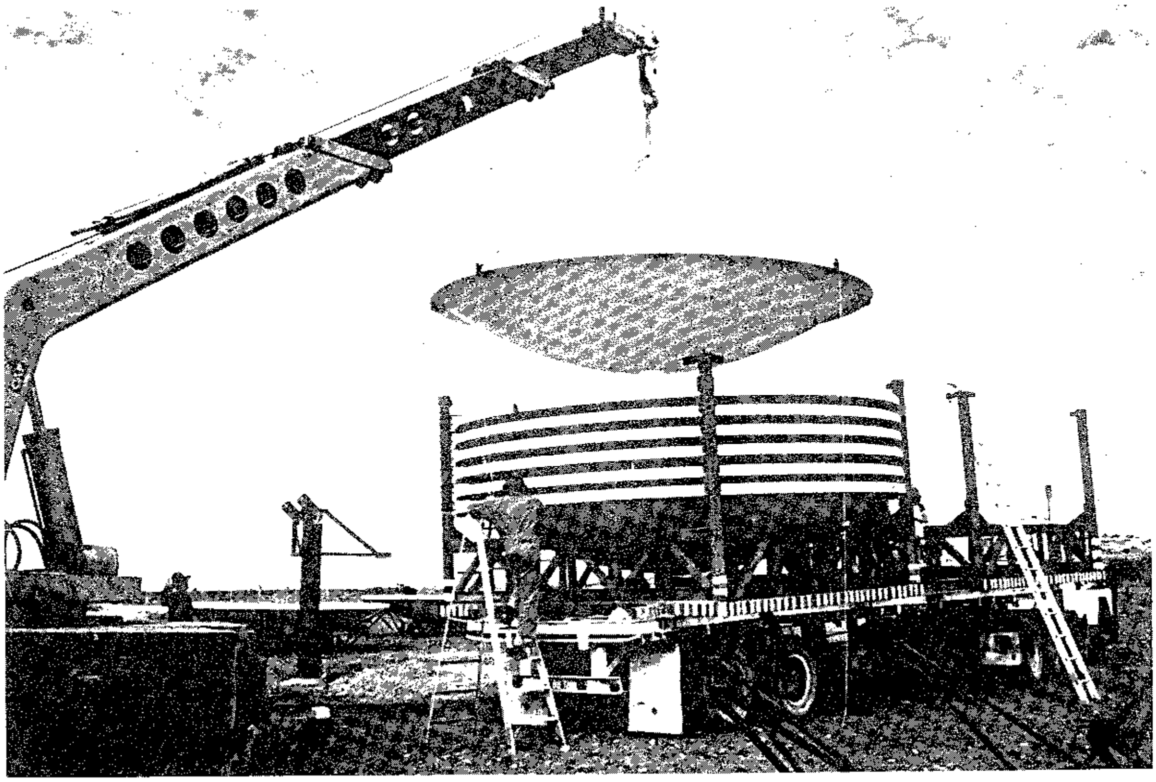


Figure 63 - At the Construction Site

Dishes being lowered onto their frames preparatory to mounting on the already installed pedestals (a pedestal is visible in the left background)

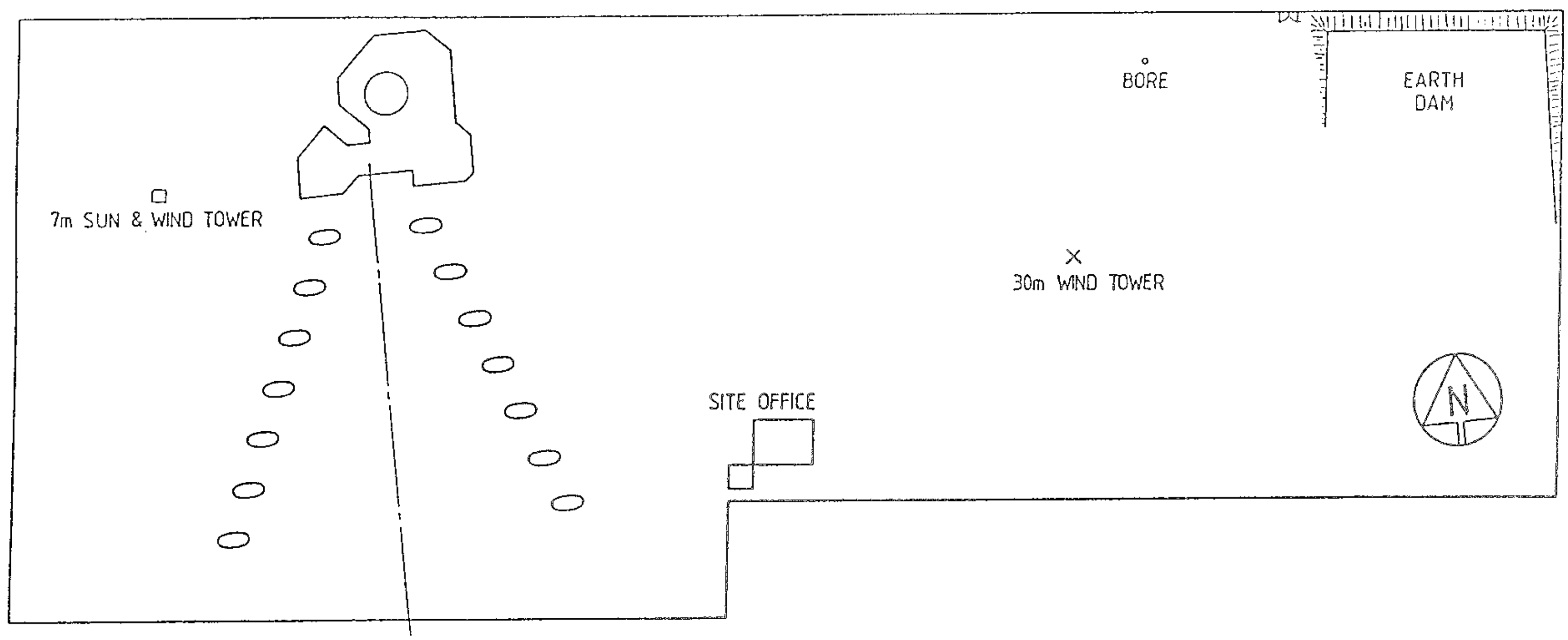


Figure 64. The Station Compound.

could cause problems in such areas), to the control room. Figure 41 shows the engine room; Figure 66 provides a view of the control room; Figure 67 shows the station battery bank.

Later the absorbers were mounted on each dish and connected to inlet water and outlet steam tubes. The water and steam lines connect through horizontal and vertical axis rotary joints to the main ducts, then to the engine room.

4.4.3 Duct Construction

All ducts are of square section galvanized steel, supplied to specification by a sheet metal workshop. The array ducts were supported on galvanized steel posts 300 mm off the ground, set in concrete some 1.8 mm apart. Figures 35 and 36 show the duct construction.

The absorber supports (serving also as steam ducts) and pedestal ducts (conveying the fluids through the centre of the pedestal pipe to ground level) were assembled complete in Canberra and transported to the site; the field ducts were assembled onsite from preformed parts. The procedure in either case was very similar: 55 mm thick microtherm slabs were sliced into widths ranging from 120–150 mm (depending on their location) and grooved by a simple hand grooving tool to take the steam lines (which vary in diameter from 9.6 mm at the dishes then increasing to 12.7 mm, 16 mm and finally 19 mm as the engine room is approached) providing tapered grooves in the horizontal plane near corners to allow for expansion of the stainless steel tubes (as indicated in Figures 34 and 35).

Installation of the steam lines, ducts and insulation proved the most onerous aspect of the array construction. Microtherm is a relatively "messy" material, crumbles readily and care had to be exercised with its handling. The procedure involved placing a 55 mm thick slab of the material in the bottom of the duct, running the groove to take the steam tube, assembling the stainless steel steam tubes (joining usually with swagelock fittings), then pressure testing the lines at twice rated pressure to check for possible leaks, following which further slabs of microtherm were groved to cap the steel tubes (forming a sandwich with the steam lines in the centre), then adding the top cap of the square section duct overlapping the lips of the bottom duct. Care was necessary to ensure that:

1. The ducts were watertight and the microtherm (which disintegrates in water) well protected. Continual care was required to achieve adequate quality control — duct joins were then sealed with silicone adhesive.

2. Heat losses were reduced to a minimum by clamping and compressing the microtherm sandwich by bands around the galvanized steel duct and adequate tensioning. End gaps were avoided by compressing each axial length of duct by special joints which ensured no joint remained open; by applying adequate precompression, even the expansion of the ducts themselves (they change in temperature by some 60°C) does not allow gaps to form.

Every reasonable effort was made to try to ensure that heat losses in the array were at a minimum. Subsequent performance measurements confirmed that the care taken had been successful.

In retrospect, a better arrangement would have been to order the microtherm insulation already formed in round ducts with a central hole through which the tube to be insulated could be inserted — a construction option offered by the makers of microtherm. This was not taken up at the time because of the difficulty of providing for expansion, or so it was perceived.

4.5 Project Schedule

Figure 68 indicates the development construction, installation and operation schedules as achieved. The array section of the project could have been compressed into a shorter time, but was not so scheduled because the initial task of getting the steam engine operational proved more time-consuming than was hoped; the same team carried on all aspects of construction and installation.

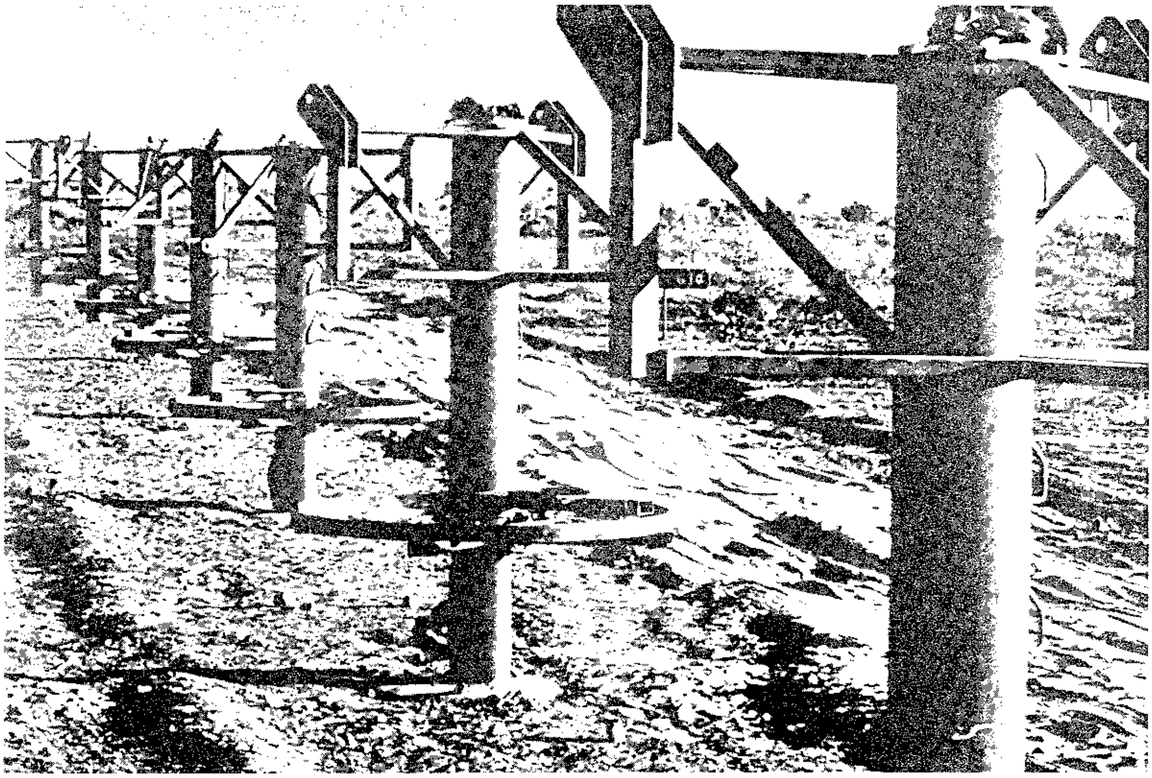


Figure 65 - Pedestal supports set in the ground, preparatory to mounting dishes

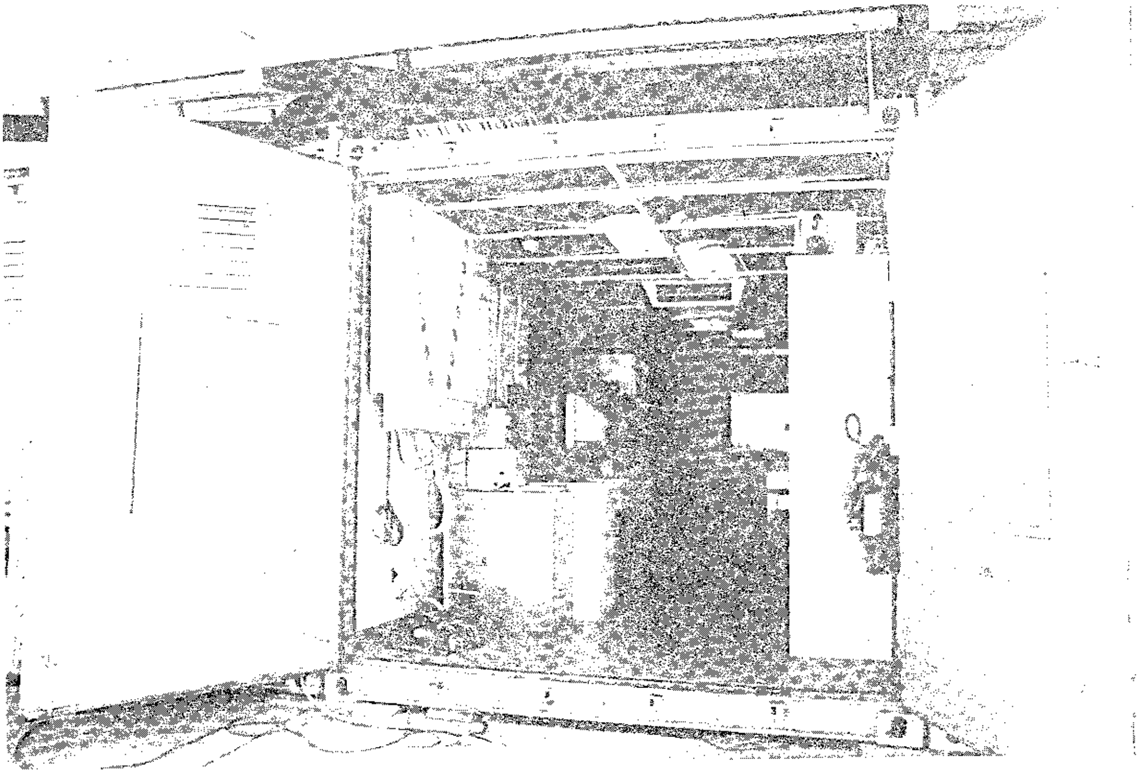


Figure 66 - View of Control Room

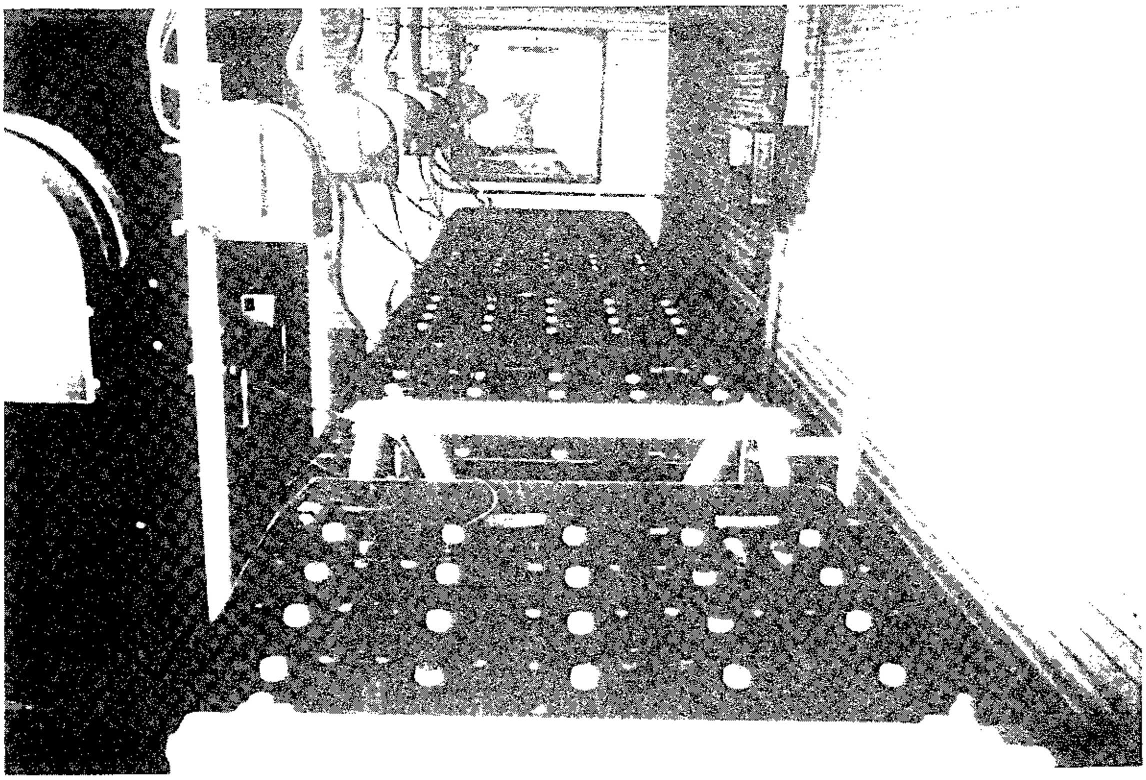


Figure 67 - View of Battery Room

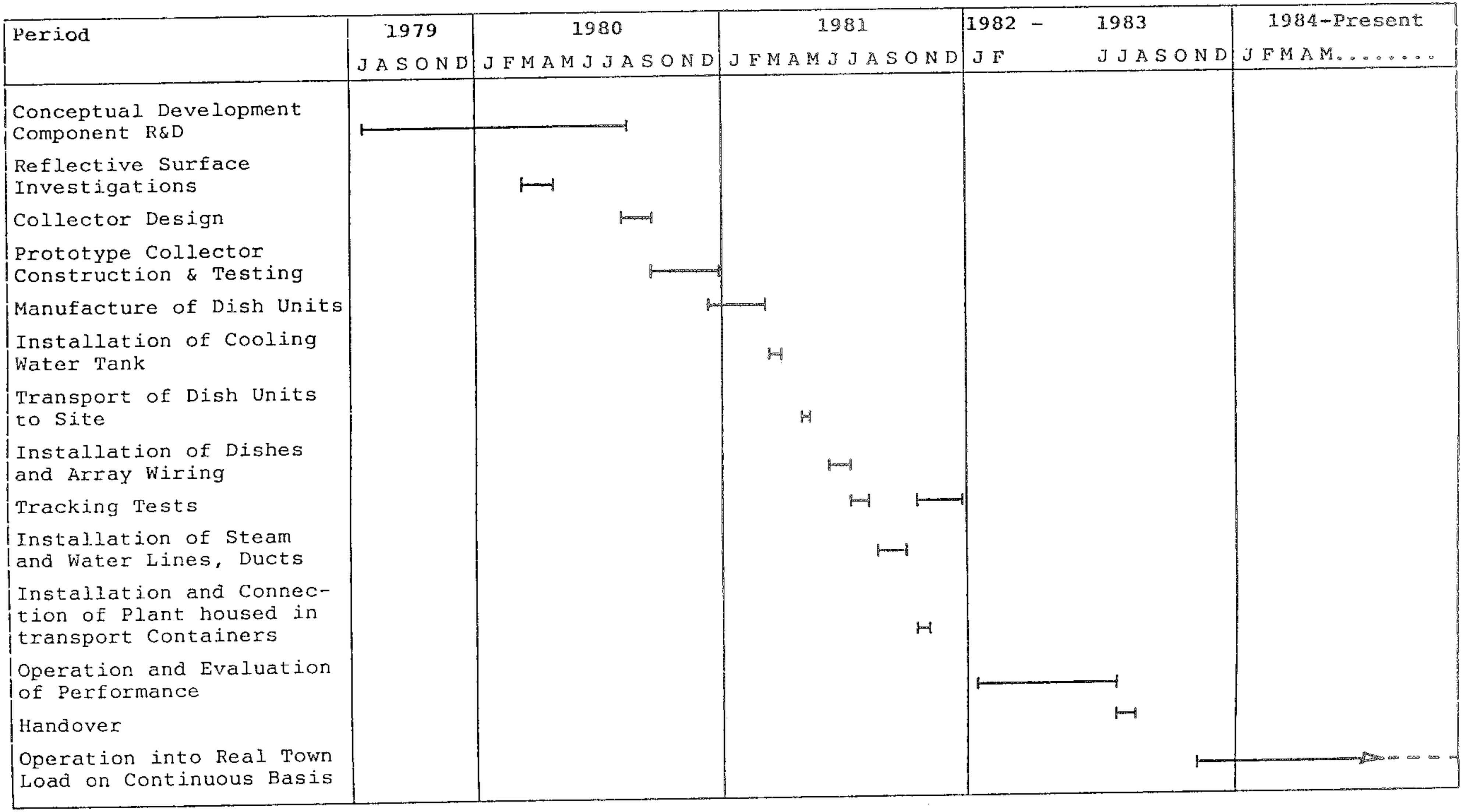


Figure 68 - Development, Construction, Installation and Operation Schedule

5 SYSTEM OPERATION AND PERFORMANCE

General Methodology

Following construction and installation, which was completed by Christmas 1981, attention has been directed to the White Cliffs project in the following order:

1. To ensure that the technology works (at all).
2. To achieve specified performance.
3. To attain reliable operation.
4. To ascertain and, if necessary, extend lifetime of components.
5. To identify what is involved in and to achieve optimal operation.
6. To enhance output and efficiency if practicable.

   Along with the above steps which are indicated in chronological order, two other aspects were pursued concurrently and continuously:

7. The gathering and organising of information about the system and the environment in which it operates.
8. The achievement of understanding in relation to system and component behaviour, of a realisation of what are the key factors which influence system effectiveness and performance, and of what can be carried over to produce better new generation systems — that is, the learning of lessons which can advance the technology into the future.

As of March 1991, the first three steps are satisfactorily complete; Step 4 is still ongoing, especially in relation to the absorbers, but generally we continue to discover means for extending lifetime and reducing maintenance requirements; 5 and 6 are ongoing as discussed in Sections 7 and 9. Steps 7 and 8 are essentially long term and would always provide new information as solar thermal technology develops.

One of the more unexpected features of the early experiences at White Cliffs turned out to be learning to understand what constitutes 'normal' and abnormal or faulty behaviour of the system. On countless occasions we spent considerable time trying to discover and remedy apparent faults, only to discover in due course, that the system was behaving quite correctly; it was our understanding which was lacking.

5.1 Checking Out and Commissioning

Checking out of the newly constructed plant was commenced on 2 January 1982; by June 1982 specified output was achieved. During the period June 1982–June 1983, the whole system was run with dummy load to ascertain and establish reliability, operation, maintenance procedures and especially to bring the engine to a robust, reliable unit (this being the most 'experimental' part of the whole system). The Energy Authority of New South Wales carried out proving tests in July/August 1983 and accepted the system which, without change, was connected to the town load on 30 November 1983 on a continuous, stand-alone basis (with diesel backup).

The township has been supplied reliably with power continuously since that time. Operational and performance highlights are reported in the Quarterly Progress Reports (1983–1987), commencing 1 December 1983.

Most of the systems had been designed and developed from a theoretical and philosophical viewpoint in the absence, for the new system concepts, of operational experience and with very little actual performance experience beyond laboratory experiments. These remarks apply most to the steam system (feedwater handling, absorbers, rotary joints, ducts, engine and engine auxiliaries) and least to the electrical/control/storage systems.

An attempt was made in the initial design stages to produce a comprehensive model of the steam system, involving the equations of state, but this exercise could not proceed because of a lack of knowledge of the many parameters which could be measured only from the working system. The equations of state, particularly as applying in the absorber, could not be readily handled; we could gain no assistance from the literature and it was not until we carried out a study in 1986–87 that there has begun to appear promise that an overall formulation will prove practicable [Bansal and Kaneff 1987]. But in 1982, through the demands of getting the station operational, we handled the problem by:

- Watching the system and its instruments, and learning.
- Puzzling out what constitutes 'normal' and 'abnormal' behaviour.
- Recording results and ascertaining parameters of interest.
- Postulating hypotheses about a wide range of operational factors and behaviours and experimenting to confirm, discount or change these hypotheses.

A good grasp of system characteristics and behaviour was gained and has been used subsequently to achieve formulation of the many complex and interesting system aspects. Formalization of these aspects is still ongoing and has provided a great deal of invaluable information useful to further system developments, especially identifying sensitive operation regions and parameters and permitting practical optimisation, including the development of appropriate operating strategies.

Much of the activities in early 1982 involved rectification of manufacturing and construction (especially wiring) faults, and in changes to the control systems and strategies to achieve more-appropriate operation. However, the major preoccupation was with the steam engine itself, which had arrived at the site in an uncertain state of perfection due to a perceived urgency to install the system. Over the period January 1982–July 1983, most (indeed almost all) attention was devoted to the engine valves which posed both short and longer term developmental problems, and to the oil–water treatment system; both had to be resolved on site. By July 1983 the engine system had become robust and reliable.

Activities over the first 18-month period required a high degree of dedication, involving attendance at White Cliffs for a week or so at a time almost every alternate week, thus allowing the carrying out of changes and assessing their effects. The necessary effort paid off in terms of a successful system.

5.2 Hardware Experience

Over the period January to June 1982 the station was usually attended during operating hours, even though the system worked on automatic control and had protection against various problems. During this time the main objective was to identify any weaknesses in the system, its components and operation and control strategies. It turned out that the array and its associated systems gave almost no trouble at all; almost all the time and resources were required by the engine and its systems, as already indicated. The array has continued to be trouble free. The modularity of the installation has proved useful in checking out problems or apparent problems, particularly in the steam system.

Of the initial batch of actual problems on the overall system, almost all were due to human error in manufacture, assembly, checking or operation; one subcontractor had provided some very poor actuator lead screws (later replaced); O-rings in some rotary joints had not been properly fitted or adjusted; mirror control unit relays were sticking initially. Now after some 6 years array operation, the schedule of problems is remarkably small. No changes to concept or detailed design have needed to be made; reliability has been excellent. The tracking approach employed has measured up to all demands. The station electrical and control systems worked from the start and have continued to operate over the years without problems. The station storage battery has given excellent service and is still in reasonable condition, given the 6 years operation and an initial year of non-operation (during station construction).

5.2.1 Component and System Problems

Main hardware inadequacies have been due to poor quality commercial components — pumps and relays especially — the most substantial item which ought to have been trouble free being a freewheel coupling through which the engine drives the AC/DC set. The first coupling was a Morse unit which lasted some 5 years and eventually failed, we believe, as a result of inadequate lubrication due to a misunderstanding of the lubricating instructions supplied by the manufacturers. This problem, in September 1986, caused the only significant station loss of supply when the diesel unit also failed while awaiting a new coupling to be sent from Sydney. An outage of nearly 24 hours resulted. Other occasions have occurred when one or other of the solar or diesel systems was out of service for whatever reason, but coincidence in which both systems were non-operational had not occurred before, or since; except for several very short periods (a few minutes) of loss of service which have required manual switchover. [By deliberate choice in automatic switching functions, the mechanical interlock does not allow automatic solar system takeover of the supply to the load in the event of a diesel failure before the battery voltage has reached 327 V on charge, such as exists during a morning solar start. The rationale behind this is to obviate multi-start diesel operation in the presence of intermittent cloud. We have not altered this approach because the occurrence has been rare.]

1. Free-Wheel Coupling

   Although there have been no further station outages since September 1986, the free-wheel coupling problems have not yet been convincingly resolved. The replacement coupling lasted only 2 months, its replacement worked for 3 months and the third replacement for 4 months. It was eventually ascertained that Borg Warner, suppliers of all these units, were essentially experimenting with modified designs, brought on by various industrial 'takeovers' overseas, whereby the original Morse components are no longer available (even in the USA). The fourth coupling in use at White Cliffs was working satisfactorily and, unlike the earlier versions, had a sealed lubrication system which has yet to prove itself over an extended period — we expected that in due course this problem would have been resolved[13].

2. Absorbers (Receivers)

   As noted previously, the steam system posed the major developmental problems on the project. In the steam generation region, solar absorbers (receivers) are very much in their infancy; problems of efficiency of collection and conversion can be and are being solved effectively; the major outstanding problem is to achieve long life (more than 5 years). [Section 3.1.3 has already discussed absorber experience at some length.] We expect our Mark IX units will prove satisfactory in this regard. One of the difficulties relates to the production of superheated steam from water in the one unit.

   Separating the absorber into compartments, each of which deals with water or steam in a single phase, is an additional concept to be investigated, as indicated in Section 9.

3. Feedwater Supply to Absorbers

   We consider the problem of rotary joints has been adequately resolved, but the use of capillary tubes to provide equal flow in each dish absorber carries with it some maintenance requirements — periodic removal of films of oil which otherwise build up inside the fine capillaries (approximately 0.9 mm internal diameter), causing pressure drops to be reduced, resulting in uneven flow in the various absorbers (the oily capillaries have more flow). This is the main and only significant consequence of imperfect oil-water separation.

   Individual flow control for each absorber is a desirable alternative which becomes more cost effective as dish size increases. The capillaries are currently cleaned by either high pressure water or steam cleaning; solvents not containing chlorine have also been used occasionally. A common 3-cylinder positive displacement feedwater pump supplies feedwater to the whole array in accordance with a control voltage input to the thyristor drive circuit to the unit, which has an extremely linear characteristic. We have had no problems from this system; the feedwater pump itself has been overhauled once in 1985.

4. Oil-Water Treatment

   One of the major problems in bringing the steam system to a reliable robust operating condition has been the removal of oil from the feedwater — oil which is gathered within the engine by the steam by mechanisms which have not been completely identified. Certainly some of the oil injected into the galleries above the exhaust ports, to lubricate the cylinder walls, finds its way into the steam and clearly, also, some oil finds its way from the sump past the bottom oil rings in the piston skirt. Most of the oil from these two sources is simply mixed with the steam and separates from the water in the vortex chamber condenser and first compartment of the feedwater tank, to be subsequently skimmed off, centrifuged and returned to the oil tank.

   But the remainder of the oil forms a colloidal suspension in the condensate and is difficult to remove. We are not clear on the precise mechanism of formation of

[13] But it was not: The fourth coupling was changed over to oil rather than grease lubrication but still gave problems. We removed the freewheel clutch in November 1990 and changed the operating strategy accordingly. Borg Warner now have a new clutch design which should be tried.

this colloidal suspension; even those oils specially designated as 'non-emulsifying' still produce this effect. Running the engine on wet steam results in more colloidal suspension than operating on dry steam. We remove the small amount of oil from the feedwater gathered in this way satisfactorily, but not perfectly, by pumping the water from the first compartment of the feedwater tank through Gaf bags (brushed nylon material) filled with non-absorbent cottonwool; this process coalesces and traps most of the oil which forms droplets that float to the surface of the second compartment of the feedwater tank, fall over a weir into the first compartment, and are skimmed off by the skimmer along with the oil from condenser and vortex chamber which floats on the surface of Compartment No 1.

The skimmer/centrifuge system is a very satisfactory means for handling the oil/water problem; however, in an effort to reduce auxiliary power, we removed the skimmer method of gathering oil from the surface of the feedwater tank in July 1987 and replaced this by two stainless steel disks on a horizontal axis, dipping into the feedwater and rotating about 10 rpm. By careful sizing and adjustment, oil is collected, brushed off and returned to the oil tank with extremely little water collection (less than was contained in the original centrifuged oil returned to the oil tank) and the centrifuge was no longer necessary. Power consumption is now only some 30 watts, compared with about 800 watts taken previously by the centrifuge and skimmer pump drive motors.

This change has not only reduced auxiliary power requirements but has substantially reduced cost and increased reliability of the oil–water treatment system.

5. Condensate Handling

Experience has caused other changes to be made to the condensate treatment system; Figure 40 shows the original system whereby a vacuum pump produces the required low pressure while the condensate from the condenser flows to a closed tank and is pumped out periodically, causing temporary loss of vacuum during this process. Subsequently the arrangement of Figure 2 was implemented to avoid system disruption during temporary loss of vacuum, by calling on the vacuum pump to handle both vacuum and condensate continuously. This operation is somewhat inferior in performance to the original and we propose to make a further change by allowing the oil–water pump to handle condensate from both the vortex chamber and the condenser, while the vacuum pump itself establishes the vacuum only. This will involve raising the condenser to permit adequate pump heads to be provided.

The new arrangement, which has been installed already on our two systems working in the USA (Troy and Albuquerque — for the Molokai Project), has been shown to perform very satisfactorily.

6. Engine Oil System

Experience demonstrated the need to install a further level switch/alarm in the oil pressure/oil level circuit to cope with high engine oil level which can cause loss of power and produce unusual operating conditions. On one occasion we spent several days trying to discover the cause for such curious behaviour before ascertaining that too high an oil level in the sump was the cause. This alarm also plays an important part in preventing water syphoning from the feedwater tank into the oil tank on centrifuge malfunction, as had happened previously. This protection has proved very useful.

A further pump (designated a scavenger pump), not shown in Figures 2 or 40, is shaft-driven by belt and used to pump oil from the bottom of the sump to the oil tank, with inlet to the original internal (diesel) engine-driven oil pump obtaining its inlet from the cooler cleaner oil tank rather than from the sump itself (its normal connection). There is, as shown in Figure 2, also an oil drier which removes water from the oil in the sump and tank. The scavenger pump has served the purpose of allowing cool water-free oil only into the engine's main lubricating oil pump and serves also to promote oil circulation between sump and oil tank, especially when the oil is cold in winter starting. But by employing the original engine lubricating pump to gain its inlet supply, as it would normally do in the original diesel engine, and providing large diameter tubes for oil circulation between sump and oil tank, the scavenger pump is not necessary, uses extra energy, is an unnecessary expense, and is not used on our two working systems in the USA.

7. Engine–Piston Operated Valves

If the steam system generally was the most demanding and resource consuming item in the overall project the engine valve mechanism and piston combination proved the major item in this area, followed by the oil–water treatment system development. The piston operated valves (POV), as illustrated in Figure 42, are an attractively (but deceptively) simple concept which has been around for a long time but, we discovered in due course, had not been developed previously to a reliable effective technology. We were obliged to set about carrying on this development in the field, between January 1982 and June 1983. Once we had grasped all the affective parameters and understood their inter-relationships, we were able to produce very effective operation which we are now optimising, preparatory to developing and building bigger engines, including engines which employ ceramic valve (and piston) components.

That geometric configuration, matching of materials and the handling of steam flow are key elements in achieving a successful POV mechanism, is obvious but does not point to just what parameters need to be employed. Our situation was not helped by the stress of timely commissioning requirements; in the event, the successful solution of the pressing problems reflects great credit on those involved — the detailed recording of the necessary 'know-how' developed is left to the future, when licence agreements no longer preclude this being revealed.

While the valve mechanism itself proved difficult to perfect, once problems had been resolved it became straightforward to implement. The pistons themselves, however, have taken a different development path. Cast-iron standard GM diesel pistons have been modified first by providing a relatively simple insert in the crown, holding the valve pins, and later by providing a mild steel cap (having removed the top of the cast-iron piston section) for the same purpose. Both approaches have been troublesome through weld failures of one form or another in the long term (more than hundreds of hours). Achieving reliable welds (X-rayed for confirmation) has been possible but not straightforward and we have investigated a number of different designs, most of them still avoiding the need to cast our own pistons; an exception has been the use of cast aluminium pistons with stainless steel tops (tried on the engine in late 1987, but found to be unsuccessful).

This is a continuing investigation directed to producing reliable piston components which can last indefinitely. The valve mechanism itself operates satisfactorily for well beyond 1 000 hours without attention. [It is expected that the use of ceramic valves and piston tops will enable cheaper components to be produced, lasting longer and able to operate at higher temperatures and pressures, so providing better efficiency and more output — that is, becoming more cost-effective. This is of importance in larger engines.]

It is worth commenting that we see much improvement still possible in this technology, as discussed further in Section 5.9.

8. The Chlorothene Experience

   In April 1984 operators at the station noticed that chlorothene, which was available as a cleaning agent preferable to carbon tetrachloride, produced a magical elimination of the colloidal oil suspension in a sample of feedwater and added a litre of chlorothene to the feedwater tank. The oil–water treatment system became perfect in producing crystal clear feedwater.

   Within 3 days all the solar absorbers had sprung multiple very fine pinhole leaks in the region where water turns to wet steam and it was found that the engine valve mechanism was also affected even though, when problems were suspected, very stringent steps had been taken to flush the chlorothene-carrying feedwater from the system. The wellknown effect of even very small quantities of chlorine when combined with oxygen and boiling water on stainless steel was not suspected as a factor; in the event, chromium was removed and numerous small pinholes resulted in the absorber coils in the boiling water zone, all within a relatively short time. This failure of communication between system designers and operator was unfortunate, and served to tighten general operation and maintenance procedures. All absorbers had to be replaced, the system flushed very carefully, engine valves replaced, and the engine oil flushed and replaced — a time-consuming exercise.

   This episode served as a warning about operating procedures and uninformed decisions on system matters being taken. It also cleared up a nagging unexplained problem which had occasionally intruded to cause some absorbers, after a relatively short time (weeks), to develop multiple pinhole faults in the region where water changes to wet steam. With the above lesson in mind, we discovered that sometimes a more than usually diligent craftsman had cleaned out the inside of wound absorbers produced in our workshop with chlorothene, without this being specified, notified or noticed at the time. A few parts per million of chlorine are adequate to cause problems with stainles steel.

9. Non-Problems

   Because it played such a significant part in our early acquaintance with the solar system, it is worth underlining the fact that many of the episodes during operation, which we perceived as problems, turned out (on further inspection) to have been non-problems but valid operational characteristics. This required a learning phase which, in some aspects, extended for several years as more subtle factors were noticed.

   A detailed record of hardware experience is given in the Quarterly Progress Reports (1983–87) and in station records.

5.2.2 Maintenance

Regular maintenance comprises:

- Daily checks of feedwater and engine oil.
- Visual (and aural, where appropriate) inspection of all system components (including the data acquisition systems) to ensure that all items are in working order.
- Periodic inspection of all oil and grease requirements for commercial units in accordance with makers' specifications.
- Battery electrolyte checks.

- Cooling water level checks.
- Generally keeping the station tidy.

Periodic flushing of the flow equalizing capillaries is carried out during operation; rotary joint O-rings need to be replaced approximately every 2 years.

Beyond these requirements, maintenance is on an 'on-demand' basis — two, sometimes three, local inhabitants are able to provide this attention; in difficult problems, reference is sometimes made to us in Canberra by telephone. This arrangement has proved workable and satisfactory.

1. Coping with Wind

   Although extremely strong winds are uncommon, during its daily operation the array experiences very severe buffetting from the wind especially from late spring to early autumn, and steep velocity fronts cause sudden mechanical shocks. As already indicated in Section 3.1.2, problems from this cause (and an undue call on maintenance) are avoided by the intermittent tracking mode employed. The wind causes loss of absorber heat by convection (a significant loss in strong winds) , deposits dust onto the collectors and occasionally a very unwelcome depositing of large quantities of dust in plant rooms as a result of wind blowing from a particular direction and sometimes by dust-laden whirlwinds which, more often than seems reasonable, choose a path to the plant.

2. Rain and Dew

   The effect of rain is only slight because of its infrequent occurrence. Most clouds moving over White Cliffs, although reducing solar energy, seem reluctant to part with their moisture. When rain does fall, it is useful in partly washing the dishes but the action is incomplete — some residual dirt remains. Dew, which is frequent in spring and autumn, results in several litres of condensate on each dish; it acts to consolidate part of the deposited dust on the mirrors which must be periodically cleaned.

3. Cleaning Dust

   Both coarse low level dust blown up by strong winds and high level fine dust occur in abundance in the inland. The former is not a problem since it rarely deposits or remains on the mirrors. The latter often reduces insolation directly and also produces a frequent deposit of fine dust on the dishes and on all other components, including those in the plant rooms. Dust of one kind or another has to be accepted as a fact of life; the equipment has been designed accordingly, either dustproof or dust tolerant.

   However, the mirrors are regularly affected and, unless cleaned, can suffer an energy loss of up to 20% after a few weeks — this loss removes valuable superheat and is a serious effect. Cleaning of dishes is therefore considered necessary and is carried out with a frequency of 10–30 days, depending on the state of the mirrors. Because of the absence of grime and due to the fact that the consolidated particles are very small, cleaning is carried out by manually rubbing with a large lambswool pad mounted on a long flexible tube. This cleans and polishes the mirrors in a time typically 5–10 minutes per dish, depending on the state of its surface; the fine dust acts as a good polishing agent. Cleaning while dishes are tracking early morning or late afternoon has been found the most satisfactory procedure, particularly as the state of cleanliness of the glass can be readily observed. About twice per year, dishes are cleaned with water to remove accumulation due to dew/dust/rain which cannot otherwise be readily removed by dry polishing.

The manual cleaning at White Cliffs is well matched to the size of the dishes and would not appear practicable, because of tedium and inaccessibility, for much larger dishes; for such large dishes we are developing an automatic cleaning system as part of the dish.

Occasionally, dust is removed from the plant rooms and equipment, more to satisfy aesthetic considerations than to perform any specific protective function, since all components have been successfully made, designed or selected to be dust tolerant or dustproof; no problems have ocurred attributable to dust.

All things considered, we believe the level of technology and the maintenance procedures established are successful in the White Cliffs environment. Further life tests need to be carried out to gain more information about component and system long term performance. Many hardware improvements can be made to improve reliability, as discussed in Sections 7 and 9.

4. Extremes of Temperature

   Temperatures from just below freezing in winter to well above 40°C (up to 47°C) in summer are a feature of the White Cliffs' climate. Humidity in summer can also be a problem. Equipment is not difficult to make tolerant to these conditions. No anti-freeze protection is used in the steam system which is always to some extent charged with water when the system is not running.

   Although the environment is harsh and inhospitable on occasions, by applying appropriate design and operating strategies, problems can be coped with readily, and no problems on the system have been attributed to high temperatures (although cooling water temperatures rise considerably) and no specific temperature-dependent maintenance problems have emerged.

5.2.3 Spare Parts Schedule — Facilities

The station carries a set of spare parts of items most likely to be needed, especially those custom-built components which are expendable, such as engine valves, gaskets, printed circuit boards, printed circuit motors, O-rings, spare rotary joints, absorbers, two complete mirror control units, sensors, relays, tuners, water and oil filters, silicone adhesive, welding and soldering materials.

Remoteness of the site has carried with it various logistic problems; it was therefore appropriate to set up a field station with adequate resources to handle maintenance and a fair amount of development on site. This has proved extremely valuable and is being slowly enhanced in capability to make the station more self-sufficient.

More-detailed information on hardware experience appears in the station Quarterly Progress Reports (1983–87) and in station records.

5.3 Operation

System operating features are discussed in Section 3.10. The following is of relevance here:

5.3.1 System Control Strategy

Overall operation is directed to gather the maximum possible nett electrical energy from the conversion of solar collected heat. Strictly speaking, the system never reaches steady state equilibrium because insolation is continually varying, even on a clear sunny day. The combination of this factor with the numerous other variables, time constants and other parameters ensures that a strategy which results in maximum electrical energy with a particular insolation profile is not gained easily. Nevertheless measured insolation, known absorber characteristics (output/steam quality/losses), transmission heat losses as a function of transmission temperature and rate of change of temperature, engine characteristics as a function of steam quality and cooling water temperature, are all available and can be used to set feedwater flow from moment to moment to gain the optimum electrical nett output energy. At present this control system, although available, is not connected pending finer control on individual absorber feedwater flows. The quantity controlled is the feedwater flow achieved by varying the thyristor drive input voltage signal. Whileever the automatic optimization circuit is not connected it is possible to achieve manual feedwater control setting by adjusting feedwater flow to correspond respectively to early morning and late afternoon — about 9.00 am and 3.00 pm, 5.00 pm and around 11.00 am, ie 4 adjustments per day with little loss in effectiveness, or even 3 adjustments per day (9.30 am, 3.00 pm and 5.00 pm, the latter value being suitable for startup next morning).

At low insolation levels, it becomes eventually unprofitable to keep the system running, as the total generated power falls close to that required to run the auxiliaries alone; the steam system is then closed down. Likewise, during certain patterns of intermittent cloud, the energy gained may be only equal to or less than the energy required to keep the auxiliaries running during the cloudy patches; again the system can be stopped for a period. Automatic control of this function is a challenge to produce the necessary 'intelligent' control system. Provision of an intermediate heat store would assist, granted satisfactory overall economics.

At present, operator intervention is required to set the 'start' and 'stop' times of the station (usually set for a week or more in advance, depending on time of year) on the master clock. Operator intervention is also required to prevent a 'start' during heavy cloud or to discontinue operation during some kinds of intermittent cloud which experience indicates leads to little or no nett energy gain. Generally, with the original auxiliary power demands, no nett useful energy was gathered for insolation less than 400 W/m^2 in the mornings, or less than about 350 W/m^2 in the afternoons following a sunny day (heat stored in the system is released to assist late in the day). More recently, with reduced auxiliary power demands, it is worth running the system at somewhat lower insolation levels, the precise crossover point depending on the current overall operation efficiency and the wind conditions which affect convection losses from the absorbers.

5.3.2 Operating Sequence and Operational Features

Operating sequence and features have been discussed previously, especially in Section 3.10, actual performance achieved depending on the insolation and wind profiles which occur for each operating period.

The automatic cycle begins on clock command some 10–25 minutes after sunrise; feedwater flow is then established in the array over an allocated 7 minutes; the array acquires the sun within the next 3 minutes; steam lines warm up and steam quality rises. At an engine room steam temperature of 180°C, the bypass valve closes. When steam pressure reaches 2.7 MPa, the throttle opens and the electric starter engages, ensuring engine start in the correct direction; the drain valve closes and the engine accelerates as it warms up. On a sunny day, engine start occurs some 12–6 minutes after the array is first tracking; within a further 20–6 minutes, the engine is delivering useful power to the load (that is, generating 3+ kWe to supply auxiliaries and some load). Useful power is generated within about 45–22 minutes from initiation of the 'start' signal, depending on time of start and insolation. These times are greatly reduced for starts later in the day.

A clock signal 20–40 minutes before sunset (approximately the limit of useful nett power output) causes the array to park horizontally facing southeast. During intermittent cloud, the engine stops and starts automatically in accordance with available steam quality; during cloud, the tracking system provides timed pulses for following the sun which can then be acquired within seconds of emerging. For obvious continuous cloud, the system can be manually locked out, the station operations manager using his judgement and prediction of insolation conditions as to whether or not to run the system.

However, decisions are usually more complicated in the presence of intermittent cloud and/or haze, noting the various insolation conditions discussed in Section 2, when the steam system has to run in uncertain conditions of energy supply and heat quality. While the station auxiliaries (especially the feedwater pump, the water and oil circulating and treatment pumps, and the cooling water pump) are running continuously, some 3 kWe energy is expended. If there is no steam energy, this quantity has to come from the batteries. It can happen, therefore, depending on the mark-space ratio of the sun/shade, that there may be a nett overall loss of energy while running in this mode, or at least the nett useful energy over the operating period may not be worth the trouble to run.

Operation in conditions of haze due to sparse cloud, water vapour, smoke and/or high level dust, presents problems associated with lowered steam quality due to low mean insolation level. The characteristic 'spikey' profile (with frequent variation in level) results in lowered station output; neither the steam system nor the engine can attain temperature equilibrium. Presence of haze often results in a marked reduction in average insolation. As even relatively short spikes of shade can cause momentary loss of superheat from which the system takes time to recover, an intermediate heat store would play an advantageous role in coping with haze and generally with intermittent cloud.

Parking the array after a day's operation has received a great deal of consideration. Although parking with dishes vertically-facing would be the safest in case of onset of very strong winds, this aspect is protected by the automatic control from the wind monitor which causes parking facing upwards for winds stronger than 80 km/hr; so the array can be parked facing horizontally to the southeast, thus requiring little azimuth movement to acquire the sun in the mornings. Experience has shown that, on balance, least dust collection and dew precipitation occur in the horizontally-facing position.

5.3.3 Operator Intervention

With automatic feedwater control in place, during normal operation, the only attention necessary each day is the checking of lubrication and feedwater needs and a visual inspection that all components are in working order. Some manual recording of data is also necessary.

Because feedwater flow in each absorber is not uniform — a result of the rudimentary system employed for this purpose — it is at present necessary to set feedwater manually to take account of day-to-day environmental and system conditions, until our new flow controls are installed. This is normally carried out satisfactorily by setting flow at about 9.OO–9.30 am, and again at 11.00–11.30 am, 3.00 pm and 5 pm (this latter setting being adequate for automatic start next morning). By a different adjustment at 9.30 am, the 11.00 am setting can be obviated, as discussed in Section 5.3.1.

In the absence of any problems requiring attention, about one hour of operator time is involved per day.

The system in fact provides a fascination and challenge for operators who tend often to run some aspects of the control on manual in order to come to know and understand the complex behaviour. Expertise has to be developed to recognize behavioural characteristics of the system and their implications. The presence of many interconnected systems sometimes can lead to difficulty in diagnosing just what is happening. On many occasions manual operation of the control system has resulted in interrelated behaviour which is difficult to grasp, but is nevertheless in order, leading operators to explore further and spend considerable time in resolving what is not a fault condition. This is the essence of learning but we hope to reduce these episodes when the feedwater flow system is more effective, allowing complete automatic operation to be installed permanently. We consider it is important to allow operators to attain an understanding consistent with their interest as a means of improving efficiency and effectiveness of the system.

5.3.4 Visitors

The station receives some 5 000 or more visitors each year, notwithstanding the remoteness of the area. Some of these visitors are overseas energy researchers and administrators who come specially to view the White Cliffs Station. Many others are interested in the possibility of establishing their own solar power unit in inland Australia and value discussions on practicability and prospects with station staff and researchers from Canberra (whenever present). General tourists also show considerable interest in the station. Operators need to spend a certain amount of time each day attending to the various groups of visitors, a situation helped by the effective display room adjacent to the station.

5.4 White Cliffs Load Characteristics

In the conception and design stages of the project, assumptions had to be made concerning the expected load curve and the effect of a very small number of users on peak and average demands from the station. In the absence of other information, the conceptual load curve illustrated by Figure 46 was taken for design purposes.

The reality has turned out quite differently; both level and characteristics of load have changed since 1983 in a manner which reflects the lifestyle of users, as well as being influenced by the provision of a 10 Ampere circuit-breaker which ensures that no one connection can draw much more than 2.4 kW for a significant time. This arrangement has worked out surprisingly well, people having adjusted to the availability of continuous power for the first time in White Cliffs. The only discontent has been voiced by one or two users who have long experience in being able to switch on 'unlimited' grid-connected power.

The connected electrical load of White Cliffs commenced with some 8 houses, the post office, school, hospital, community hall and streetlights, all consumers being located within about 1 kilometre from the power station. A hotel and general store were not connected, relying on previously-existing diesel generator sets; nor were numbers of people living further out in the mine workings — this latter group is very transient in its residence practices. The load consists mainly of lighting, refrigeration, evaporative coolers, intermittently-operating household appliances, and some power tools and welders. Electric power is supplied continuously on a stand-alone basis with diesel backup.

5.4.1 Supplying White Cliffs — The Early Days

The conventional wisdom in power supply circles suggested that 25 kWe to supply a community of 40–50 people with connections, as detailed above, was hardly adequate. The system was not in fact sized to power White Cliffs but was determined by other factors; the site was not chosen until some time after main parameters were set[14].

It was therefore not without some interest that local citizens, Energy Authority and Australian National University personnel gathered at the station site at 11.00 am on 30 November 1983. The switch was thrown by Graham Wellings and the subsequent loads drawn over the next 24 hours were as indicated in Figure 69. When noting the frugal nature of all things in White Cliffs, the magnitude of the load is not so surprising.

City dwellers who practise little economy in the use of electric power find it hard to come to terms with the fact that 25 kWe peak capacity is adequate to supply the abovementioned load. But in the first 6 months of fulltime operation, the town load did not reach even one-half the station capacity. Even in early 1986 the peak load had not exceeded 15 kW and it was not until late 1986, when the shop, cafe and further domestic users had been connected, that the peak load has ever reached 25 kW. The continuious average load (monthly) over the period November 1983 to December 1987 is shown in Figure 70; the rising characteristic is noted, as users increase in number and in demands on the system.

5.4.2 Characteristics of the Load

Figure 69 indicates the character of the load over the first 24 hours of connection to the town; this level of load did not change markedly for many weeks as if the townspeople, having gained a power supply, were not particularly keen to take much advantage of it.

Over the period November 1983 to about September 1986 there was a gentle increase in average power demand, as indicated in Figure 70. During this period the shape of the

[14] There are now some 25 connections to this system of 25 kW plus streetlights.

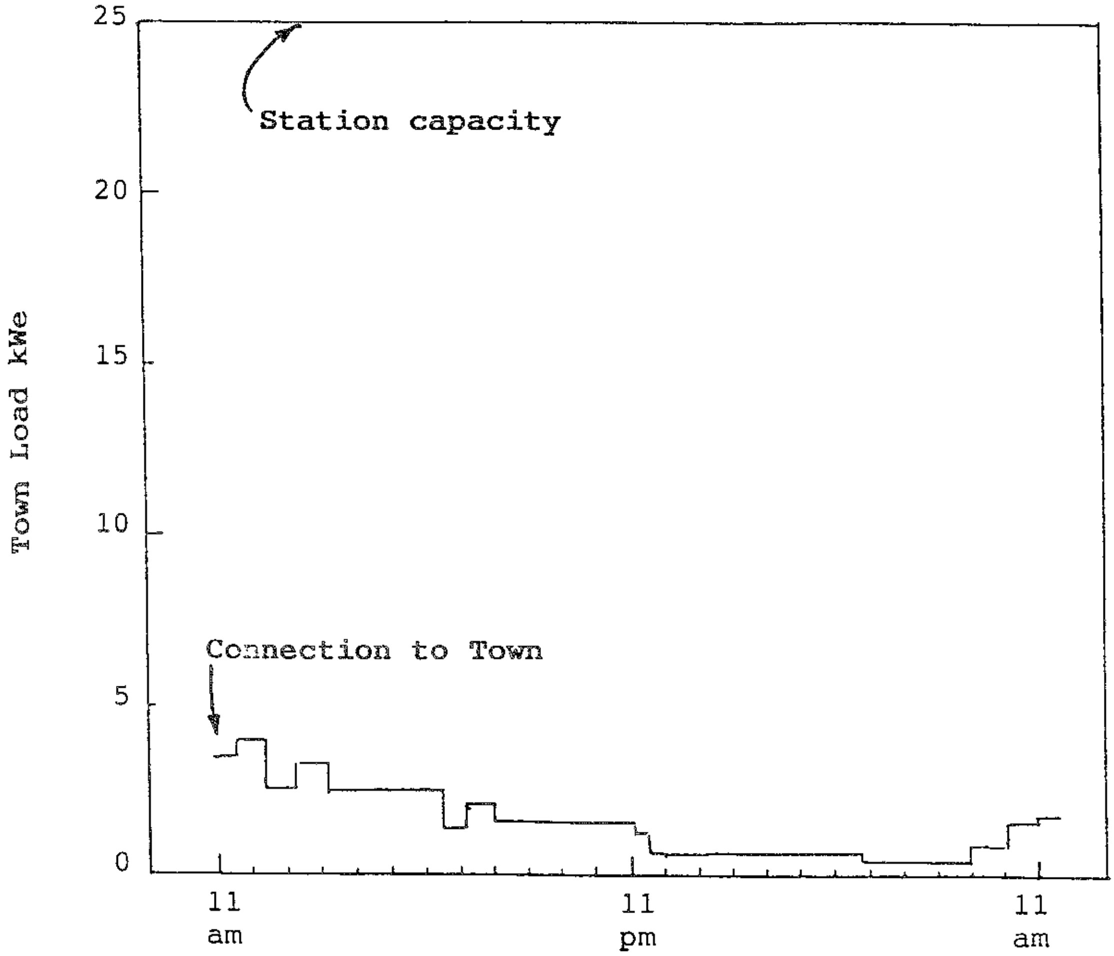


Figure 69 - White Cliffs Load - The First 24 Hours

load characteristic was as indicated in Figure 71(a) and in the simplified presentation in Figure 71(b) (both for June 1985) but very representative in shape for the whole period in question. The general shape of the load demand from the summer of 1986/87 to the present is indicated in Figure 72(a) and 72(b) (simplified); this pattern has persisted through summer and winter, the total load being somewhat higher in winter.

A general observation can be made that, whereas prior to September 1986 the load curve possessed very pronounced peaks and troughs, subsequently it has more or less evened out and shows no very marked differences dependent on time of day.

5.5 Solar System Characteristics and Performance

Not all of the direct axis solar radiation can be used effectively because of the influences of losses at the higher temperatures and the need to supply a basic minimum of high quality heat to the engine to provide for engine losses and auxiliary power before useful power can be gained. Thus insolation, around sunrise and sunset and in the presence of heavy haze and/or frequently varying clouds, results in unavailability of a significant amount of solar energy when assessed annually. Improvements in system efficiency and in reduced auxiliary power work to assist in these respects.

The collector layout results in negligible shading during useful operating periods; the array is able to run and produce steam soon after sunrise and nearly until sunset but the quality and amounts of steam produced must be adequate to overcome the system losses before useful power is available, as already indicated. The amount of energy not available is not substantial during sunny days, but in intermittent cloud or haze becomes quite significant and both design and operating strategies are worth improving to capture this energy. Developments discussed in Sections 7 and 9 address these and other issues relating to system improvement.

We are here concerned with characteristics and performance of the current overall system and its subsystems.

5.5.1 Solar-Array and Steam Reticulation System

Figure 29 shows the efficiency of conversion from direct beam solar radiation to heat energy into the steam emerging from Mark II absorbers at different steam temperatures and different insolation levels. This steam flows through two rotary joints which cause transfer of some of its heat energy across the rotary joints to the feedwater, as discussed in Section 3.1.4, dropping the steam temperature as indicated; that is, losing heat quality but not quantity; the steam then flows through the microtherm-insulated ducts to the engine room.

Figure 73 indicates the kW thermal energy entering the engine-room at different steam temperatures and at different insolation levels.

As the losses due to radiation and convection at the absorbers are dependent mainly on temperature and not on mass flow, the efficiency drops rapidly as total energy gathered drops due to low insolation. Similarly the array heat transmission losses are dependent almost only on transmission temperature (and change of temperature due to the 'soaking'

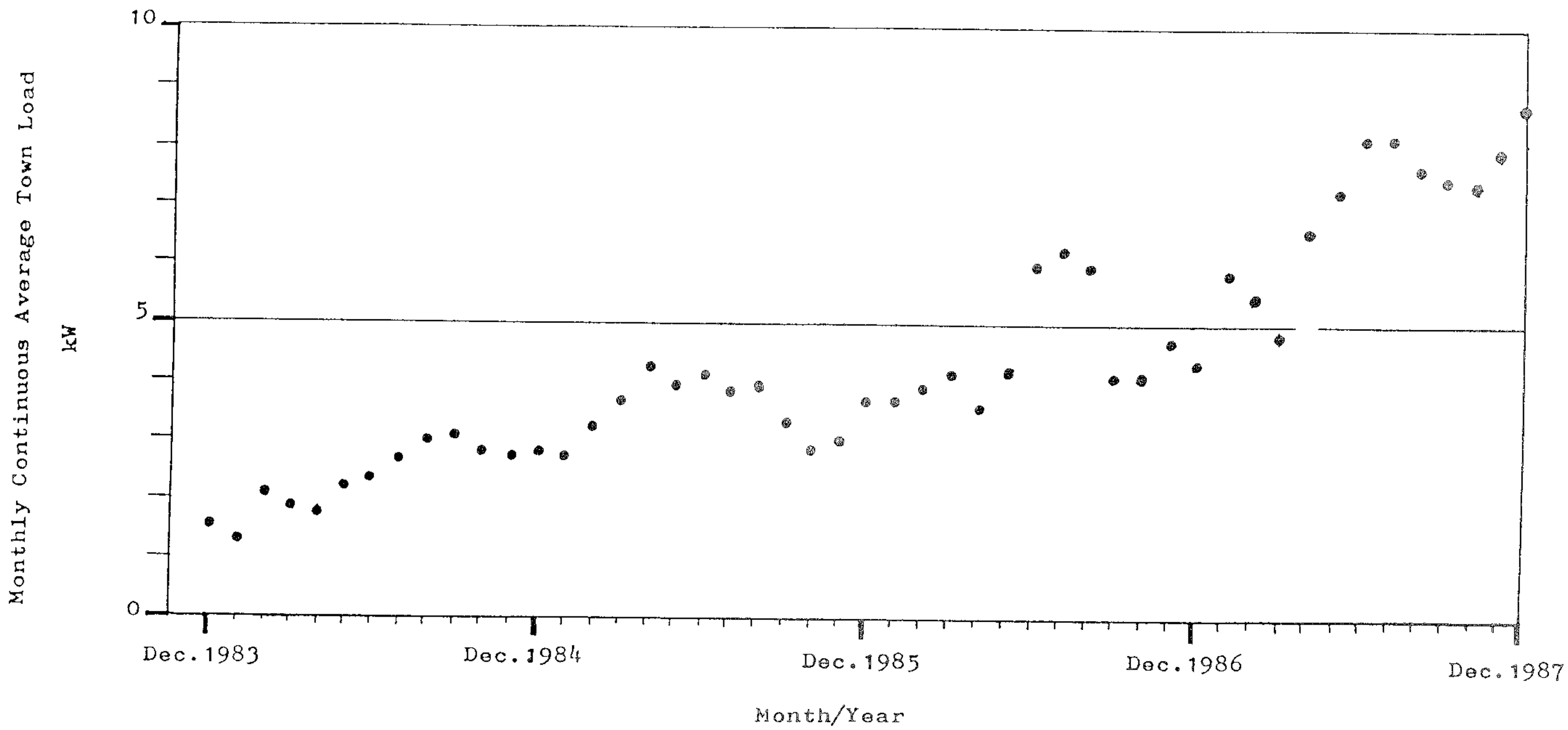


Figure 70 - Average Continuous Load (Monthly Average)

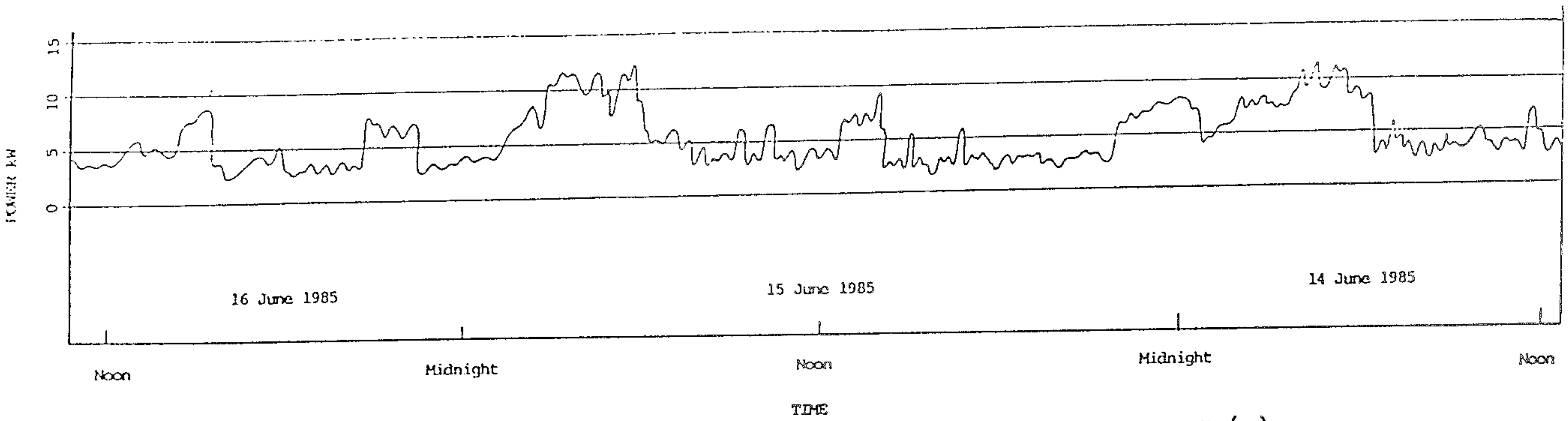


Figure 71(b) - Simplified "mean" load curve for Figure 71(a)

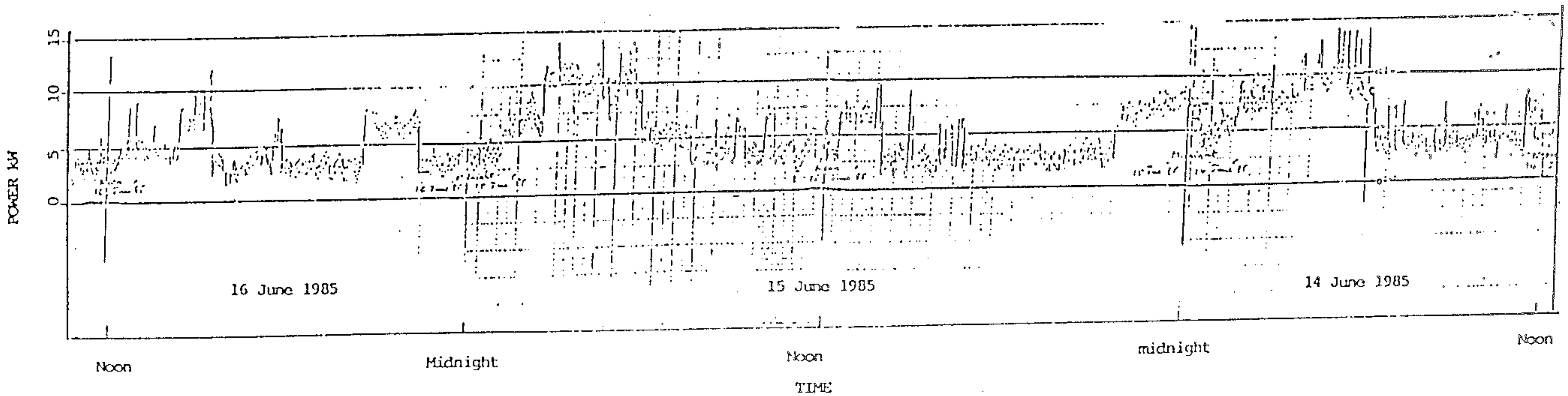


Figure 71(a) - Typical White Cliffs Load Characteristics representative over the period November 1983 to September 1986

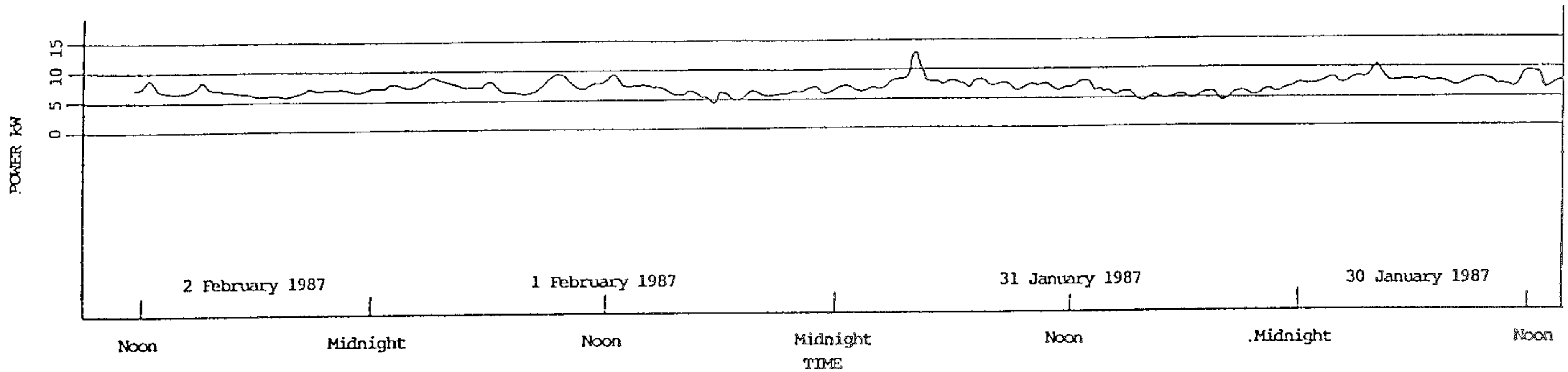


Figure 72(b) - Simplified "mean" load curve for Figure 72(a)

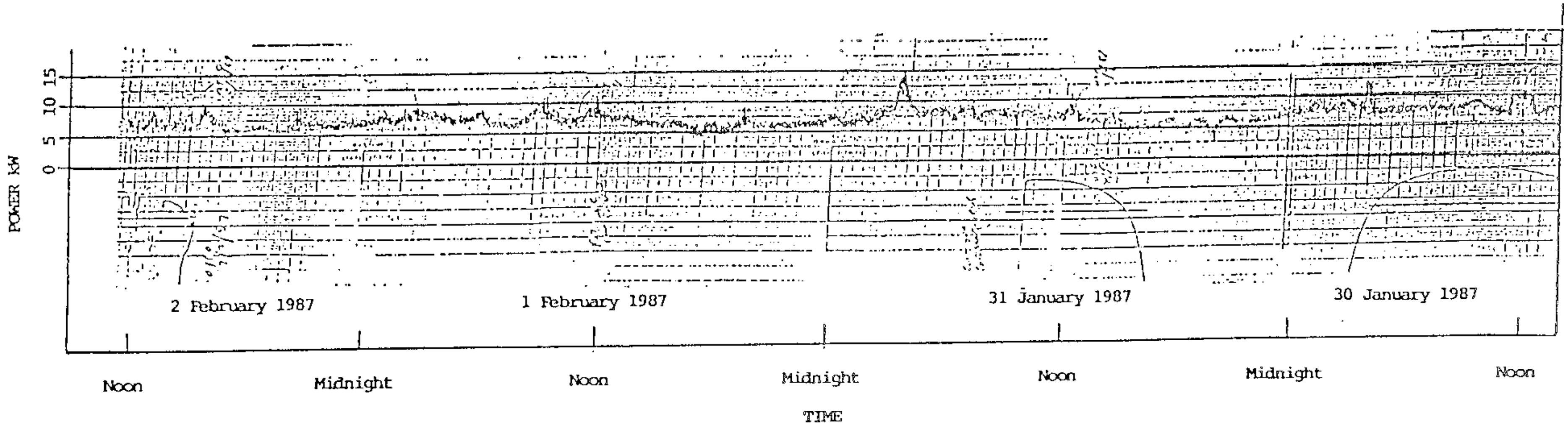


Figure 72(a) - Typical White Cliffs Load Characteristics representative over the period October 1986 to December 1987 effect in the microtherm insulation); so the array transmission efficiency also drops rapidly as the mass flow falls as a result of insolation being lower, as is so evident in Figure 73, which combines these effects from both absorbers and steam ducts. The reason for not operating much below an insolation of 400 W/m2 is clear from Figure 73.

1. Losses

   The characteristics of the array heat collection conversion and transport systems as portrayed in Figures 29 and 73 apply for still air; their components are analysed and detailed in Table X, which shows the variation of losses, collector efficiency, overall collection and heat transport efficiency as a function of insolation for maintaining an engine-room steam temperature of 360°C, when possible.

   But wind effects are also significant; Figure 74(a) shows the results of a practical measurement of the array and steam reticulation systems at two different wind velocities, by P. Holligan and M. Williams of the Energy Authority of New South Wales on 7 and 8 August 1983, extending over a period from 10.00 am to 4.OO pm on each day with some output perturbation due to offsteer of a collector. The insolation records for the two days in question are included in Figures 74(b) and 74(c). The effect of wind on the various absorbers is indicated in Figure 24 and Table III; also in Kaneff and Kaushika [1987].

   Apart from the heat losses by convection and radiation at the absorbers and the various heat transmission losses, energy is required to pump high pressure water and steam around the system; electrical energy is required to cause the dishes to track the sun.

   Pumping power to circulate feedwater varies from 0.3 kW at zero flow to 0.8 kW at rated flow. Power to cause the dishes to track is less than 20 watts per dish average (motion is extremely slow and drive is intermittent).

   Energy losses are very dependent on operating strategy as regards steam quality (mainly temperature dependent) throughout the system, while output depends largely on mass flow and on steam quality; radiation and convection from the absorbers depend very markedly on temperature irrespective of output, and duct steam losses depend very largely on temperature independently of throughput. Consequently, the system is highly non-linear as regards useful output and efficiency dependence on insolation. Array output and efficiency improve markedly as insolation increases (accentuated by the generation of greater amounts of superheat with consequent improvement in engine efficiency and output). For 360°C steam into the engine-room, which can be achieved at an insolation of 1 000 W/m_2, losses are detailed in Table X and Figure 79 (in diagramatic form) for the conditions of Figure 78. Further analysis is presented in Section 5.55.

2. Annual Collection Efficiency

   With the system as it stands, when operating with steam of 360°C and 6 MPa into the engine-room, collector and steam reticulation efficiency of 62.5% is achieved in still air with an insolation level of 1 000 W/m_2 as indicated in Table X. At other operating conditions, array collection and steam reticulation efficiency will generally be less, as shown by the curves in Figure 74(a), which are typical of practical operation. Wind has a substantial influence on the Mark II absorbers.

   Since the above represents peak operation consistent with good overall system performance, average collection efficiency over a year — that is, annual collection efficiency = total annual energy into engine room divided by total energy incident on collectors over one year — is likely to be less. Figure 75 gives the detailed total

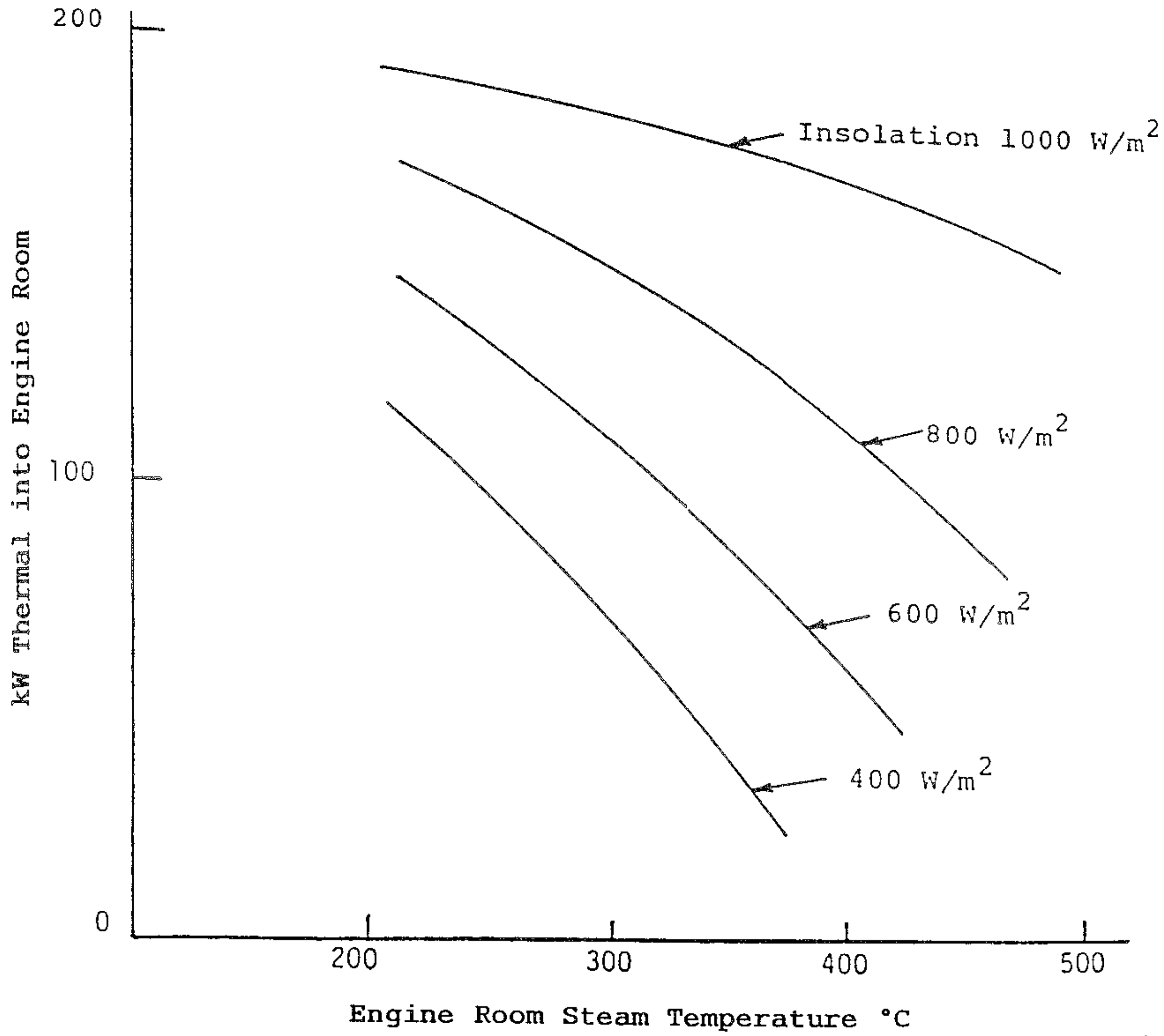


Figure 73 - Solar Array Heat into Engine Room vs. Steam Temperature in Engine Room at Different Insolation levels in still air.

TABLE X —IDENTIFICATION OF LOSSES AT DIFFERENT INSOLATION LEVELS FOR THE SOLAR ARRAY AND STEAM RETICULATION SYSTEM (Numbers apply for all 14 Collectors).

Insolation W/m^2	1 100	1 000	800	600	400
Direct Insolation to Dish kW	305	277	222	166	111
Reflection Loss (Reflectivity for Clean Dish = 0.86) kW	43	39	31	23	16
Intercept Loss Mark II Collector kW (Intercept Factor = 0.98)	6	6	4	3	2
Insolation Intercepted by Absorber kW	256	232	187	140	93
Absorber Enthalpy received from Feedwater at 30°C (kW)	8	7	5	5	3.6
Absorber Enthalpy from Rotary Joint Transfer kW	5.5	5.5	5.5	4.5	4
Absorber Convection, Conduction and and Radiation Losses kW	46	46	48	26.5	16
Losses in Absorber Connections to Duct, plus Absorber Duct Losses (kW)	11.5	11.5	12	6	5
Transfer from Steam to Water Side of Rotary Joints (kW)	5.5	5.5	5.5	4.5	4
Heat Loss in Pedestal Duct kW	1.3	1.3	1.3	1	1
Heat Loss in Main Duct kW	7.3	7.3	7.3	5	5
Heat into Engine-Room kW	198	173	124	107	70
Collector Efficiency(1)	69%	67%	63%	70%	69%
Temperature T_s (Absorber Steam Outlet)	550°C	545°C	610°C	460°	303°
Array Collection and Steam Transport Efficiency(2)	65%	62.5%	56%	66%	63%
Steam Temperature in Engine-Room	380°C	360°C	360°C	290°	220°
Steam Pressure in Engine-Room(3)	60 Bars	60 Bars	60 Bars	40 Bars	24 Bars
Feedwater Flow ml/s	63.5	56.28	40.4	36.5	28.0

(1) Collector Efficiency $= \frac{\text{Nett Energy in Steam at Absorber Outlet}}{\text{Insolation Input to Dish Aperture Area}} \times 100\%$.

(2) Array Collection and Steam Transport Efficiency
$= \frac{\text{Nett Steam Energy into Engine-Room}}{\text{Insolation Input to Dish Aperture Area}} \times 100\%$.

(3) 1 Bar = 0.10132 MPa, ie 60 Bars = 6 MPa; 40 Bars = 4 MPa; and 24 Bars = 2.4 MPa, all within 1%. Steam tables available in Bars.

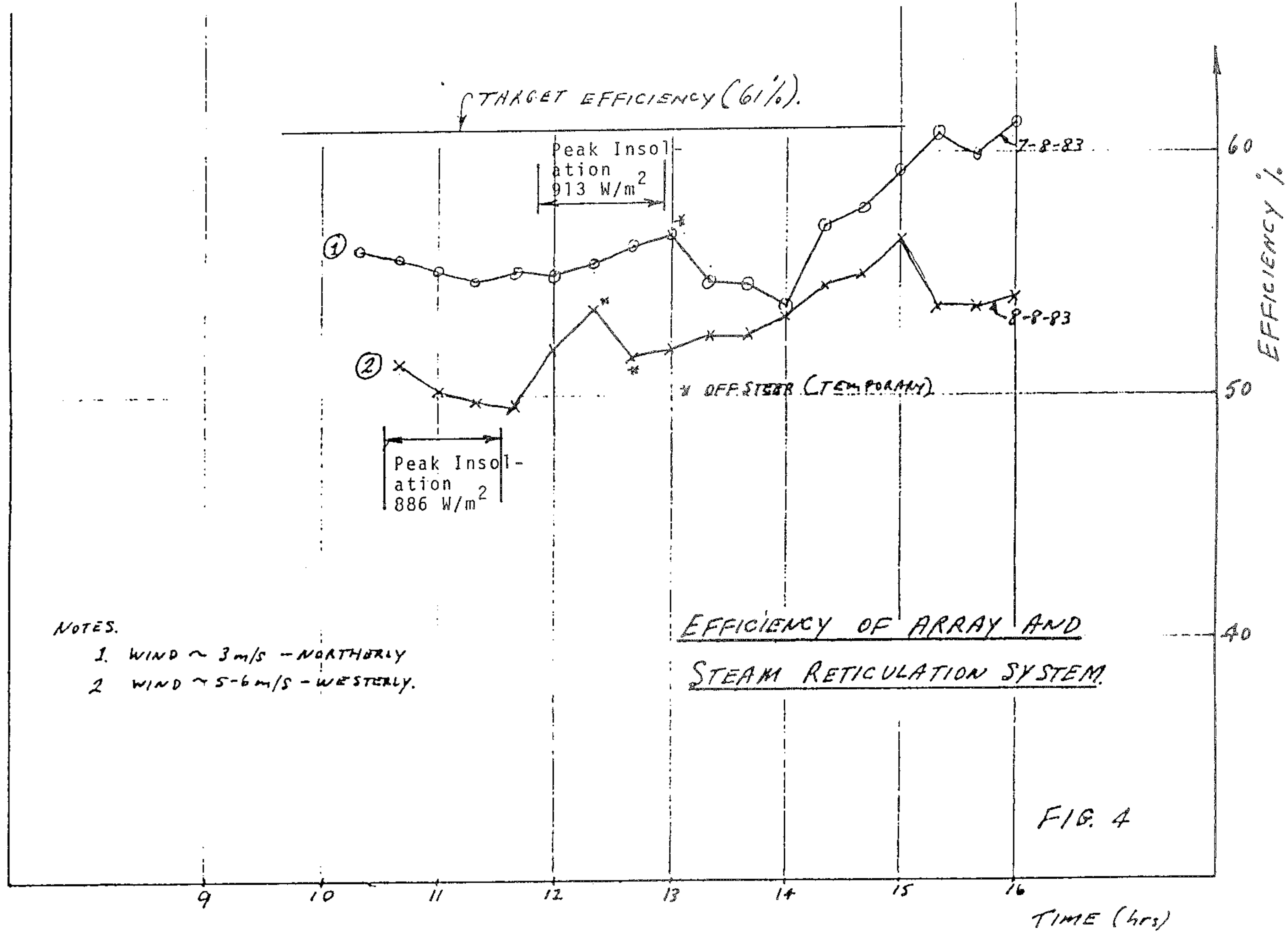


Figure 74a. Measured efficiency of array and steam reticulation system.

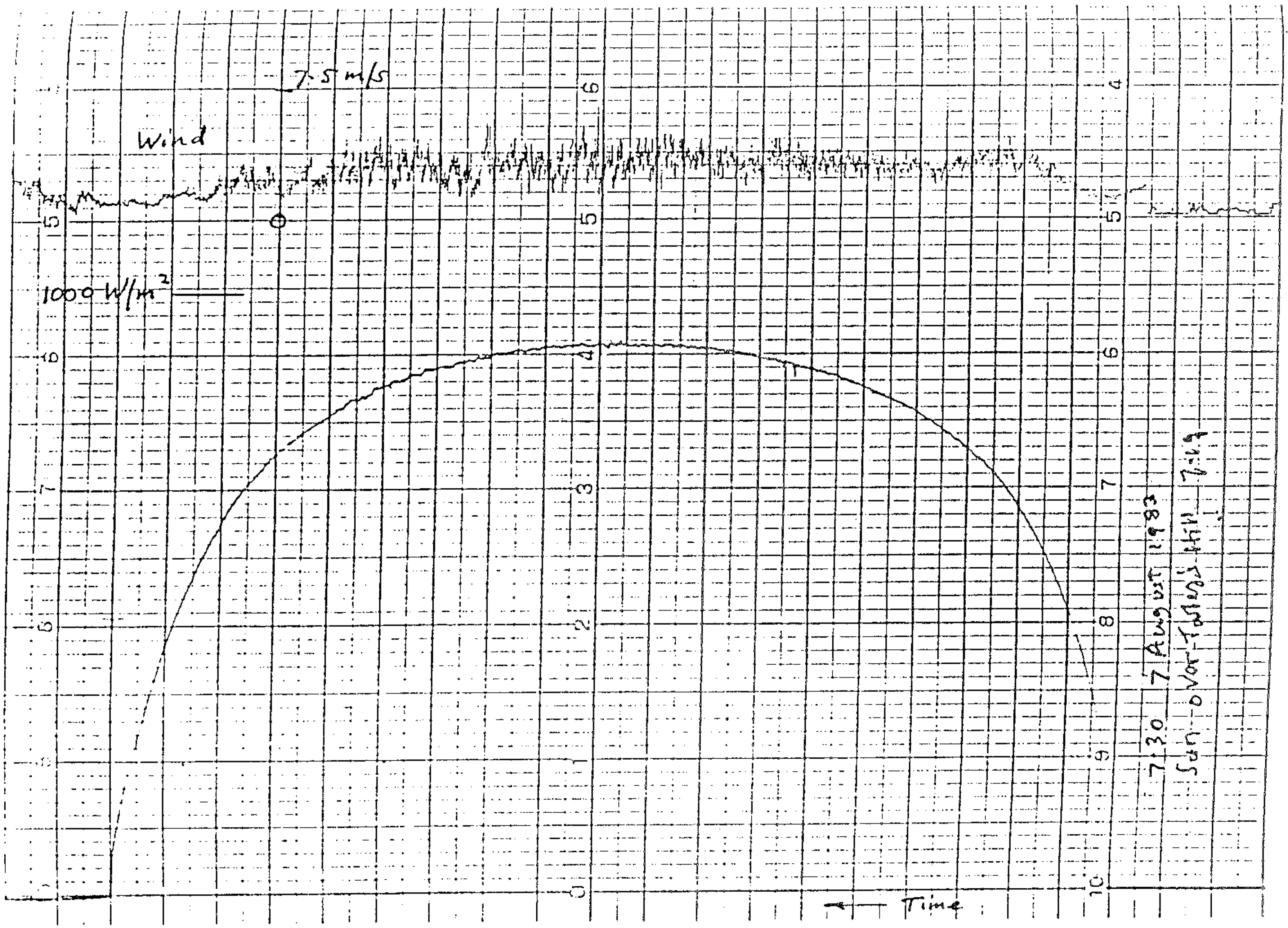


Figure 74b. Insolation and Wind on 7 August 1983.

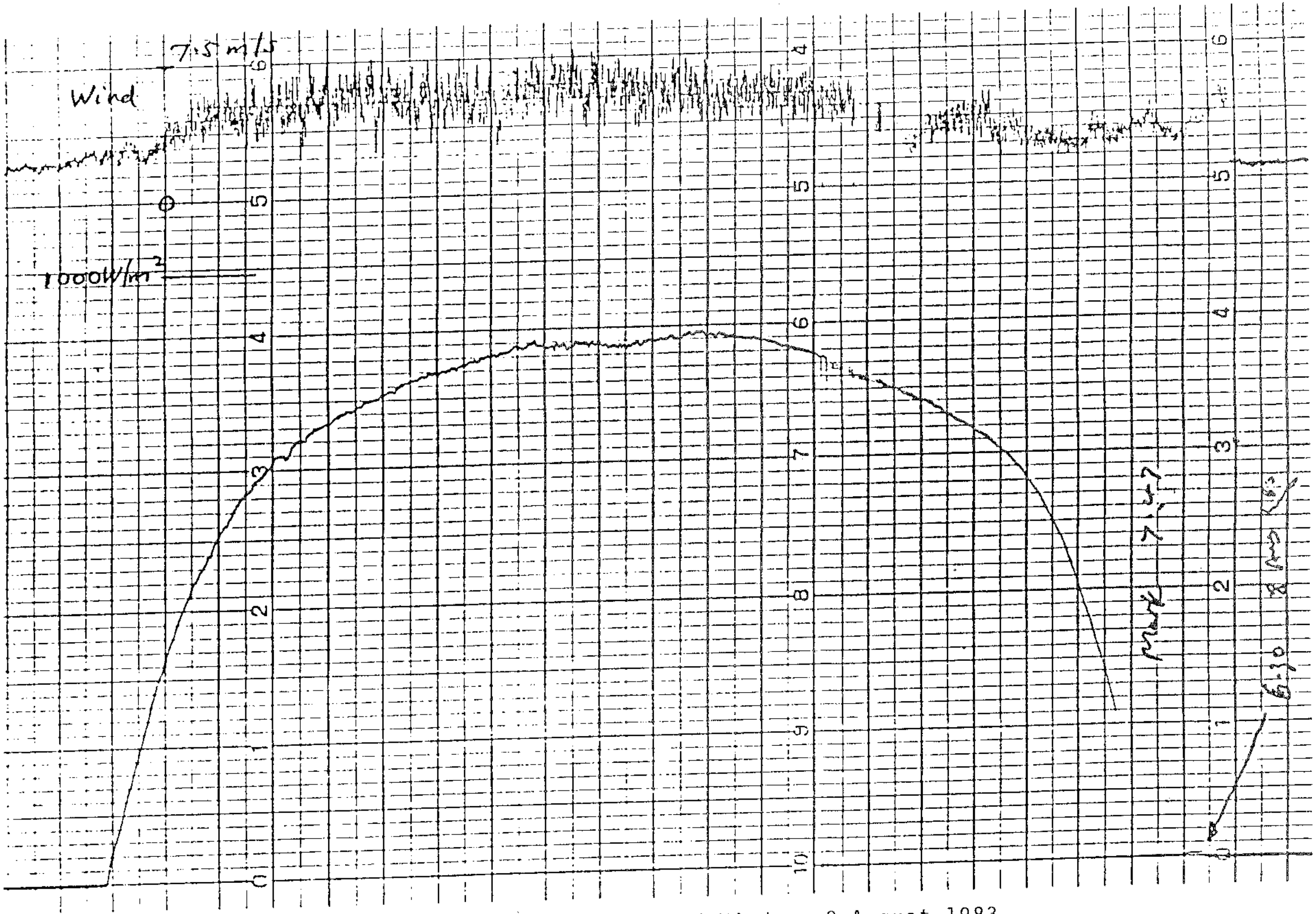


Figure 74c. Insolation and Wind on 8 August 1983.

solar energy into the engine-room on a monthly basis from November 1983 to April 1984 and compares this with overall total incident solar energy and total solar energy incident while-ever the array has been working. The averages in Figure 75 are typical of operation over other periods; the poor showing in April 1984 was due to the chlorothene problems mentioned in Section 5.2.1(8).

Figure 75 indicates an annual collection efficiency of 47%, which is typical for most other extended periods of array operation. This value may be compared with similar annual collection efficiencies for other systems detailed in Table XI, which is a summary of performance reported in the Proceedings of the International Energy Agency Workshop on Large Solar Thermal Arrays, San Diego, June 1984. It may be noted that the White Cliffs performance in this respect is comparable with the much easier-to-achieve lower temperature systems reported to the International Energy Agency Workshop. We have still no long term performance indications for other paraboloidal dish systems. The LUZ parabolic trough systems in Table XI do not appear to have as yet achieved their goal of 51% annual collection efficiency.

It is probable that the White Cliffs array will be able to attain well over 50% annual collection efficiency on a routine basis; further advances beyond this must depend on developments discussed in Chapters 7 and 9, particularly the reduction in wind loss effects in absorbers (this is expected in our Mark IX designs) in higher overall collection efficiency, in reduction of transmission losses as a result of placing engines close to absorbers, and in taking advantage of the economy and lower relative loss effects consequent on increasing size of units. In essence this reduces to being able to run absorbers at lower temperatures in order to get the same energy into the engine-room, thereby reducing total losses and extending lifetime of components.

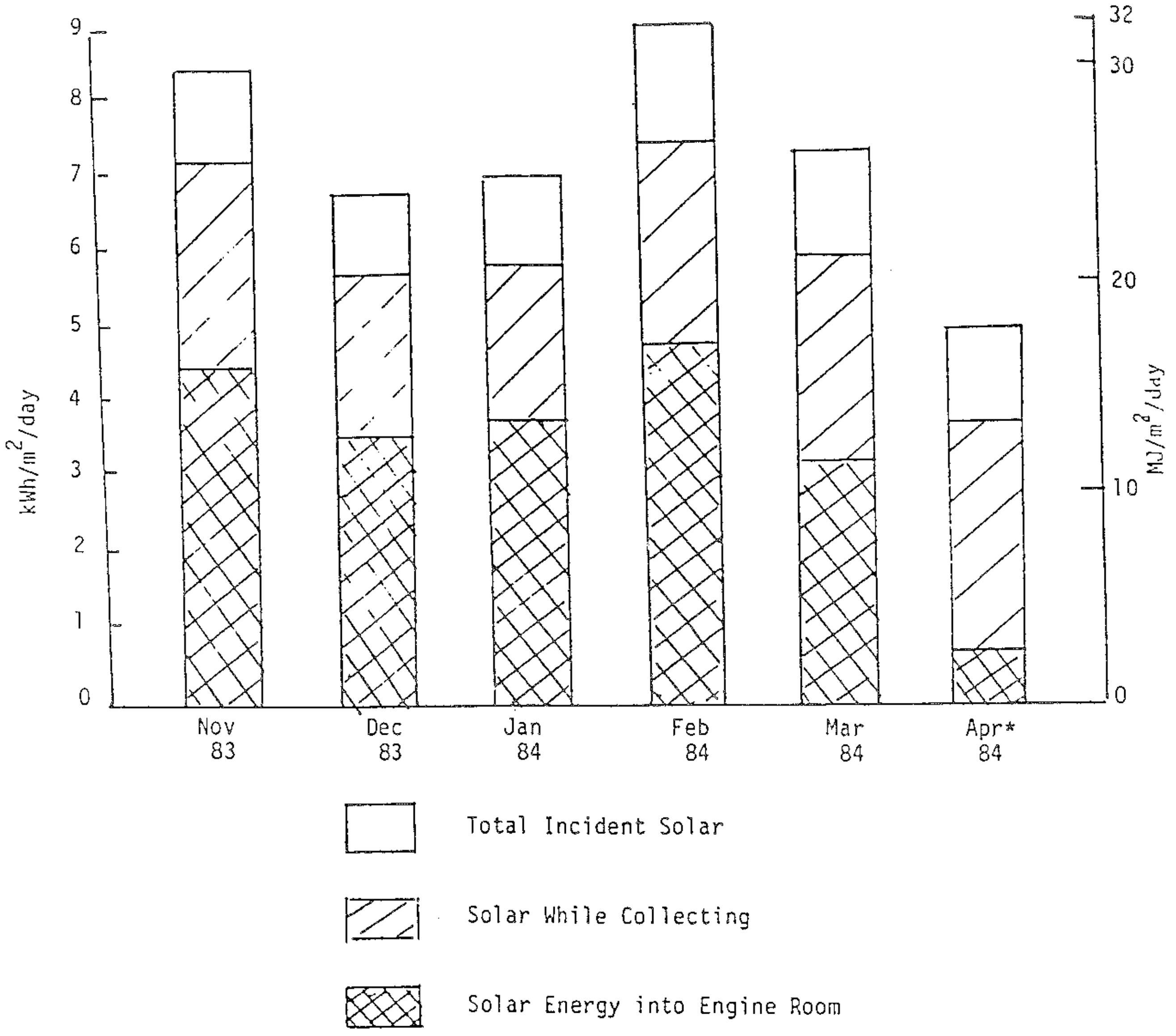
It may be stressed that annual collection efficiency is also set in our case by the power taken by auxiliaries; reducing this power demand will lengthen the time for useful energy gathering. Other measures which allow lower quality array heat to be used will also have the effect of improving annual collection efficiency; probably well above 65% is reasonable to expect in the short term. Improvement in reliability is also a useful contributor to this aspect of performance and, in the longer term, annual collection efficiency of over 70% may be realisable for high temperature systems.

3. Transient Behaviour

The performance characteristics discussed so far have referred to 'steady state' performance, in so far as this can be applied to systems with continually varying inputs, a situation which is a feature of solar-driven systems — insolation is rarely constant even during the middle of the day, but the general flat profile of insolation versus time has superimposed on it small changes due to atmospheric and other perturbations. On a more gross level, insolation does change with the passage of clouds and feedwater flow is changed accordingly.

Under such operating conditions absorbers respond rapidly, but not instantaneously, and steam conditions will vary. More subtle changes occur on the system in such operating conditions when waves of pressure, temperature and flow move about the system in a manner we have not yet been able to quantify. The starting point for studying these effects — which make complete automatic control very difficult to apply — is the equations of state for each absorber subjected to different conditions; Bansal and Kaneff [1987] have addressed this aspect which is a step towards quantifying overall system behaviour. Typical time constants for the response in steam temperature to changes in feedwater flow are illustrated in Figure 29(b), where the time constants are seen to depend on whether feedwater is reduced or increased.

SOLAR HEAT PRODUCED



(* Array out of action due to problems resulting from inappropriate flushing of the system with chlorothene).

Figure 75. Monthly solar energy enthalpy delivered to the engine room.

(Corresponds to an annual collection efficiency of 47%.)

But this is just the tip of the 'behavioural iceberg' which has to be coped with in control systems. Our feedwater control system does not set out to produce 'steady state' operation which is not a practical goal; instead we ensure that the continual variations in steam temperature from each absorber are reasonably small. This is an adequate solution to the problem. Nevertheless we are continuing with a study of the overall problem of understanding the complex beiiaviour of the solar-driven steam system in order to be able to achieve optimum control of output.

4. Comments on Performance and Limitations

Overall, the solar array has performed well from the start and continues to operate in essentially trouble-free manner after 6 years of service. In terms of annual collection efficiency, it is at least equal to systems operating at much lower temperatures. As regards heat collection, its performance can be considerably better with no change except in allowing it to run for periods currently not used due to central plant constraints which discontinue collection of energy in periods of low or intermittent insolation and during periods when the central plant is out of service for whatever reason.

Leaving aside the limitations imposed on solar heat collection by the characteristics and operating conditions of the present heat-to-work conversion plant, array performance is close to that which is determined by the inherent collection and loss mechanisms involved in the basic design; that is, it can operate with almost maximum availability and reliability. The limitation on perfect operation is set more by steam system requirements (absorbers and rotary joints) than by any other factors, for example dish mechanical, electrical or optical aspects.

The collector layout results in negligible shading and steam can be produced almost directly after sunrise and continue while-ever the sun is shining, nearly until sunset. Any application which can take advantage of this heat can therefore be served, including industrial process heat, the appropriateness of the system for which forms an additional reason for conducting the White Cliffs Project.

5. Efficiency, Throughput and Insolation

The loss mechanisms involved in both absorber operation and heat transport to the engine-room have similar features and characteristics: operation at a given temperature and constant wind velocity results in conduction, convection and radiation losses being essentially independent of energy collected or transmitted since all such losses, for a given physical structure, are temperature dependent only. The efficiency of collection or transmission therefore will increase with throughput of energy, as can be confirmed from Figures 29(a) and 73, where efficiency is higher at greater insolation (ie more collection and throughput).

These matters are discussed further in Section 5.5.5 in conjunction with engine characteristics and overall system performance.

The implication of these effects is very clear — larger units operating at the same temperature as smaller units will have generally higher collection and transmission efficiency, a valuable pointer to further development directions. Thus larger dishes and absorbers will be expected to have greater collection efficiency than the current White Cliffs efficiency, and heat transport in larger througput networks will have much lower relative losses; for example whereas the main duct system for White Cliffs, which handles up to about 200 kW thermal, has some 8 kW losses to transport the heat to the engine-room, that is, 4% transmission loss, a 1000 MW thermal network would have only some 0.90% transmission loss involving some 10 000 dishes of 100 m^2 each [Carden and Bansal 1987].

TABLE XI — DISTRIBUTED TRACKING SYSTEM CHARACTERISTICS(1)

System	Collection Type (2)	Field Area $m^2 \times 10^{-2}$	Location	Field Temperature Out °C	Process Temperature °C	Startup Date	Months Operation to June 1984	Annual Beam Insolation GJ/m^2	Typical Annual Efficiency %
US DOE IPH									
Caterpillar	PT	46.9	N. California	113	91	11/82	19	5.7	52
Dow Chemical	PT	9.2	Georgia	187	96	1/83	10	4.4	23
Home Laundry	PT	6.0	S. California	166/66	82/9	2/83	8	5.1	42/34
Lone Star Brewery	PT	8.8	Texas	177	88	6/82	12	5.9	32
Southern Union Oil	PT	9.3	New Mexico	174	149	8/82	17	9.0	32
USS Chemicals	PT	46.9	Ohio	151	135	2/83	15	3.9	36
OTHER									
IEA SSPS	PT	53.6	Almeria, Spain	295	280	9/81	33	7.2	29/32
DOE Shenandoah	PD	40.9	Georgia, USA	399	382	1/83	Assorted Tests	5.1	—
White Cliffs	PD	2.8	Australia	460	375	1/82	18	8.5	47
COMM POWER SYSTEMS									
La Jet (private)	PD	299	S. California, USA	371	371	12/84	—	8.1	—
LUZ SEGS-I (private)	PT	717	S. California, USA	307	247	12/84	—	8.1	51(3) predicted

NOTES: (1) Information from International Energy Workshop, San Diego, June 1984.
(2) PT = Parabolic Troughs, PD = Paraboloidal Dishes.
(3) As at 1 December 1987, no figures have emerged regarding achieved performance.

The experience gained with the array (from design, operational and economic viewpoints) indicates that considerable benefits follow from building units larger; they should also be designed to achieve rated output at insolation levels corresponding to average values, say 880–900 W/m^2 rather than for peak values, which are attained infrequently. In this way a better collection and transmission efficiency can be ensured for normal average operation and a better annual performance will result.

5.5.2 The Steam Engine and Auxiliaries

In most engineering systems involving conversions from heat energy to mechanical work, the greatest single cause of inefficiency occurs in the step from heat energy to mechanical energy; the situation in the solar station is no exception. The steam engine developed for the purpose, using concepts from the work of steam car enthusiasts gathered over many years, has proved robust and effective after a great deal of effort was expended to achieve reliability and efficiency.

The advantages of employing a maximum practicable complement of standard commercially-available components to realise this technology have been noted previously but bear repeating because of their major contributions to cost-effectiveness and ready maintainability in the field.

The engine, with vacuum-assisted exhaust/condensation, is surprisingly efficient — in current configuration, efficiencies of over 20% are achieved readily and, as discussed in Sections 7 and 9, higher efficiencies seem attainable with improved cost effectiveness as an additional advantage.

The engine technology achieves its high performance as a consequence of the use of high quality heat, a simple but carefully configured valve mechanism, combined with measures to reduce losses in the cylinder and piston heads. Robustness and long life are assisted by a judicious choice of material properties and high efficiency is very dependent on the maintenance of advantageous configuration, dimensional and other constraints in the manufacturing, and assembly of the cylinder head and valves — particularly the maintenance of various clearances in the steam paths and in setting a high expansion ratio.

Use of a vacuum pump to assist extraction of maximum work from the expanding steam is an essential ingredient to the high output achieved. Because of the restrictions imposed by licence agreements, details of the engine which result in its high performance are not included here.

1. Input–Output Characteristics

   Attempting to determine steam engine performance raises the problem of the long thermal response time constants involved. The steam engine system requires some 2 hours of operation in the morning before it has attained its optimum conditions, although variation in performance after the first half-hour is not very significant. Consequently, any performance measurements must cope with this time delay. Once adequately warmed up, small changes in energy input or in feedwater flow and consequently in steam quality require some 3–6 minutes only for the complete change to be effected.

   Because of the above characteristics, it is difficult to carry out performance measurements on the steam engine or system when supplied from the solar array.

Consequently, the engine performance indicated in Figure 43 and Table VII was determined by experiments using the auxiliary boiler as a steam source after allowing adequate time for the system to reach operating equilibrium at start and after each adjustment to input conditions. The load on the system was conveniently a bank of resistors connected to the AC machine plus the DC machine/battery combination which, alone or in conjunction with the resistor bank, ensured that all generated energy was accepted with little transient effect on the engine shaft caused by any transfer of load between AC and DC machines. One disadvantage in boiler/engine tests is that boiler heat output is less than peak solar array output, so that solar performance maximum cannot be attained in such tests.

Figure 76(a) shows engine performance from the solar array under various solar conditions, plotted on the curves of Figure 43 (boiler supplied steam) for comparison. The origin of the several results is as marked on Figure 76(a). Whereas the boiler/ engine tests were allowed to reach equilibrium for each measured point, the solar/engine test results were taken as close to equilibrium as insolation variations allowed.

Remarks made in connection with the absorbers and steam transmission ducts regarding operating temperatures, losses, efficiency and throughput, apply to the engine performance also; there is an economy and advantage of size. In the case of the engine, which runs at a constant speed of 1500 rpm and therefore (once warmed up) sustains constant friction and windage losses, operation at a given temperature results in constant conduction, convection and radiation losses as well, so that as throughput increases, all other factors kept constant, efficiency will increase with throughput. This is evident from Figures 43 and 76 for both solar and boiler operation — while for any given input energy (or throughput), efficiency and output rise with increase in steam temperature at any given steam temperature, efficiency also rises with throughput. In applying the argument and comparison, it is worth underlining that for any given input power (which here is set by insolation available or by boiler/burner characteristics), steam temperature is determined by adjusting the mass flow, with which is also associated steam pressure. These quantities were omitted from Figure 76(a) to avoid confusion, but are plotted for comparison in Figure 76(b).

2. Effect of Vacuum Pump

The vacuum-assisted exhaust system has a marked effect on engine performance, determined by mass flow, cooling water temperature and input steam quality, among other factors.

For the engine whose configuration is listed in Section 3.4.1, for vacuum (with 25°C (inlet) cooling water) of −80 kPa, inlet steam temperature 415°C and pressure of 600 psi, exhaust temperature of 73°C and input steam enthalpy of 129 kW thermal for a mass flow of 41.5 grams/second, shaft output is 28 kW_{mech} and efficiency is 22%. With no vacuum assistance, exhaust temperature for the same inlet conditions rises to 106°C, output falls to less than 20 kW_{mech} and efficiency drops to 15%.

An identical engine with appropriately adjusted valve settings (to handle more energy throughput) operating at 1800 rpm, provides an output of 49 kW_{mech} with a vacuum of −70 kPa, and 420°C steam inlet, 73°C exhaust.

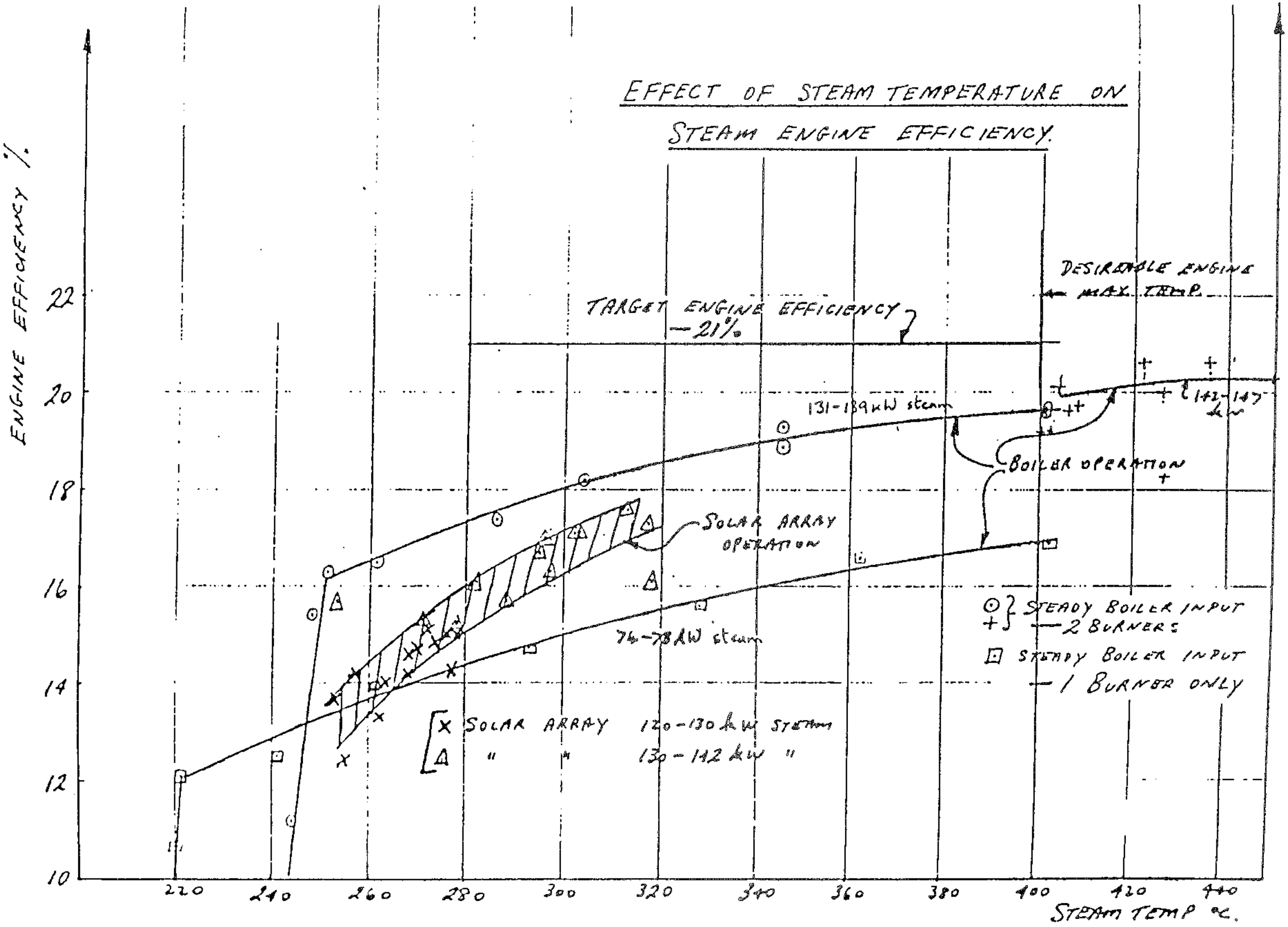
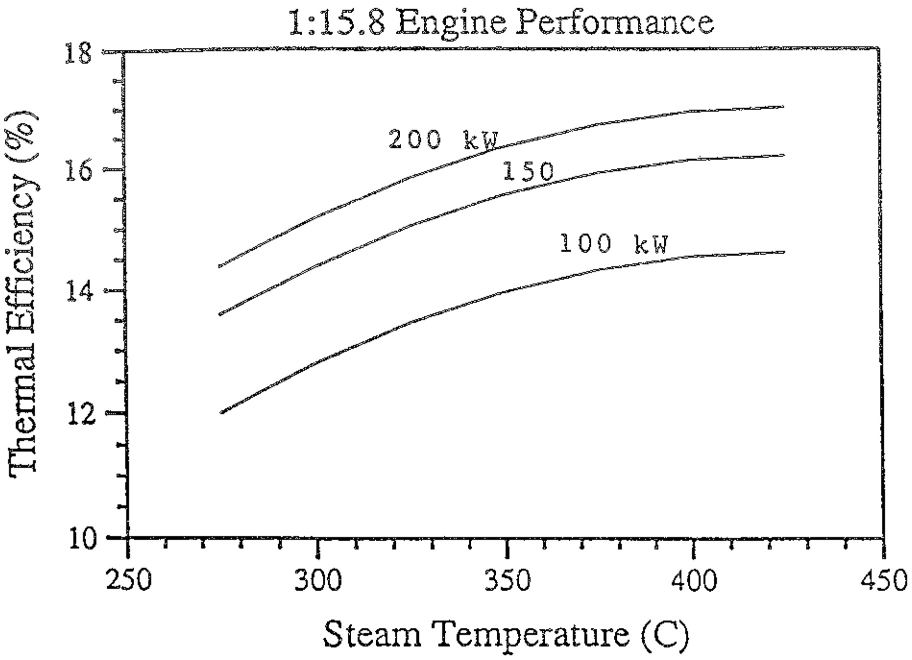
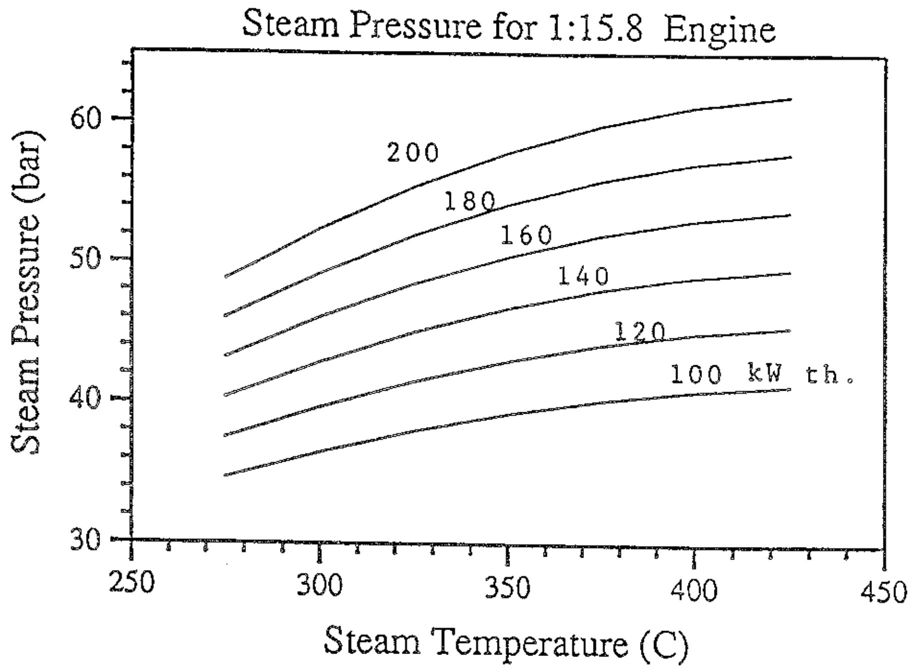


Figure 76a. Measured engine performance on solar and boiler operation.





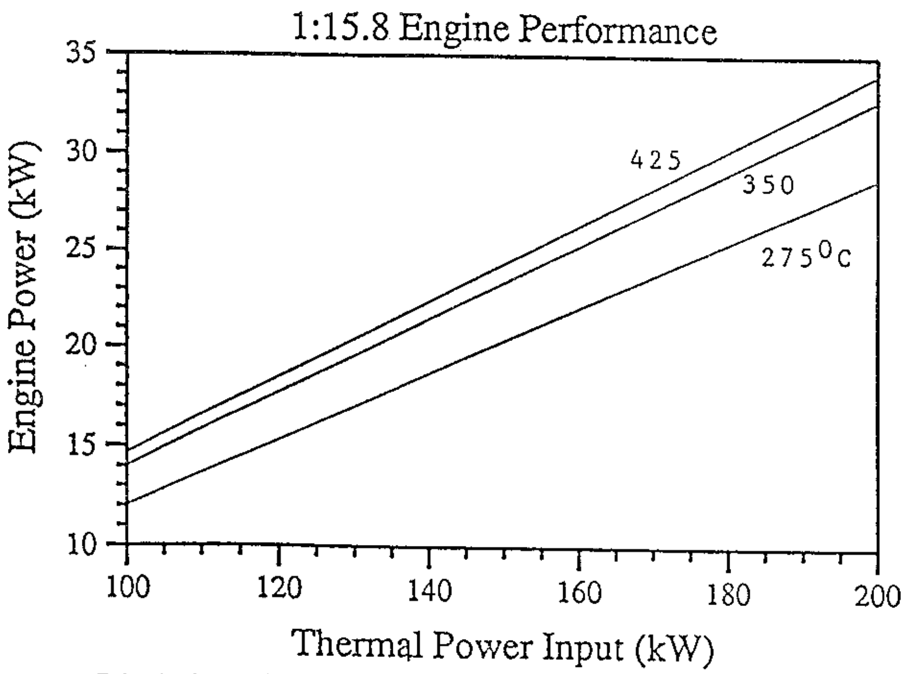


Figure 76 (b) - Engine Performance vs. Temperature, Pressure and Mass Flow.

5.5.3 AC–DC Machines, Battery and Energy Storage

Figure 45 identifies the system for ensuring that all energy from the steam engine is accepted either directly by the load or stored in the battery [Kaneff 1980b, 1980c; West 1982].

1. Frequency Control and Transient Performance

   The control system ensures that speed of the rotating machines is kept at 1500 rpm, resulting in a system frequency of 50 Hz; this frequency is maintained constant to within ±1% at all normal times except for very substantial sudden load changes — for example if full load is suddenly applied or removed, in which case the system frequency recovery response is as indicated in Figure 45(b). The exact response can be adjusted by setting parameters in the DC machine field circuit controls, the setting being a compromise between fast response to changes and tolerable overshoot and oscillations [West 1982].

2. Battery System Storage Efficiency

   As noted from Figures 2 and 45(a) and Section 3.5, the storage process takes energy from the steam engine shaft, converts the mechanical to electrical energy via the DC machine and further converts this to chemical energy in the battery; to utilise the stored energy involves a conversion from battery chemical energy to electrical energy to drive the DC machine, then to mechanical energy to drive the AC machine, finally to electrical energy in the AC machine before being transmitted to the load. Had there been no need for storage, engine shaft energy need be converted only to electrical energy directly by the AC machine before being transmitted to the load.

   We have already noted (Section 3.5.1) that for substantial load flows, AC power output via storage equals approximately 52% of the original power from the engine and that this power is some 57% of the power that would have come from the alternator had this supplied the load directly instead of being stored first. At best, these are simplified numbers since the various machine efficiencies depend on actual throughput of energy; battery conversion efficiency (for energy flow in and out) depends on the magnitude and rate of current flow, and on the general 'state' of the battery which in turn depends on a range of factors, including electrolyte temperature, state of charge, condition of the electrode plates and electrolyte, and generally on the charge carrying capacity. A simple measure of battery 'state' can be expressed by its internal resistance which varies from time to time but becomes higher with battery deterioration.

   Overall, the most objective practically useful measure of battery performance can be obtained from the integrated input/output performance over a period. Such information is recorded in the Quarterly Progress Reports (1983–87). Because low currents/low charging/discharging rates for the battery generally lead to higher conversion efficiency, but such low in/out currents are associated with relatively low DC machine efficiency, while high currents/high charging/discharging rates lead to lower battery performance but high DC machine efficiency, overall performance must be assessed over periods sufficiently long to have experienced all typical operating conditions. Under these circumstances, the overall battery system storage efficiency may be summarized as in Table XII.

   Overall it may be noted that no more than 50% of the energy, which would have gone to the load directly via the AC machine, actually was delivered to the load, the remainder having been lost in the storage process — DC machine losses, battery

TABLE XII — MAIN DC BATTERY STORAGE SYSTEM

Internal Resistance of Battery (R)

New cells, r = 0.001/cell

Battery of 150 Cells, R = 0.15–0.015 charged
R = 0.45–0.045 discharged

Measured Values of R

Date	Battery Volts V	Current A	Internal Resistance R	State of Charge
5 November 1981	315	80	0.06	charged
	297	50	0.10	part discharged
28 February 1983	286	22	0.20	part discharged
9 October 1984	286	44	0.22	part discharged
13 December 1987	288	79	0.14	part discharged
	298	5	0.14	part discharged

Internal resistance is satisfactory.

Battery System Efficiency

AC/DC Machines

AC Out (kW)	5	20	20	25
DC $\frac{\text{AC Out}}{\cancel{\text{CD}}\text{ In}}$ %	68	81	82	78
$\frac{\text{AC Out*}}{\text{Overall Mechanical In}}$ %	61	57	52	47

* Including battery storage efficiency (typical).

Integrated long-term performance: Approximately 50% of energy fed to the storage system is eventually usefully employed.

input/output conversion losses. Whereas operation in the earlier years involved charging the battery at a relatively high rate during the day and discharging at quite a low rate (less than 5 or 6 kW), in later years (and particularly in 1986/87 due to the increase in town load), the battery charges at a relatively low rate and discharges at a high rate (15–20 kW).

We are bound to stress that the AC–DC machine/battery storage and control system has operated flawlessly over the years, having justified all expectations. Maintenance requirements have been negligible — topping up battery water, cleaning dust off terminals very occasionally, and replacing DC machine brushes once. The electromechanical relays in the DC machine field controller have on one or two instances needed refurbishing to improve contact resistance which had increased due to continual switching of the more demanding branches of the field control circuit. The AC machine and its associated electronic voltage regulator has required almost no attention beyond replacement of a faulty printed circuit board during the original checking out of the system in early 1982.

3. Battery Condition and Charge/Discharge Rates

Various concerns have been expressed from time to time regarding the economies and efficiency of battery storage; these concerns are especially important when this form of storage is applied in areas such as White Cliffs where environmental conditions are difficult as regards temperature and dust.

Sensitivity to the various difficulties which might apply caused us to select lead acid batteries somewhat reluctantly, but cost considerations were paramount and forced this choice. In order to improve the prospects for satisfactory long-term battery performance, we selected heavy-duty Lucas Marathon Mining Cells developed for use in underground traction vehicles in the Mount Isa (western Queensland) copper mines, with a maximum electrolyte operating temperature of 70°C.

One of the protective measures introduced was over-temperature sensing for each of the 5 banks of 30-2 Volt cells; a temperature of over 70°C would cause the DC system to close down. We doubt if the electrolyte temperature has, over the years, ever risen above 55°C and no over-temperature problems have occurred, in spite of the extreme summer temperatures (up to 47°C) encountered in the area. As it has turned out, both charging and discharging currents have been relatively undemanding; in the earlier years charging rates of up to 60 Amperes were common but later, as town load increased, this rate has been considerably less. Discharge rates in the early years were typically only up to 20 Amperes; later they have been creeping up to 90 Amperes which, however, is still less than the maximum recommended rates (over 100 Amperes).

As a general operating policy, the battery has been regularly charged to near full charge (by boiler steam in the absence of solar steam, usually in winter) but, beyond these excursions, battery gassing voltage has not usually been much exceeded. In spite of the harsh environmental conditions, the battery has been treated reasonably well and has responded by being still in reasonable condition, as indicated in Table XII which records capacity and internal resistance at different times, pointing to a relatively long and useful life for this component.

Overall, this electrical/energy storage system may be considered commercially viable.

TABLE XIII — SOLAR STATION AUXILIARIES

Unit	Normal Power Drawn kW
Feedwater Pump	0.3–0.8
Centrifuge	0.8*
Skimmer Pump	0.1*
Vacuum Pump	0.9
Oil Coalescing Pump	0.4
Cooling Water Pump	0.5
Oil Water Pump	0–0.2 occasional
Oil Drier Pump	0.1
Battery Charger	0–0.6
TOTAL	3.1–4.4 kW[‡]

* Replaced in early 1987 by disc oil collector drawing 20 watts.

‡ Present power drawn = 2.2–3.5 kW.

NOTES

(a) The scavenger and engine oil pumps are part of the engine and considered as no load engine losses.

(b) The throttle, drain and bypass valve drives each draw about 100 W but only rarely and so are not listed above. The drain valve is no longer used (from mid-1987).

5.5.4 Station Auxiliaries

The solar station auxiliaries comprise various pumps and driving motors and battery chargers (as detailed in Table XIII) to meet the needs of the system, as illustrated in Figures 2 and 40. While all auxiliaries employ standard commercial units, performances and reliability have varied; the feedwater pump system, involving an ASEA thyristor-driven DC servo motor driving a Catt positive-displacement pump through a gearbox, has given extremely reliable service but the gear pumps originally employed required replacement due to unduly rapid wear. The original Siemans vacuum pump also required replacing after some 5 years; it has subsequently been successfully refurbished in our workshop. The cooling water pump motor also needed replacement because of an internal wiring fault causing damage. On the whole, we have not been impressed with many commercially supplied components which should have lasted longer and provided better service.

Total power drawn by the auxiliaries varies somewhat depending on whether or not intermittently operating units are running (for example, the oil water pump and the auxiliary battery chargers for the control supplies); typically with centrifuge and skimmer units in place, total auxiliary power varies in the range 3.1–4.4 kW. With the centrifuge/skimmer combination removed (as is currently the case) and replaced by spinning disk oil collectors, auxiliary power varies in the range 2.2– 3.5 kW.

Scope exists to reduce these overheads by further rationalization of the overall system and by using possibly a steam ejection system in place of the vacuum pump, as discussed in Section 9.

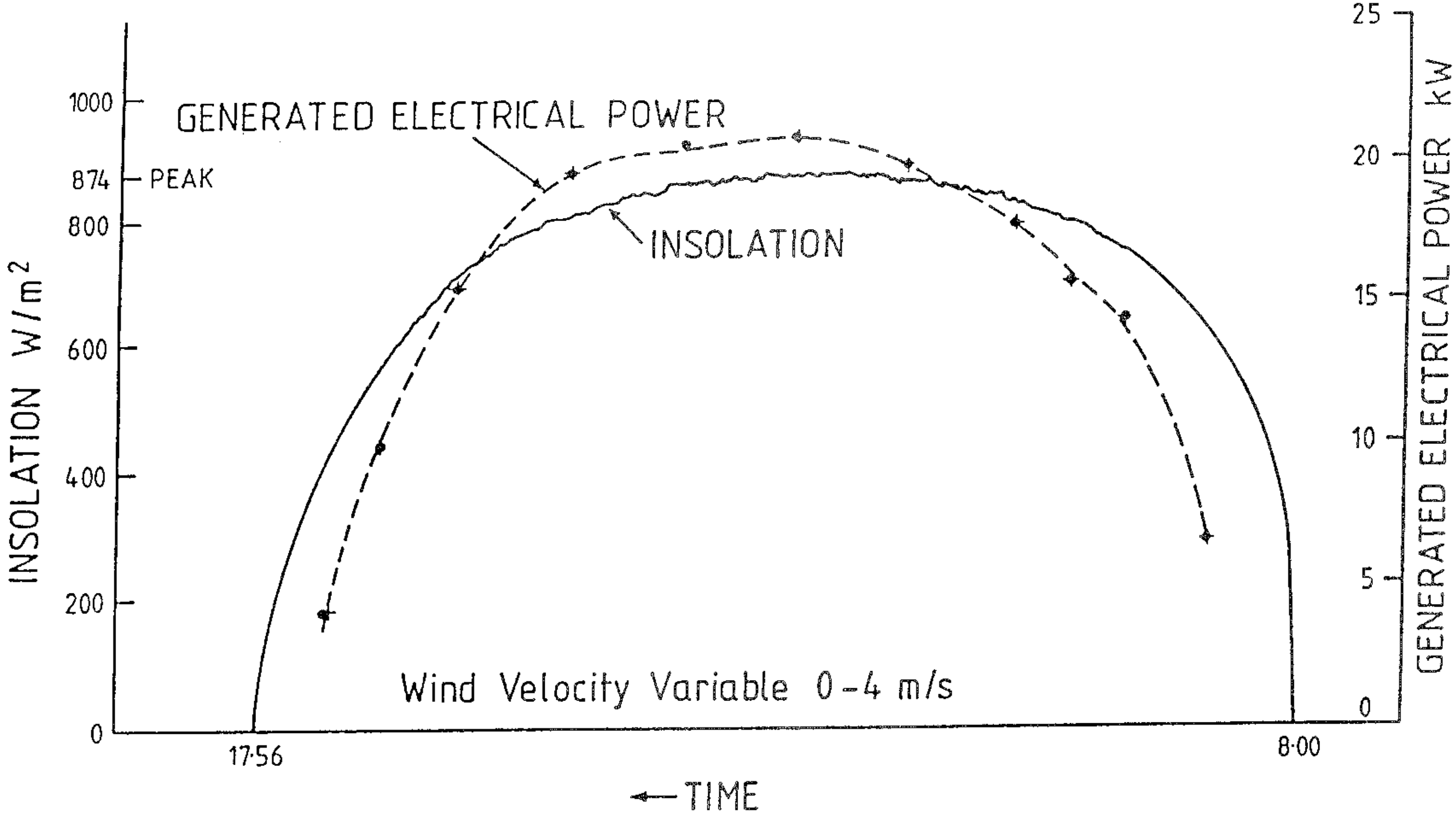


Figure 77a. Generated electric power vs. Insolation for a day in early June. (The discontinuity at sunrise is due to obscuring of the sun by Turley's Hill.).

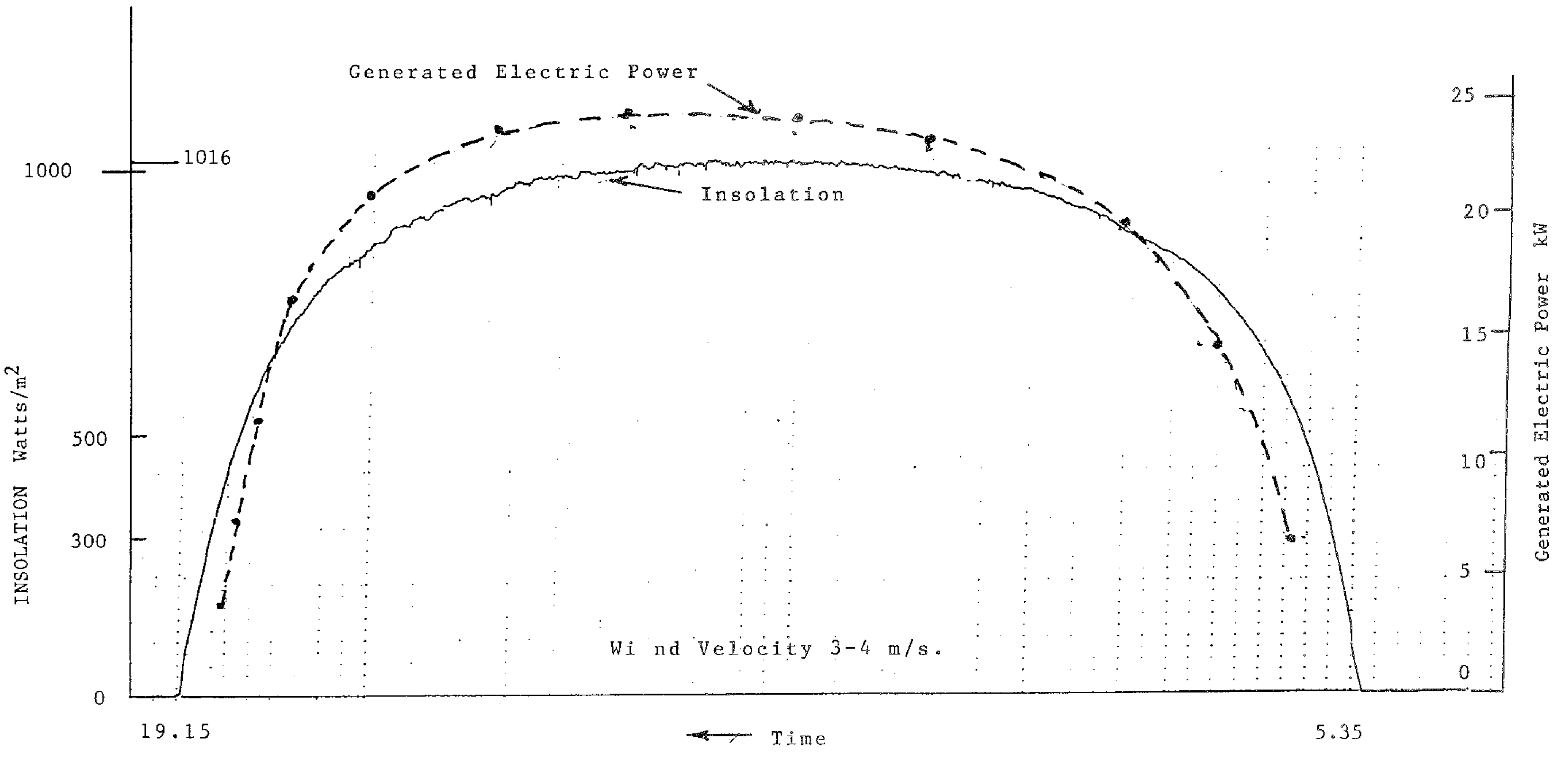


Figure 77 (b) - Generated Electric Power January 1985
and corresponding Insolation.

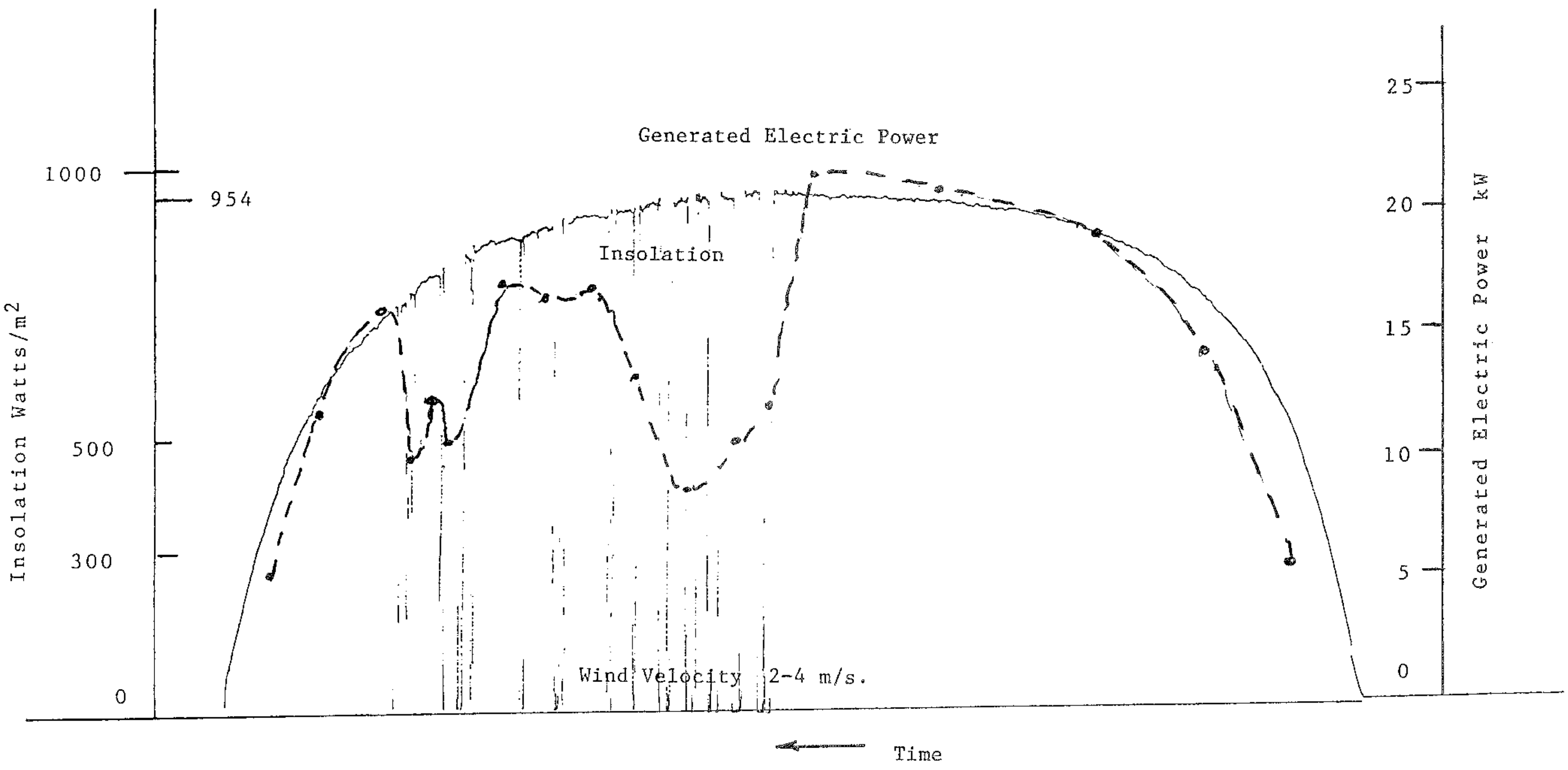


Figure 77 (c) - Generated Electric Power vs, Insolation for an Intermittently cloudy day (15 Feb. 1985)

5.5.5 Overall Solar System Performance

Day-to-day operation of the system produces a wide range of behaviour, consistent with the very changing nature of insolation, wind and other environmental conditions. Often, perfectly clear sunny days with little wind allow the system to produce outputs approaching optimum but, all too frequently, cloud and wind intrude to reduce energy gathered. Because of the highly non-linear effects which result from the basic physical processes involved in energy collection, transportation, conversion and because of the limits imposed on operating behaviour by losses, understanding the elements of system performance and their interrelationships is not a trivial process, nor is the optimizing of performance by involving automatic control systems.

The following performance details give a broad indication of system behaviour and parameters, including economic factors.

1. Typical Performance Characteristics

   During a sunny day system output follows the insolation profile reasonably closely, as indicated in Figures 77(a) for a day in winter, 77(b) for a summer day, and Figure 77(c) for a partly cloudy day.

   The output power and insolation curves are not coincident in time because

   - The system starts some 20 or more minutes after sunrise.
   - The effects of insolation changes take time to reach the engine-room, especially early morning when heat storage occurs in the metallic and insulating components of the system.
   - Due to the energy required for meeting the changing latent heat needs of the water.

   The system is not run when the total solar input is less than that required to supply the engine losses and to power the auxiliaries.

   Figure 78 shows the 'cascade' or 'waterfall' diagram for the system operating with insolation of 1 000 W/m^2. This portrays the energy flows and conversion efficiencies in different parts of the system: collection and conversion to fluid heat, heat transport, heat-to-mechanical work conversion, work-to-electricity conversion and supply of auxiliaries, finally giving nett energy out. This diagram is understood as applying for steady-state conditions so long as the inputs are maintained. The delivery of the steam at 360°C at the engine (pressure 6.0 MPa) requires steam to be generated at about 545°C at the absorbers and represents about the limit in absorber normal operation; all absorbers therefore need to have equal performance for this diagram to apply, requiring in turn a 'finely-tuned' system as regards feedwater subdivision, dish cleanliness and absorber efficiency.

   Figure 79 gives a diagramatic representation of losses for Figure 78, while Table X provides similar information in more detail. The significance and consequences of these aspects of system operation warrant further consideration because of their importance in defining and delimiting performance.

2. Throughput, Losses, Insolation Level and Steam Conditions

   Inspection of the steam engine efficiency/steam temperature relations for different energy inputs, for example Figures 43 and 76, indicates the benefit of engine

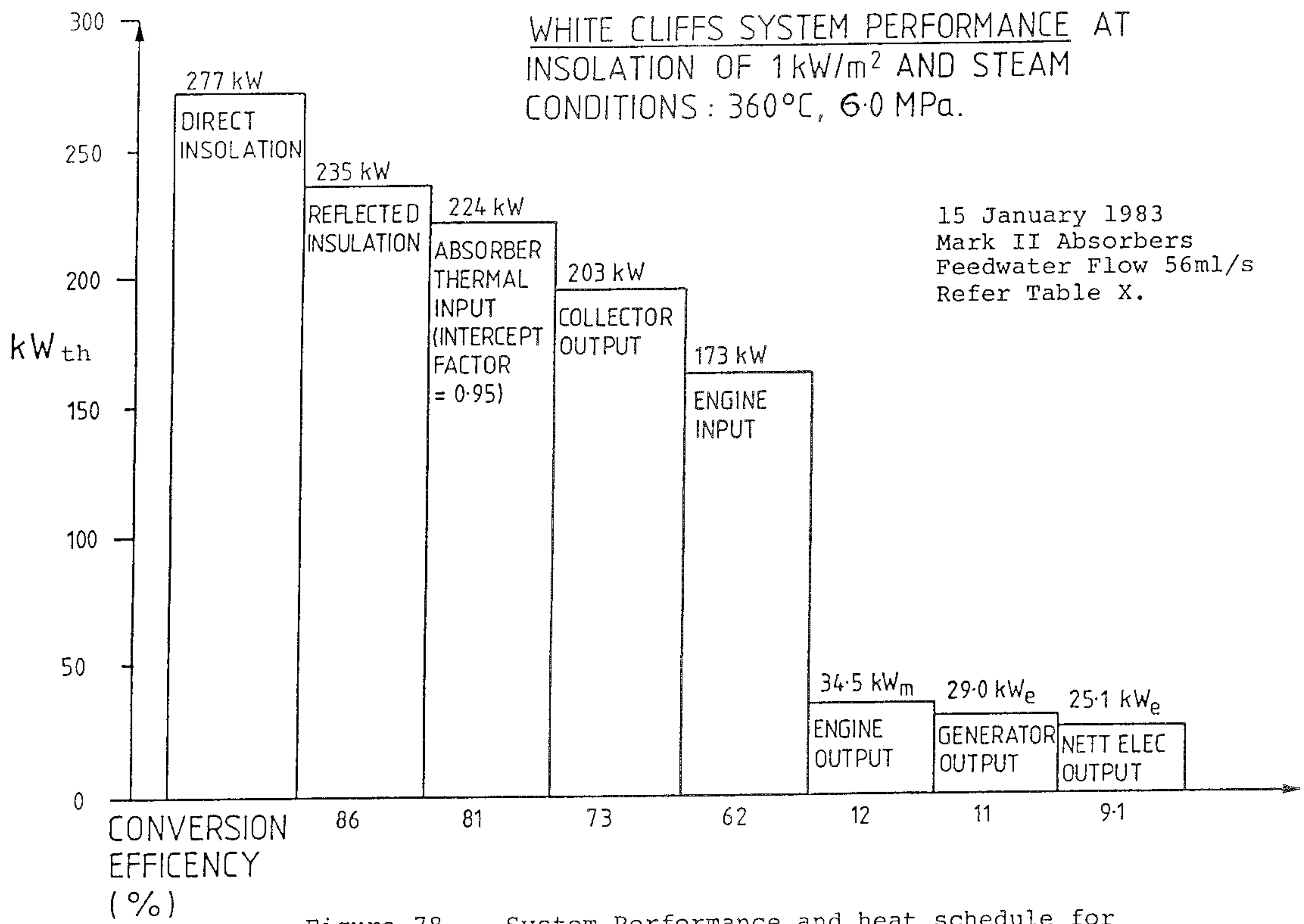


Figure 78. System Performance and heat schedule for $360^{o}C$, 6.0MPa steam at engine.

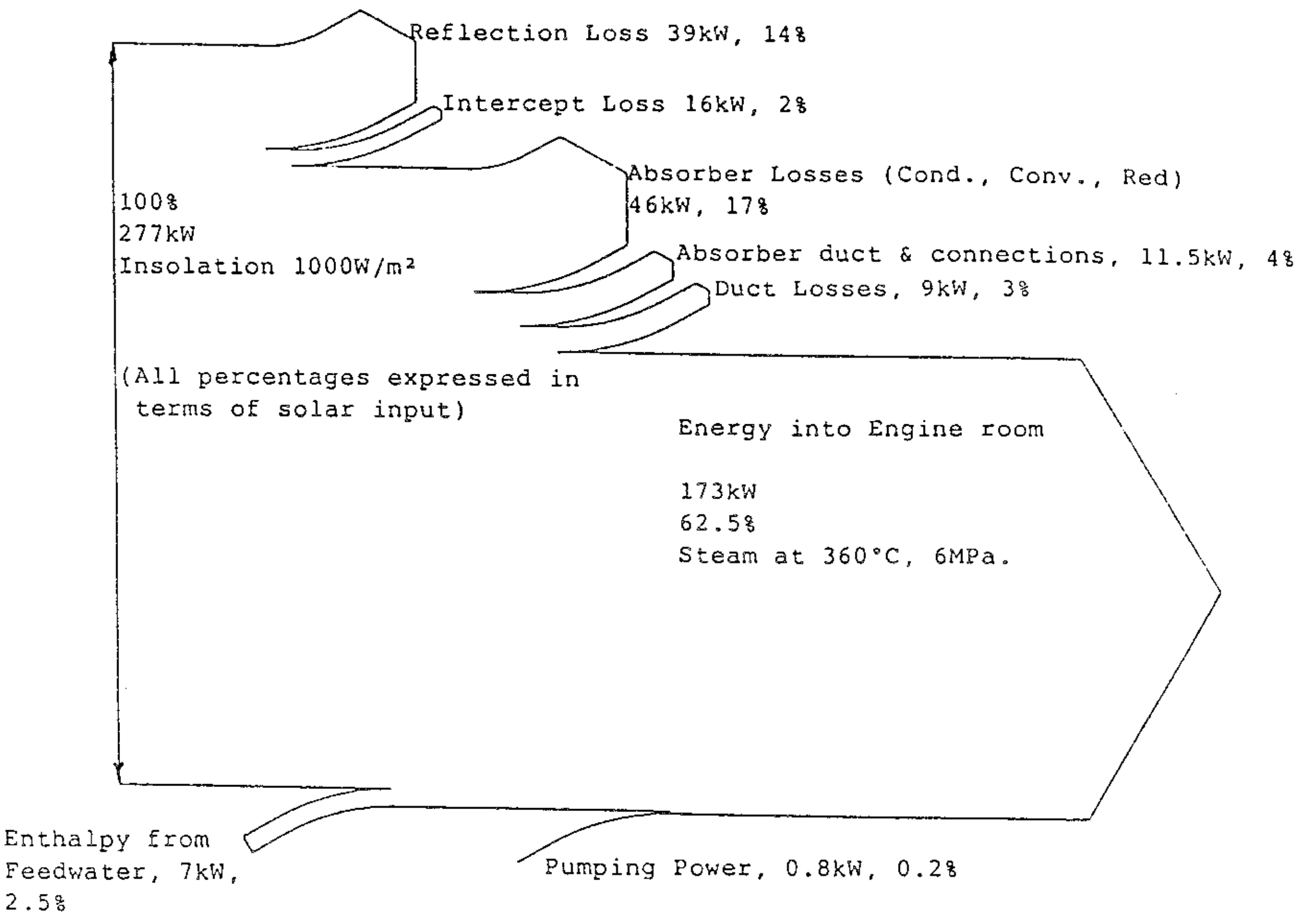


Figure 79 - Losses for the conditions of Figure 78 - Maximum Output

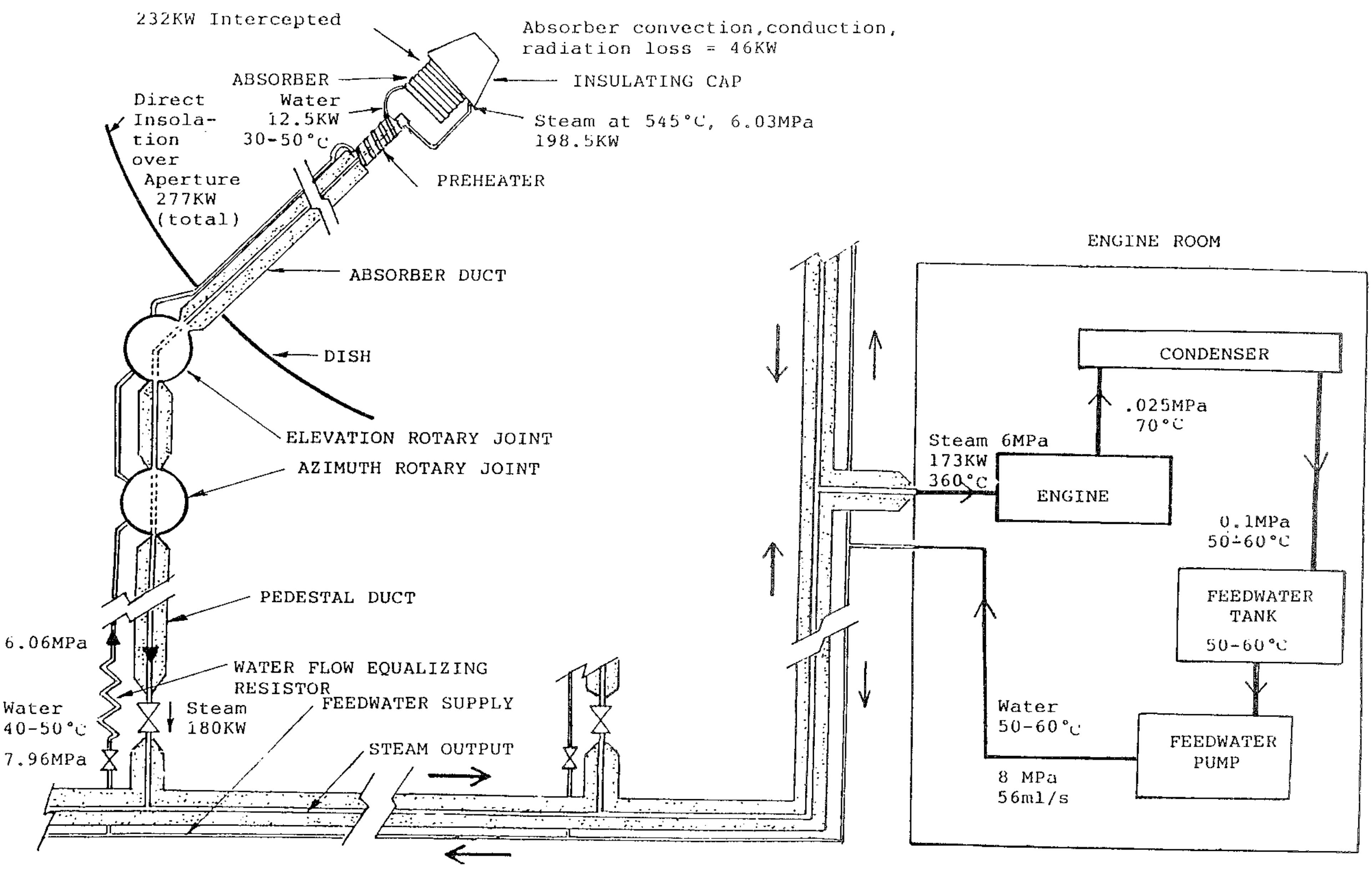


Figure 80 - Energy, Temperature Levels and Losses on the Solar Array/Steam Reticulation System Conditions at Insolation of 1000W/m^2 (SeeTableX). Numbers apply for 14 Dishes.

operation with high steam temperatures and high input power. Collector system operation also is advantageous when operating at high power levels (high insolation), as indicated in Figures 29 and 73, but high steam temperatures are disadvantageous because of the influence of losses. This matter is taken up further in the next section in relation to maximum efficiency/maximum output conditions, but here it is useful to identify and analyse the various collector array and steam reticulation losses and their significance on the system in order to understand the nature of the matching needs and practicabilities for the whole system.

Reference to Figure 80 allows a convenient introduction to the effects of interest.

Feedwater, at a temperature of 30–50°C and at an appropriate pressure, is injected through the flow-equalizing capillary of each collector, then traverses the vertical and horizontal axis rotary joints, where it collects some hundreds of watts of heat from the outgoing steam — the amount of heat transfer depending on steam temperature and other factors, as discussed in Section 3.1.4 and illustrated in Figures 31, 32 and 33. The outgoing steam cools down a total of some tens of degrees, the enthalpy it loses being imparted (but not lost) to the incoming feedwater which warms up accordingly. A small amount of this heat is lost before entering the absorber where the water changes to high quality steam.

The absorber gains its energy from the concentrated sunlight reflected from the paraboidal dish, a very small part of this reflected energy (ideally zero) being lost through non-interception. Energy is lost by conduction, convection and radiation; the convection losses being particularly dependent on wind velocity and direction.

Steam temperature at the absorber outlet is determined by a number of factors including insolation level, dish reflectivity, absorber losses (including wind effects), amount of feedwater flow and system pressure which in turn is a function of engine parameters, steam quality, feedwater pump setting, pressure drop across capillaries and pumping losses due to resistance of steam and water tubes. Under steady-state conditions , the pressure drop across the absorber is quite small (typically a few psi at most).

In the interests of minimum collection and conversion losses and of subsequent reticulation losses, generated steam temperature should be as low as possible; this requirement basically contradicts the engine efficiency demands which require a steam temperature in the engine-room which is as high as possible. There will be, therefore, an optimum condition in which overall system output is a maximum, a compromise solution which will vary as insolation level varies.

The practical limit to the highest steam temperature attainable in the absorbers is set by absorber material properties, lifetime and general structural integrity of this high-pressure high-temperature unit. With the stainless steels used in our absorber construction, 580°C material temperatures should be considered a maximum working limit, even though our many tests have gone well beyond this temperature at times. Under steady operating conditions, this steel tube material temperature corresponds at most to a steam temperature of some $550/circ$C, which is the peak rating we have set on absorber steam temperature.

Steam emrging from the absorber has to negotiate a number of loss hurdles before entering the engine room:

- Connection to the absorber duct through an arrangement which still allows the absorber to move outwards by some 13 mm from cold, to cope with expansion of this steam line from the horizontal axis rotary joint, in order to occupy the correct focal position when in operation.

In the case of the original Mark II absorbers, this connection involved a steam line from the inside top of the absorber straight into the duct, occupying a position which is illuminated by the sun and therefore acting as an energy collector as illustrated in Figures 31 and 38(a). Heat loss from this connection (which had to be protected from the very intense radiation originally by a ceramic tube, later by a stainless steel tube) was relatively small but the configuration was changed later because of practical difficulties, particularly involving change of absorbers. Later Mark II absorbers and Mark III–VIII units have a duct connection, as illustrated in Figures 38(b) and 38(c), and involve considerable energy loss when the complete connection is considered, as evident from Table X.

- A small energy loss (about 30 W/m×1.8m = 55 W) in traversing the absorber duct.
- A transfer of heat from the steam to the incoming feedwater amounting to 150–350 W per rotary joint, as discussed in Section 3.1.4 and Figures 32 and 33.
- A small energy loss (about 30 W/m×3m = 90 W) in traversing the pedestal duct and isolating valve, before entering the main ducts.
- Losses in the main duct to the engine-room. Although this duct is long [a total in each brach of some 81 metres plus the 10-metre run to the engine-room (Figure 34), ie 172 metres], losses are not substantial, varying in the sections near the engine-room from 50 W/m to 30 W/m at the extremities of the array, as indicated in Figure 34.

It is interesting to note that, whereas in the duct run from collectors 13-11 and 14-12 the end collectors must supply all the losses of 30 W/m, between collectors 3-1 and 4-2 the 50 W/m losses in each case are contributed by 6 collectors; in the single run to the engine-room from the branch point, the 50 W/m losses are contributed by 14 collectors. Accordingly, as noted from Table X, main duct losses are les than 8 kW total. This gives an understanding of why the total losses from a massive 10 000-collector array of 100 m^2 collectors estimated by Carden and Bansal [1987] is less than 1% of throughput when the transport network is of appropriate configuration.

At each operating condition — depending on the enthalpy carried by the feedwater from the engine-room (and there is some clear advantage in insulating the feedwater runs although this is not currently done); the enthalpy gained by the feedwater in traversing the rotary joints; the heat gain from the collector; heat losses from absorber by conduction, convection (dependent on wind) and radiation; rotary joint transfer loss and losses in all the ducts — there will exist on the system a particular temperature profile on which losses are dependent and the nett result will be a transfer of heat of a particular quality to the engine-room.

For given insolation and wind conditions, substantial variations in losses and delivered steam quality can be achieved by control of the feedwater flow; major restrictions to the range of this control arise from the need to limit absorber temperatures to safe values, on the one hand, and to achieve acceptable engine output on the other, that is, to have not too low an engine-room steam mass flow.

Table X provides an overview of the detailed losses, throughputs and outputs of the collector and steam generation and reticulation system controlled by feedwater flow to provide heat quality into the engine-room, at different insolation levels, to achieve a reasonable (near maximum) output.

At 1 000 W/m^2 insolation, steam temperature of 360/*circ*C at 60 Bar pressure can be delivered to the engine-room with an absorber steam temperature of 545/*circ*C, with a collector efficiency of 67% and total array collection and steam transport efficiency of 62.5% at a feedwater flow of 56.28 ml/s (60 Bar = 6 MPa within 1%).

Figure 78 is the cascade diagram for this condition; Figure 79 illustrates the losses and inputs diagramatically.

Designed feedwater flow for the system was 50.4 ml/s, the value being set by expected engine performance requirements; with this flow, higher temperatures can be attained in the engine-room but at the cost of higher absorber temperature and reduction in absorber life; consequently it is not desirable to operate in this mode on a long term. Above 1 000 W/m^2, not a rare occurrence, higher engine-room steam conditions can be gained with increased feedwater flow; the greater throughput can be achieved at absorber temperatures the same as those for 1 000 W/m^2 or lower; and higher collection, conversion and transport efficiency resulting in higher heat quality and quantity in the engine-room (above 360°C and 6 MPa) with higher engine efficiency and output.

Below 1 000 W/m^2, it is not desirable to maintain an engine-room temperature of 360°C; as indicated for 800 W/m^2, the cost of achieving this condition is the penalty of running absorber steam at 610°C outlet, as well as reduced collector efficiency (63%) and reduced array collection and steam transport efficiency (56%).

For the more common daily peak insolation applying at White Cliffs, 900–1000 W/m^2, reasonable heat quality into the engine-room can be obtained — some 300–350°C, at pressures of 45–60 Bars (approximately 4.5–6.0 MPa). Under these conditions, collection efficiencies in the range 65–70% and array collection and steam transport efficiencies of over 60–65% can be obtained to provide still reasonable engine performance.

At lower insolation levels, as indicated in Table X, it is necessary to operate the array to give lower engine-room temperatures and pressures in order to confine absorber temperatures to reasonable values. The values used in Table X provide near optimum overall system performance, balancing steam temperature and mass flow in accordance with engine demands. The optimum is reasonably flat and many combinations of flow, temperature and pressure are possible. But attempting to run the absorbers when insolation is 600 W/m^2 or less at 500°C–550°C (which is still safe) causes more losses and less engine output than at lower absorber temperatures but higher steam mass flow.

Thus at 400 W/m^2, attempting to run absorbers at 550°C results in very low collection and transport efficiency and provides inadequate steam quality and mass flow to run the engine and supply the auxiliaries; reducing absorber temperature to nearly 300°C, on the other hand (as noted from Table X), still allows efficient collection (69%) and collection/transport efficiency (63%) — adequate to run the engine, supply the auxiliaries and give a very small nett electrical output, even though the engine-room steam temperature is only 220°C at a pressure of 24 Bars (approximately 2.4 MPa) with a total feedwater flow of 28 ml/s.

Comments

- Many combinations of parameters may be used in collecting, converting and transporting the solar heat in steam but, for optimum conditions, very definite restrictions apply. Generally, the limits are influenced by absorber design and efficiency, insolation (throughput) level, required conditions in the engine-room (or other application for the high quality steam), the means for connecting absorbers to ducts, rotary joint performance and duct losses. In the particular White Cliffs configuration, the major loss factors are: mirror reflectivity and absorber intercept factor, absorber conduction, convection and radiation losses, and losses in the connections from absorbers to insulating ducts.

- While the rotary joints do not directly cause energy loss (the heat is merely transferred across to the incoming feedwater and is not lost) and while the heat quantity involved seems relatively small, these joints (together with the effects of the heat losses from the absorber-to-duct connections) cause very significant temperature drops, as indicated in Figure 80, which constrain the absorbers to work at a considerably higher temperature (with efficiency) than would otherwise be the case and consequently impose a major constraint on system performance, causing a great deal of the valuable superheat generated in the absorbers to be lost.

  Fortunately, both these sources of effective loss can be almost removed. The rotary joint losses and temperature drops can be reduced to very small proportions as indicated in Section 3.1.4 by building larger dish units with much higher throughput, resulting in temperature drops of only a few degrees at each rotary joint (and utilising only one rotary joint by allowing the engine to move with the azimuth axis as in the White Cliffs II configuration discussed in Section 9). This approach reduces temperature drops due to rotary joints by one-half and also reduces to one-half the heat added to the incoming feedwater by the transfer of energy across the rotary joints; the absorber connection-to-duct losses can be removed by a change in the means for achieving this connection, that is, employing an arrangement illustrated in Figure 38(d) whereby the outlet from each absorber enters directly the insulated duct without any exposure to conduction, convection or radiation losses which occur in the exposed connections of Figures 38(b) and 38(c).

- The small loss due to some of the reflected energy from the mirror not being intercepted by the absorber can be totally eliminated by appropriate design.

- Two major losses remain to be considered:

  (a) Mirror Reflection Loss: In the case of the White Cliffs dishes, this is some 14% (at best) of the incoming energy with clean mirrors. The need for regular and effective mirror cleaning is obvious. Higher reflectivity glass was not available to us in 1980 but glass reflectivities of 94% (even 96%) can now be attained and, with some difficulty, maintained. Use of 94% (or higher) reflectivity mirrors not only provides a given system with a direct increase of some 8% in system input but, by permitting lower temperture operation, can result in lower losses in many components of the system and can lead to more than 8% increase in system output. The cost penalty is that of somewhat higher material cost and cleaning costs — both can be more than compensated by the improved annual collection efficiency.

  (b) Absorber Conduction, Convection and Radiation Losses: These act in the same manner as the mirror reflection loss above; that is, reducing these losses allows lower temperature operation and reduction in losses in the remainder of the system, leading to a percentage increase in output which can be greater than the percentage increase in input and result in components being subjected to lower stresses. Absorber designs are still evolving and it is not unreasonable to expect a few percent increase in absorber efficiency from the overall relatively low Mark II White Cliffs units considered in the previous discussions (low 80%) to units achieving efficiencies in the low 90%.

We conclude there is much scope for improvement in all areas of solar array collection, concentration, conversion and transport.

- When the above direct and implied improvements are effected, the remaining area for loss reduction is the duct system itself, which currently is of good quality and would not be expected to be improved substantially in loss properties. Simple vacuum-insulated steam lines can be constructed more cost-effectively than the microtherm-insulated ducts now used; the building of larger collectors will improve the throughput and consequently the relative losses applying but, unless very large systems are constructed, duct losses would not be substantially reduced beyond the present values. Placing engines close to absorbers would achieve a useful reduction.

All matters considered, we must conclude that, as regards duct loses (which are already low) and collection, concentration and conversion processes (which can be improved greatly), no real constraint on the use of central plant with large numbers of paraboloidal dishes is indicated. Carden and Bansal [1987] confirm this analytically and numerically for the reticulation networks for very large arrays.

Consequently, one of the major objectives of the White Cliffs Project has been met and resolved in the demonstration that arrays of collectors operating at high temperature can be effective so long as they are appropriately sized and designed; this applies to electricity generation and, by implication, also to the provision of industrial process heat.

3. Engine Performance and Maximum System Output Conditions

As has been evident from the foregoing, with the present system configuration and parameters there is a mismatch between array and engine, preventing the most effective utilization of the high efficiency attainable by the engine because the array is not able to provide, with adequate efficiency, engine-room temperatures sufficiently high to allow the engine to work at the upper values of its efficiency range — over 20%. In this context, the rated feedwater flow of 50.4 ml/s at 1 000 W/m^2 requires absorber temperatures which are too high (as implied in Table X) thereby resulting in absorber and array losses which are greater than can be otherwise achieved, causing engine output (because of lower input enthalpy) to be less — in spite of higher efficiency at the higher input temperatures — than would be the case with lower absorber temperatures and lower steam temperatures entering the engine-room.

Engine details and performance have already been considered in Sections 3.4 and 5.2.1 and in Figures 42, 43 and 76, while Section 5.5.5(2) above details array properties at different insolation levels; Table X summarizes conditions in the array energy collection and steam reticulation network at different insolation levels for specific feedwater flows. What is noteworthy from Table X is that good array collection and transport efficiencies can still be achieved and significant heat energy can be delivered to the engine-room even at relatively high temperatures in spite of the various losses. While these temperatures are not as high as can be utilized by the engine, advantage can be taken of the fact that the engine is able to operate even on wet steam with not unreasonable efficiency and output.

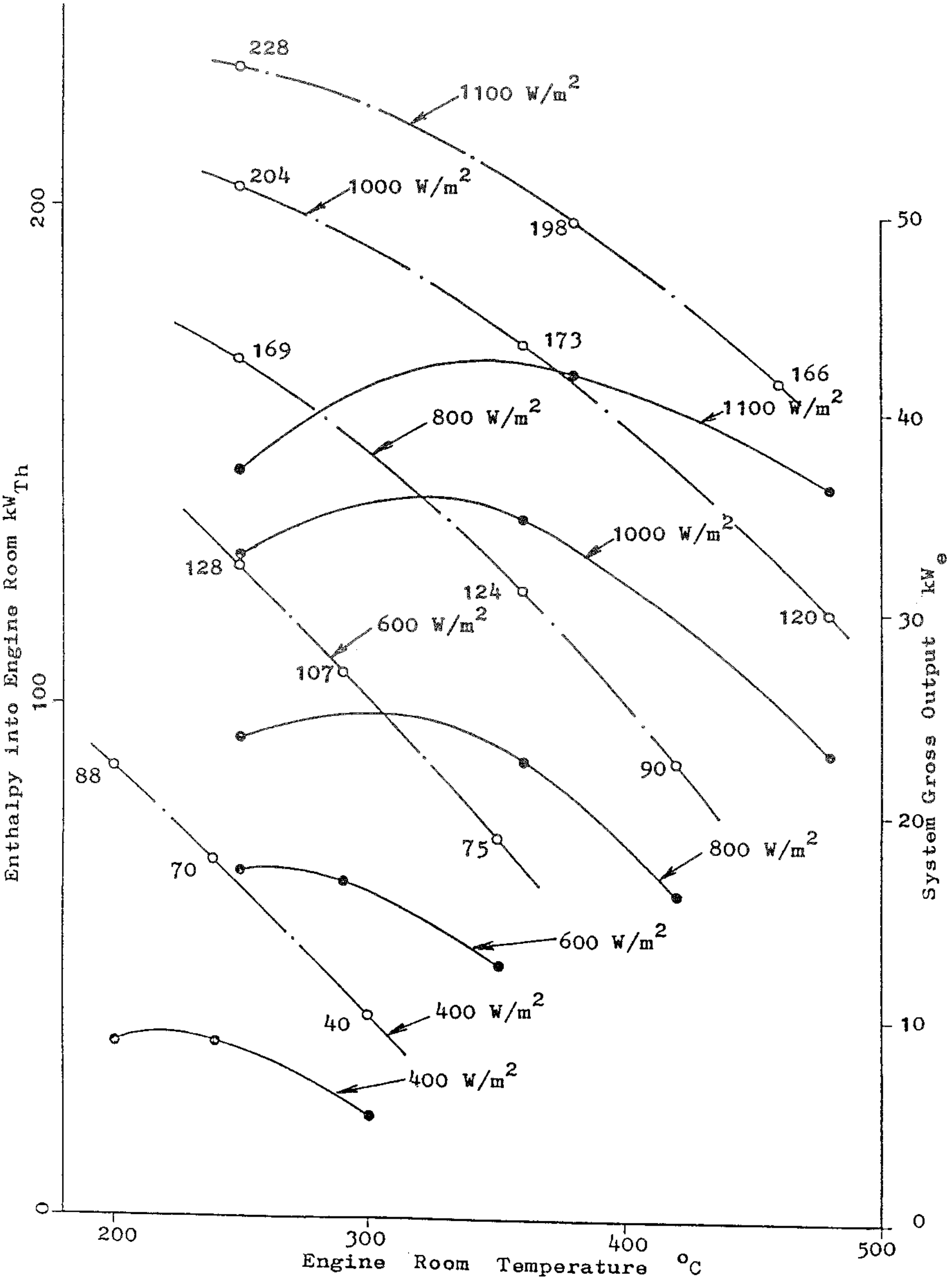


Figure 81 - Output as a function of engine room input enthalpy and steam temperature at different Insolation levels.

(See also Table XIV)

TABLE XIV — PERFORMANCE OF SOLAR ARRAY AND ENGINE TAKEN TOGETHER

Insolation W/m^2	Direct Beam Incident Energy kW thermal	Engine-Room Input Enthalpy kW thermal	Engine-Room Steam Temperature °C	Engine Efficiency %	System Gross Output kWe	Overall Efficiency %
1 100	305	228 198 166	250 380 480	16 21 22	36.5 41.6 36.5	12.0 13.6 12.0
1 000	277	204 173 120	250 360 480	16 20 19	32.6 34.6 22.8	11.8 12.5 8.2
800	222	169 124 90	250 360 420	14 18.2 17.5	23.4 22.6 15.8	10.6 10.2 7.1
600	166	128 107 75	250 290 350	13 15.5 16	17.0 16.6 12.0	10.2 10.0 7.2
400	111	88 70 40	200 220 300	10 12.4 12	8.8 8.7 4.8	7.9 7.8 4.3

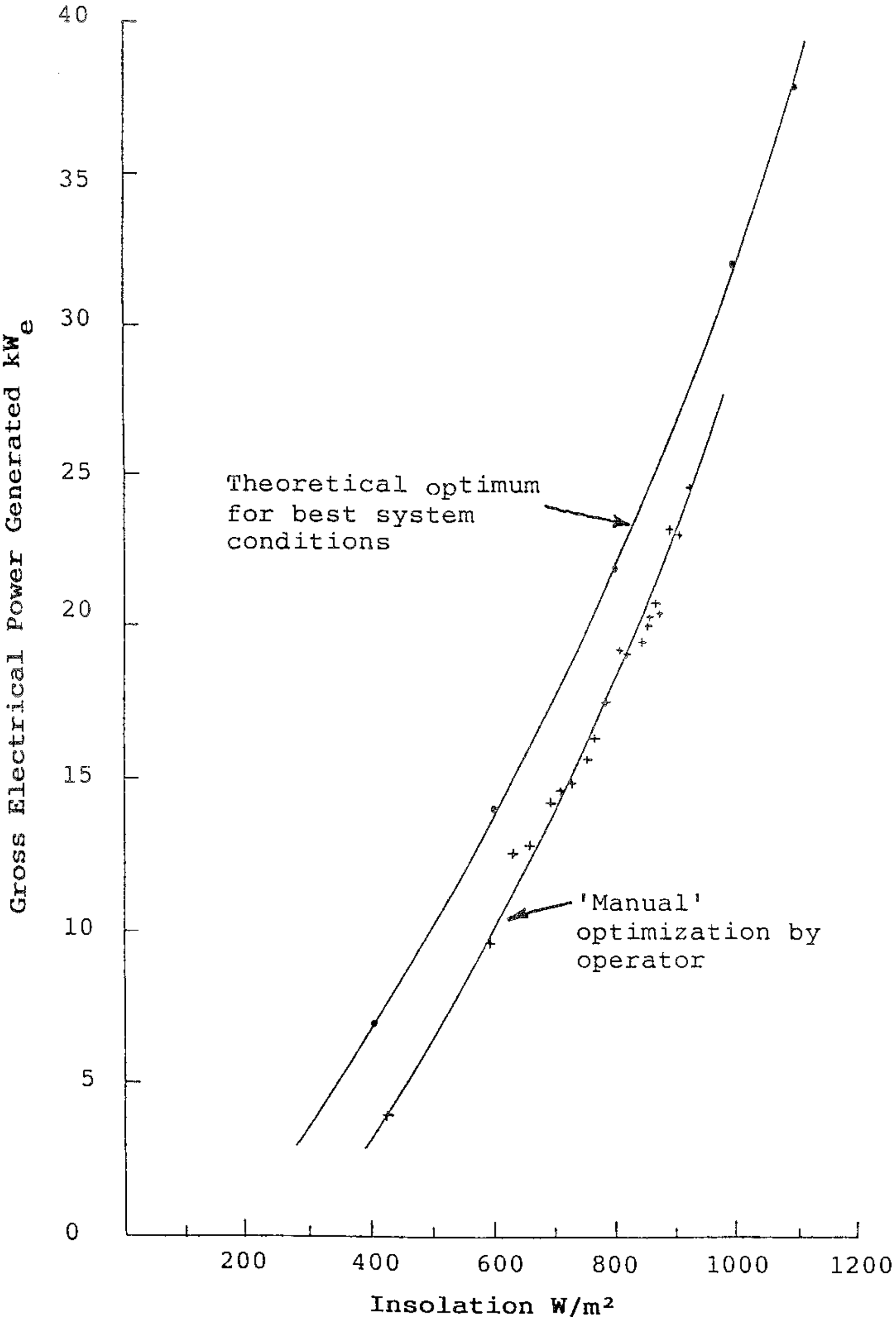


Figure 82 - Output vs. Insolation for Optimum Conditions

Figure 81 and Table XIV summarize the performance of array and engine taken together; the various operational points have to be recognized as being multi-dimensional, with different steam conditions at each point. Other values of feedwater flow for each level of insolation could have been taken, but the general relationship between system optimum output and insolation is evident: higher insolation levels allow higher engine-room temperatures to be maintained with higher efficiency and, in turn, higher engine efficiencies and outputs are achieved. But if too high an engine-room temperature is sought, mass flow drops and engine output falls even though engine efficiency may be higher. A relatively flat optimum system output applies for each insolation level: clearly the maintenance of a true optimum output requires regular adjustment of feedwater flow (resulting in changed steam conditions) as insolation levels change during the day.

Maximum system output as a function of insolation level is plotted in Figure 82, based on the above considerations. For comparison, actual outputs, 'optimised' by manual adjustment on the basis of operator learning and experience, are also plotted; the discrepancy between these sets of values warrants explanation, especially since there appears to be a systematic difference.

The higher curve of Figure 82 results from calculations based on the assumptions that all absorbers are identical in performance — operate under identical conditions of unchanging insolation, dish reflectivity, feedwater flow and steam outlet temperature — in still air; it is assumed that steady-state conditions have been attained. Similarly, the duct system is also assumed to have reached steady-state operation — no heat absorption or release by the microtherm insulating medium. The engine is assumed to have reached an operating state whereby the efficiency corresponds to pseudo-stable conditions in which immediate mass flow or steam quality changes have produced their short-term effects; that is, effects with time constants of a few minutes superimposed on an engine which has reached its appropriate operating conditions — see Section 5.5.2(1). These conditions are, of course, a 'practical' ideal.

On the other hand, the lower curve of Figure 82 records actual values of output at different insolation levels which have resulted from manual adjustment of feedwater flow to achieve what, in the operator's experience and understanding, represents optimum output under those conditions, acting without the benefits of the curves of Figure 81. While feedwater flow can be adjusted as rapidly as required, insolation must be taken as it comes; the lower values of insolation necessarily come as quantities which are varying relatively quickly (as may be noted from Figures 4-10) and consequently it is not easy to judge optimum adjustments manually — a degree of prediction is required. Moreover, wind conditions at White Cliffs are rarely if ever 'still'; at best a wind velocity of approximately 2–3 m/s may be considered a realistic minimum. Non-uniformity of feedwater flow, dish reflectivity, wind variations (at different positions on the array), and absorber losses usually ensure that steam outlet temperatures vary over a range; for example, when the array was in pristine condition with new Mark I absorbers and 'clean' conditions, absorber temperature varied (at most) 480° ±20°C (for target temperature of 480°C). Currently typical temperature variations are 420–500°C; such variations do not allow the most effective collection and transport efficiencies to be attained. Furthermore, neither the absorbers, ducts, nor engine have a good chance to reach stable operating conditions due to insolation and especially wind variations (a glance at any of the wind records in Figures 4–10 will confirm the variable wind velocity at the measuring point — and on top of this, variations across the array also occur); consequently the actual outputs are less than ideal.

The two major factors leading to the discrepancy between the two curves of Figure 82 are:

(a) Lack of time for the components of the system (absorbers, ducts and engine) to reach stable operating conditions because of insolation and wind changes and due to the various influential time constants involved. Predictive control, taking account of the various time constants, can improve correspondence beyond that apparent in Figure 82, but the usual gusty winds do not lend themselves to prediction.

(b) Non-uniformity of feedwater flow in each absorber and non-identical absorber characteristics — both these factors can be controlled to effect overall improvement.

All things considered, the lower curve can be improved by appropriate action (see Sections 7 and 9).

4. Transient Operation

From the foregoing, it might be appropriately considered that the solar system is always operating under transient conditions since, strictly speaking, insolation is always varying and wind velocity is forever changing. But on sunny days these changes are not substantial for a few hours around midday when the system can settle down to operation which involves relatively small, though significant, changes from the viewpoint of system performance. During these periods there is a need for sensitive control to take full advantage of the solar input because much, indeed most, of the added enthalpy is in the form of latent heat while the useful enthalpy comes from the superheat. But we are not concerned here with this operating regime which has already been considered in previous sections, but with several more-substantial variations from 'normal' running:

(a) Starting and Stopping

The system may start and stop under several different conditions, the most usual being from normal clock control; less frequently due to intermittent cloud and very rarely as a result of fault conditions.

Early morning start follows the procedures outlined in Sections 3.10 and 5.3.2 when (depending on the season, insolation levels and start time set) the engine takes some 12–20 minutes to start following time initial clock command and may take a further 5–6 to 15–20 minutes before useful nett electrical energy is supplied (again depending on insolation levels). During this starting sequence, auxiliary power is supplied either by the battery or (if this is discharged) by the diesel set which would be running from the time the battery has reached its allowable discharge level.

Starting is much more rapid in the presence of higher insolation levels, especially if the system is already substantially in operational condition; for example following offsteer due to a system fault condition, emergency stop or operator initiated stop. In such circumstances useful power can be delivered within 2–3 minutes (or less) following dish reacquisition of the sun.

Starting when powered from the auxiliary boiler is particularly rapid, even from 'cold', when useful power can be delivered within 3–4 minutes from initiation of the 'start' sequence, including time for the burner/boiler unit to start. The engine will deliver useful power within a few seconds of receiving steam from a hot boiler. In the latter case, the prototype engine for the Molokai Project (see Section 6) was regularly able to reach 1500 rpm within some 3–4 seconds and

1800 rpm within a further 1–2 seconds when provided with adequate steam energy.

Such rapid starts, although able to be tolerated, are not recommended because of the uneven heat distribution in the early start-up stages and the consequent frictional forces resulting from pistons expanding before cylinder walls. In one or two cases in which initial tolerances between respective pistons and their cylinder lines had been too tight, considerable overheating of components occurred (to the point of red heat) as a result of these frictional forces in the early very rapid start period. When powered from an already 'on-line' boiler, cold engines should be started less dramatically, allowing say 10 seconds or more to reach full speed from zero. When solar powered, this situation does not arise because the absorber and duct heating time constants provide in-built delays before full steam power can be applied to a cold engine.

Beyond the undesirability of very rapid starts, there is no virtue in delaying the time taken for the system to generate useful power since, until self-generation is adequate at least to supply auxiliaries, energy for this phase must come from the battery or from the diesel unit, whichever may be supplying the load at the time the solar system starts. Control decisions need to be taken as to when to initiate or discontinue operation in the light of incoming insolation levels.

While these decisions are not difficult for operators to take, because of the need to be able to predict insolation conditions ahead, obvious problems are posed for automatic control systems which are designed to reduce auxiliary power used to a minimum.

Normal stopping of the system at the end of an operating day is accomplished by clock command which causes the array to discontinue tracking and to park in the horizontally-facing south-east position, ready for a start next day; this allows continued generation of steam from the stored heat energy in the whole system and eventually the engine stops after it has literally 'run out of steam'. This process takes some minutes from initiation of the stop sequence, the time depending on insolation and wind conditions. Auxiliaries are allowed to run on for some 10 minutes longer to allow the system to cool down and for the feedwater tank to be cleared of any oil. As in the starting process, auxiliary energy is used during shutdown, in this case supplied by the battery.

Fault conditions on the engine/steam system or an emergency stop initated by the operator, cause the array to offsteer and allow the engine to stop rapidly (within seconds) by closing of the throttle valve and opening of the bypass valve. Again, the auxiliaries operate for a further 10 minutes, then stop automatically unless subject to operator intervention. A less sudden stop may be operator initiated by simply offsteering the array and allowing the engine to come to rest as it runs out of steam. In extreme conditions resulting in engine overspeed which has not been protected because of faulty normal overspeed protection (say), a 'last ditch' protection is invoked by the original mechanical governor on the diesel block which causes, by a separate emergency system, the throttle to close, thereby stopping the engine immediately and allowing the cut-off steam in the system to escape, due to pressure buildup, via the safety valve.

Due to the normal protective devices (engine oil pressure in particular) the array then offsteers, the bypass valve opens and the system closes dovn as for the usual fault condition sequence.

As already indicated, start and stop sequences occur at the expense of auxiliary power which must be supplied by the battery or the diesel.

(b) Response to Insolation Changes

System output follows insolation changes with time delays caused by the various time constants involved in components — absorbers, duct system and engine, as illustrated in Figure 77.

During operation in intermittent cloud, the system will continue providing energy even after a cloud has obscured the sun, drawing on the heat stored in various components. Eventually, if cloud persists, engine speed will fall below synchronous and the engine will coast along at successively lower speeds until it runs out of steam, when it will stop — power for the auxiliaries and the load being provided from the battery. When adequate steam conditions are re-established, the engine will start automatically and take over supply of the load from the battery.

In the afternoon cloud conditions often met at White Cliffs (see Section 2), this mode of operation — continual starting and stopping — may continue for several hours.

Decisions have to be taken as to whether or not it is worthwhile to run in the period between clouds and what to do during the passage of clouds. If the system is allowed to run on in such circumstances, the nett energy gained should be worthwhile in relation to the auxiliary power used during the cloudy patches; actual insolation level plays a part in this decision. During haze, for example as in Figures 8 and 9 in which insolation does not fall to zero, the conditions are somewhat different since the engine does not stop, but the overall generation efficiency is low; again the total useful energy gathered during the day should be worthwhile.

Operating strategies have been developed for various insolation conditions to allow decisions to be taken more readily; usually it is deemed not worthwhile to operate in heavy rapidly varying intermittent cloud and the system may be closed down for a time. The occurence of such conditions can usually be predicted by experience.

(c) Load Change Effects

The general problems of load on the system are illustrated in Section 5.4 and daily load curves are shown in Figures 69–72. While average system loads may be relatively uniform over a period, due to the small number of users and their varying individual use patterns, quite substantial load changes can occur on the system. There are few, if any, problems associated with such changes since the engine/battery-store combination permits a continuous sharing of load between the two sources. If engine output is inadequate to meet load demands at any moment, the automatic torque balance system causes the DC machine to draw energy from the battery to assist in supplying the load; at other times the same control system causes excess energy to be stored in the battery. These transient changes are largely unnoticed by users beyond a very small frequency variation (better than $\pm 1\%$).

(d) Load Transfer Between Solar and Diesel Systems

More-drastic transients occur when changing over supply from diesel to solar or vice versa, when operating conditions as in Section 5.5.3(1) and Figure 45(b) may occur, resulting in larger frequency swings for a few seconds.

(e) Overload Responses

Various overload conditions can occur to cause the system to discontinue supply, when the diesel set can take over. Such operation is discussed in Sections 3.1.5, 3.3.6, 3.3.15, 3.5.2, 3.5.5, 3.10, 5.5.3, but in practice, shutdown from overload has been extremely rare and has not been due to overheating of the AC or DC machines or batteries, nor due to limitations in supply. On one occasion, a DC machine over-current trip has followed a non-tripping of the main station breaker (set at 25 kW) when a town load of probably well over 30 kW has been in place, possibly due to user action to circumvent operation of the individual breaker. Such an overload condition has also put the diesel unit out of action on occasion.

(f) Useful Transient Operating Strategies

The most productive strategy to be employed during any transient condition is one which reduces duration of the transient to a minimum and/or maximises integrated output over the period, or at least minimises auxiliary energy used in the event of no nett output being available.

It is not convenient to have individual automatic controls for the various steam system auxiliaries, otherwise a fine tuning of auxiliary power could be based on a switching on or off of particular auxiliaries. It is also basically imprudent to switch off the feedwater pump (and consequently the vacuum pump) during periods of cloud on the supposition that no feedwater needs to circulate in the absorbers when the sun is not shining, since not all absorbers are necessarily out of the sun together and would therefore have only their overheat/offsteer protection. Moreover, proper feedwater flow would be re-established somewhat after the onset of sunshine again, causing undue heating.

On the other hand, it is beneficial to reduce feedwater flow in accordance with reduced insolation on the grounds that during intermittent cloud the general operating temperatures in the array, ducts and engine, are thereby maintained at a higher level than they would be if too high a feedwater flow during cloudy periods were retained. This strategy ensures that the whole system becomes operational more rapidly when the sun shines again and so minimises auxiliary energy and increases useful output.

In this mode, general array offsteer (in the event that the insolation monitor is shaded by cloud but more than one dish is not) is prevented by increasing absorber temperatures causing increasing feedwater flow as a result of the automatic control system function overriding the insolation monitor signal.

Significant auxiliary energy is used during early morning starting, particularly in winter when insolation levels are low, so requiring a relatively long time for the various parts of the system to reach operating temperatures. There is consequently an optimum time for initiation of the start. Unfortunately, any but an approximate best start time requires accurate prediction of the insolation variation from sunrise, clearly an extremely difficult requirement. Nevertheless it has proved useful to decide on the previous evening whether or not to allow the solar system to start at the normally set clock time, a decision taken on the basis of the weather predictions and on local weather conditions. It is not often that a mistake is made to disable the system on a particular day but, if such a mistake is made, the system can be allowed to start later, in which case the transient starting period is much shorter than it otherwise would have been for an earlier start since a later start occurs in the presence of a high insolation level.

Except in the summers of the earlier operating years (when town loads were low), the solar system usually starts at a time when the town load comes from the diesel set (the battery having been 'discharged'), and the solar system auxiliaries are arranged (as indicated in Sections 3.5.5. and 3.10) to be supplied also from the diesel set. This strategy is advantageous in that the battery is not run down by the start cycle unless there is adequate charge stored; it also allows the solar generator to charge up the battery quickly to the voltage (approximately 327 V) which causes the diesel set to cut out but with still a reasonable battery charge to prevent the diesel set from having to start again soon in the event of cloud obscuring the sun, and to prevent frequent diesel stops and starts in intermittent cloud. A further advantage arises from the direct generation and supply of auxiliary power without the inefficiency resulting from the use of battery storage.

The situation regarding starting and operation at other times is illustrated in Figure 54, which shows typical conditions involving solar operation during the day, followed by battery supply to the load, then diesel operation prior to further solar generation. If the solar output is adequate, the battery continues to supply the load until the solar system starts the next day (otherwise the diesel takes over early in the morning, as illustrated).

Auxiliary power used when the solar system stops can be effectively reduced to zero on initiation of a stop sequence either on fault conditions (involving offsteer) or on clock command at the end of a generating day. This is not currently the strategy used because of the perceived advantage in clearing oil from the feedwater by allowing the auxiliaries to run on for about 10 minutes or so, the time taken for the array to park in the south-east orientation ready for the next day. Energy so lost from the batteries amounts to some 0.5 kWh during the stopping sequence.

This mode of stopping differs from that involving operation during intermittent cloud when the auxiliaries do not stop, not even if the cloud lasts for tens of minutes; no stop signal is given, the engine running down due to lack of steam and starting again when adequate steam quality is re-established. In this case the system may not be inactive for very long during the cloudy periods (the engine may not even stop) and it would be inappropriate in many or most cases to stop auxiliaries.

However, when cloudy periods are relatively long, say more than 20 minutes at a time, a decision has to be taken about the nett energy generated and the benefits of operation at all, since long cloud spaced by short sunshine periods results in little nett generation gain. In such cases, however, it can be worth switching off auxiliaries. This is difficult to achieve by automatic control systems which have no sunshine predictive properties. The strategy currently used is to allow the system to run when sunny periods are relatively longer than cloud but when both are of not long duration (upto 20 minutes). For cloud of long duration with short bursts of sunshine, the system is not run; for long periods of both cloud and sun the system is switched off during the cloud and switched on for the sunshine, so long as insolation levels are reasonable.

The development of transient operating strategies is dependent on the actual installed capabilities for automatic control; this is an area of study which still has much potential for improved understanding and development as regards practical application.

5. Non-Linear Input-Output Relationship

Figures 81 and 82 and Table X well illustrate the essentially non-linear relationship between solar system input and output, reasons for which are discussed in Sections 5.5.5(2) and 5.5.5(3); but briefly follow from the fact that the system thermal losses depend mainly on temperature and that mechanical losses depend on engine speed, while efficiency depends on throughput and losses. With fixed temperatures and engine speed, efficiency tends to improve with throughput (insolation). A consequence of the array and engine characteristics is that whereas efficiency of all components improves with throughput, the efficiency of absorbers and heat transport ducts increase with decrease of temperature, while engine efficiency increases with temperature; as a result, overall optimum output and efficiency of the system is a compromise between array, duct and engine, contributing to the non-linear behaviour.

Because engine mechanical losses must be supplied and some of the generated energy must drive the station auxiliaries, a further non-linear feature is introduced, leading to the fact that system operation for low insolation levels much below 400 W/m^2 is not profitable, as little or no nett energy is generated.

As is evident from the curves of Figure 82, output rises increasingly more rapidly as insolation increases from 400 W/m^2 for the present White Cliffs configuration and it is a matter of careful perceptive design as to what collection areas and other parameters are chosen to get the most from a given system on an annual basis.

These aspects have an important bearing on the insolation levels chosen to provide 'rated output', as discussed in Section 5.5.7.

6. Annual Energy Generated

Table XV lists the energy generated by the solar station for each of the years 1984, 1985, 1986 and allows comparison between insolation and output. 'Prospective' values are also indicated, that is, those outputs which would be achieved if the hardware systems are all working with no impediments for a whole year of 'average' insolation.

The metering diagram is shown in Figure 83, setup in accordance with contractual arrangements for the project.

Tables XVA to XVC summarize the station energy flow, water use, etc as reported in the various Quarterly Progress Reports presented since December 1983.

Table XVD details the energy flows specifically for 1985 to identify the 'missing energy' in the overall system, which has sometimes been misunderstood and held against the solar system. In fact, by a simple rearrangement of connections and operating strategy, the solar system can provide nearly 100% more useful energy when assessed on a load supply basis.

On the Solar Output

The information in Tables XVA to XVC summarizes the operation and performance integrated quantitites for the station over the period 1983 to 1989.

An analysis is presented of the year 1985 as an illustration of some of the features of the system and some of the imperfections which depend not on the solar component, but on the way the operating strategies were organized.

Suffice to say that the objective was to cause the station to operate effectively in the first instance before attempting optimization or considering the installation more than an experiment but rather commercial-like equipment (which it was never intended to be — that was the task of later developments).

In the process, a number of loads were connected to the system which depended on the particular way the diesel set was connected: Essentially the solar electrical machines have have been run 24 hours a day irrespective of whether the solar system was running or not. Other loads, such as array battery chargers, also ran continuously as did some loads not related to the solar station at all.

As a consequence, the auxiliary power apparently used by the solar station appeared to be extremely large, whereas the real situation was quite different. We had plans

Additional Meters Required	
Hour meters for diesel load dump, HC	14, 15
kWh meter for Power into Battery	6
" " " " out of "	7
" " for solar auxiliaries	1
" " to Information Centre	3
" " from Solar (nett)	4
kW meter, nett to town	16

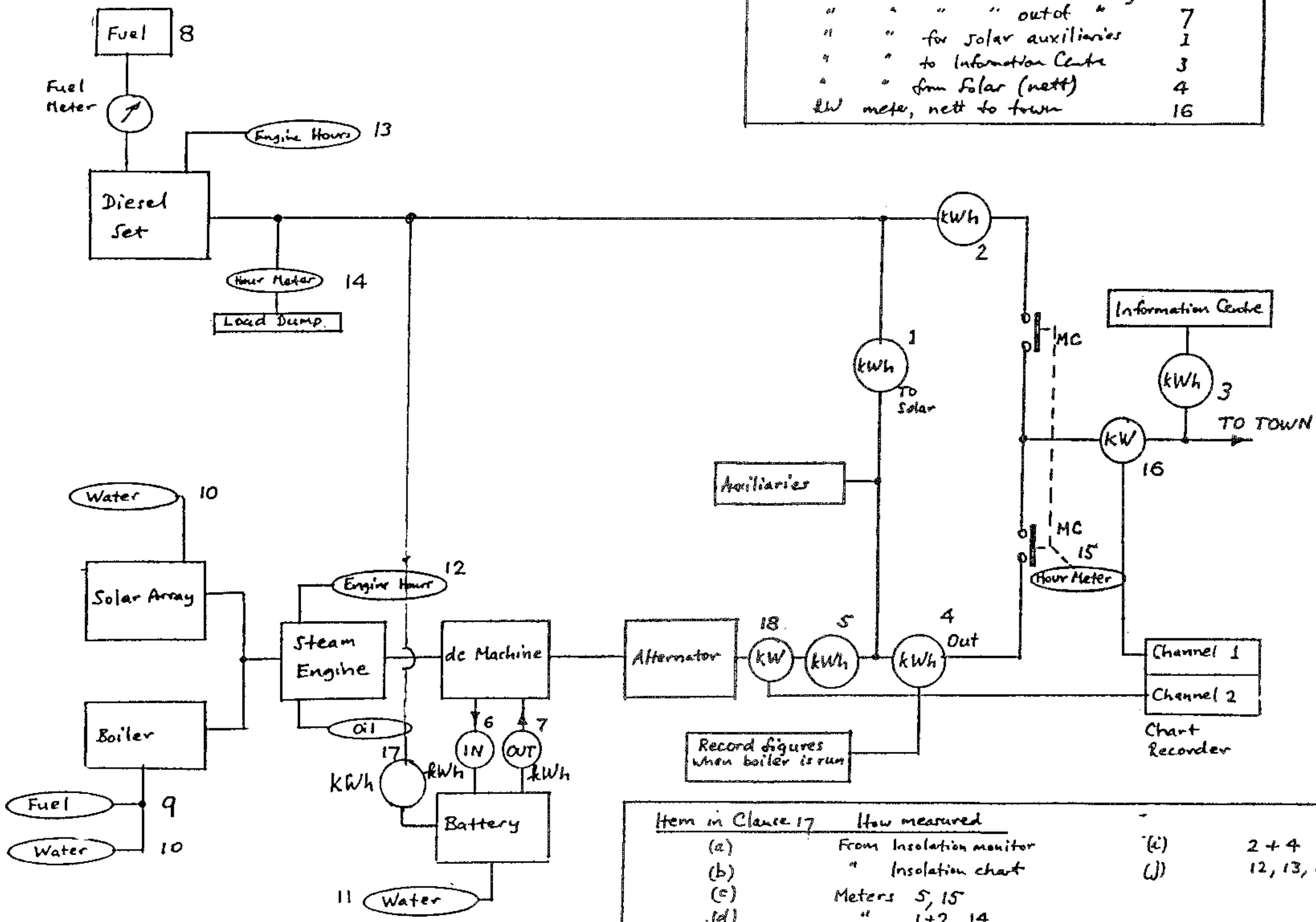


Figure 83. Contractual Metering Requirements Clause 17 (a)-(l)

Item in Clause 17	How measured		
(a)	From Insolation monitor	(k)	2 + 4
(b)	" Insolation chart	(l)	12, 13, 15
(c)	Meters 5, 15		
(d)	" 1+2, 14		
(e)	" Fraction of 5 recorded		
(f)	" 6, 7		
(g)	" 5-4+1		
(h)	" 8, 9, 10, 11		

TABLE XV — WHITE CLIFFS SOLAR kWh GENERATED AND GENERATION COSTS

SOLAR	1984	1985	1986	PROSPECTIVE
Equipment and Expendable Materials $	2 659	2 048	3 467	1 000
Local Contractors $	15 312	12 296	9 196	5 000
Communications $	810	922	541	100
Travel $	1 334	625	384	—
Total O&M Costs $	20 115	15 891	13 588	6 100
Solar Station Availability	70%	93%	86%	100%
Insolation — Total kWh/m^2	2 282	2 091	2 120	2 380
Insolation — Total above 700 (W/m^2 kWh/m^2)	1 828	1 588	1 557	1 900
(1) Electrical Energy Generated kWh	20 500	25 187	19 620	38 000
(Solar-generated incl. auxiliaries)				
Costs of Generated Energy:				
O&M Costs ¢/kWh	91	63	69	16
10% Capital Costs ¢/kWh(2)	141	124	159	82
Total Costs ¢/kWh	232	187	228	98
(1) Nett Energy to Town kWh	10 193	12 461	10 140	30 000
(including through battery)				
Costs of Energy to Town:				
O&M Costs ¢/kWh	197	128	134	20
10% Capital Costs ¢/kWh(2)	306	250	308	104
Total Costs ¢/kWh	503	378	442	124

(1) In 1986, continuing diesel problems prevented solar system from operating at times; waiting for replacement parts (commercial) to arrive also put solar supply out of action for 46 days on items not expected to be troublesome. Output was consequently low.

(2) On Capital Cost of $312 000 (1981).

Table XV-A - White Cliffs Insolation, Operational State, Cloud, Diesel-only operation

DATE	Total Insol-ation kWh	Total Insolation above 7ØØ W/m^2 kWh	No. of days worth operat-ing on Solar	No. of days actual operat-ion on Solar	No. of complet-ely cloudy days	No. of days of Diesel Only operat-ion
DEC 83	57800	48400				
JAN 84	59700	49200				
FEB 84	71500	57500				
MAR 84	58850	51200				
APL 84	36360	30090				
MAY 84	46830	35750				
JUN 84	47180	34600	23	14	7	12
JLY 84	28660	20220	14	15	17	7
AUG 84	44870	34450	21	18	10	10
SEP 84	47465	35800	26	26	1	3
OCT 84	57310	47740	26	22	3	9
NOV 84	55770	48250	27	26	2	4
TOTAL	612295	493200	137	121	40	45
DEC 84	66450	52310	29	29	2	2
JAN 85	63780	49930	29	26	2	5
FEB 85	49940	36940	23	13	5	15
MAR 85	57080	45760	30	24	2	7
APL 85	47530	35940	24	29	6	1
MAY 85	35170	23220	20	13	11	16
JUN 85	32800	25310	17	18	13	12
JLY 85	38420	27710	22	24	8	7
AUG 85	39880	31560	22	22	9	9
SEP 85	51190	39740	25	25	5	5
OCT 85	46410	32570	20	15	11	16
NOV 85	50780	39360	23	21	7	8
TOTAL	579430	440350	284	259	81	103
DEC 85	61600	48620	28	20	3	11
JAN 86	69100	50100	26	20	5	11
FEB 86	60200	47400	26	20	2	8
MAR 86	61080	46240	30	31	1	0
APL 86	42160	30540	25	27	3	3
MAY 86	38240	25580	23	23	7	8
JUN 86	30920	19200	20	20	10	6
JLY 86	36100	25400	24	20	7	3
AUG 86	37120	25800	20	20	11	11
SEP 86	47280	33680	23	13	6	18
OCT 86	47580	33870	24	23	7	8
NOV 86	51380	39630	21	13	7	17
TOTAL	582760	426060	290	250	69	104

Table XV - A ctd. White Cliffs Insolation, Operational State, Cloud, Diesel Only Operation.

DATE	Total Insolation kWh	Total Insolation above 700 W/m^2 kWh	No. of days worth operating on Solar	No. of days actual operation on Solar	No. of completely cloudy days	No. of days of Diesel Only operation
DEC 86	61690	50790	24	18	7	13
JAN 87	59660	48260	25	21	6	10
FEB 87	45030	34360	21	14	7	14
MAR 87	50800	41270	25	10	6	17
APL 87	49290	37160	27	24	3	6
MAY 87	44960	35080	22	20	9	11
JUN 87	29300	21100	14	12	16	18
JLY 87	48300	38130	26	26	5	3
AUG 87	34380	24900	16	9	15	15
SEP 87	55390	43920	24	22	6	7
OCT 87	49460	38280	23	19	8	10
NOV 87	50280	40890	22	9	8	14
TOTAL	578540	454140	269	204	96	138
DEC 87	56100	44300	23	17	8	8
JAN 88	74430	61900	29	21	2	10
FEB 88	64490	55630	27	18	2	11
MAR 88	46950	36140	24	16	7	15
APL 88	35590	26710	20	12	10	12
MAY 88	32500	20580	22	19	9	12
JUN 88	39300	31130	24	24	6	5
JLY 88	37070	26670	22	6	9	24
AUG 88	47100	36030	24	22	7	9
SEP 88	40080	29690	22	7	8	23
OCT 88	46550	34610	27	19	4	12
NOV 88	55770	46350	26	20	4	10
TOTAL	575930	449740	290	201	76	151
DEC 88	41470	33770	20	20	11	10
JAN 89	61810	53250	28	28	3	3
FEB 89	52500	43610	25	11	3	17

Table XV-B White Cliffs Solar Generation details, Auxiliary Energy, Boiler and Diesel Operation and Generation, Nett energy supplied to town.

DATE	Total energy generated by solar kWh	Total hours town suppld by solar power hrs	Total solar power to town kWh	Aux power reqd by solar station kWh	Total boiler Gen power kWh	Totl hrs boiler supp town hrs	Aux power req by boiler kWh	Total power gen by diesel kWh	Total power diesel to town kWh	Nett elec energy to town kWh	Average continuous power to town kW
DEC 83	1088	277			760	57		1320	1320	1160	
JAN 84	1700	426			232	16		1368	1368	984	
FEB 84	2176	483			48	3		1041	1041	1476	
MAR 84	951	288		873	53	3	45	1732		1408	
APL 84	649	258		536	19	1	14	1899		1292	
MAY 84	0	287		795	1184	58	795	1588		1676	
JUN 84	1370	82	545	870	290	18	60	3113	840	1720	
JLY 84	1070	69	455	930	560	40	140	3610	1145	1988	
AUG 84	2060	118	925	1175	270	19	70	3623	990	2232	
SEP 84	2387	255	1080	1550	69	5	8	3574	1100	2208	3.07
OCT 84	2554	314	1111	1405	128	8	23	3251	923	2084	2.80
NOV 84	2386	287	1050	1325	184	12	36	3125	850	1972	2.74
TOTAL	18391	3144	5166	9459	3797	240	1191	29244	9577	20200	
DEC 84	3197	436	1495	1380	19	1	5	2397	598	2100	2.82
JAN 85	2985	403	1355	1350	19	1	5	2730	677	2040	2.74
FEB 85	1877	236	910	1060	38	2	10	3376	1263	2190	3.26
MAR 85	2740	290	1438	1390	0	0	0	3948	1327	2730	3.67
APL 85	2800	302	1508	1250	18	1	5	3821	1558	3069	4.26
MAY 85	1350	184	766	1020	251	21	70	4635	2060	2933	3.94
JUN 85	1850	222	956	1120	0	0	0	4460	2004	2960	4.11
JLY 85	1650	217	837	1300	0	0	0	4654	2013	2850	3.83
AUG 85	1770	228	880	1160	0	0	0	4621	2040	2920	3.92
SEP 85	2170	272	1010	1240	0	0	0	3546	1365	2375	3.30
OCT 85	1810	230	828	1030	0	0	0	3523	1302	2129	2.86
NOV 85	2010	243	897	1130	0	0	0	3601	1278	2175	3.02
TOTAL	26209	3263	12880	14430	345	26	95	45312	17485	30471	
DEC 85	2175	224	1076	1245	0	0	0	4277	1681	2757	3.71
JAN 86	2140	240	1018	1010	0	0	0	4193	1738	2756	3.70
FEB 86	1566	166	714	775	0	0	0	4392	1923	2637	3.92
MAR 86	2525	259	1361	1645	0	0	0	4242	1719	3079	4.14
APL 86	2048	225	1053	1345	0	0	0	3714	1512	2565	3.56
MAY 86	1546	181	796	1066	0	0	0	4829	2281	3077	4.14
JUN 86	1627	168	855	1280	150	16	40	5729	3342	4307	5.98
JLY 86	1716	145	970	870	170	12	40	6144	3510	4610	6.20
AUG 86	1709	150	982	1040	0	0	0	4935	3248	4410	5.93
SEP 86	858	85	451	600	0	0	0	3531	2482	2933	4.07
OCT 86	1510	155	750	1250	120	6	25	4255	2243	3049	4.10
NOV 86	895	79	500	880	0	0	0	4656	2760	3261	4.53
TOTAL	20315	2077	10526	13006	440	34	105	54897	28439	39441	

Table XV-B (ctd) White Cliffs Solar Generation details, Auxiliary Energy, Boiler and Diesel Operation and Generation, Nett energy supplied to town.

DATE	Total energy generated by solar kWh	Total hours town suppld by solar power hrs	Total solar power to town kWh	Aux power reqd by solar station kWh	Total boiler Gen power kWh	Totl hrs boiler supp town hrs	Aux power reqd by boiler kWh	Total power gen by diesel kWh	Total power diesel to town kWh	Nett elec energy to town kWh	Average continuous power to town kW
DEC 86	1480	157	690	1190	0	0	0	5077	2514	3204	4.31
JAN 87	1738	157	1032	1280	0	0	0	6015	3287	4319	5.81
FEB 87	1459	114	816	890	0	0	0	5206	2853	3669	5.46
MAR 87	1466	138	721	286	357	25	82	5552	2806	3709	4.99
APL 87	1848	170	858	592	0	0	0	6723	4057	4915	6.83
MAY 87	1625	147	742	473	0	0	0	6836	4770	5512	7.41
JUN 87	763	63	390	182	0	0	0	7913	5560	5950	8.26
JLY 87	1437	132	730	322	126	9	30	7835	5410	6214	8.35
AUG 87	712	55	426	560	787	102	147	7438	4846	5780	7.77
SEP 87	2075	103	1050	440	143	11	20	7035	4274	5504	7.64
OCT 87	1663	94	963	233	134	10	24	7573	4588	5624	7.56
NOV 87	1144	83	668	224	616	42	104	7503	4794	5818	8.08
TOTAL	17410	1413	9086	6672	2163	199	407	80706	49759	60218	
DEC 87	2011	126	1289	364	837	44	167	7499	4789	6587	8.85
JAN 88	2296	157	1457	383	0	0	0	8290	5098	6555	8.81
FEB 88	2090	88	920	348	0	0	0	7766	5088	6008	8.63
MAR 88	1653	94	989	265	0	0	0	8207	5314	6303	8.47
APL 88	1164	64	647	283	640	45	60	7450	4877	5857	8.13
MAY 88	1175	52	530	218	0	0	0	8187	5315	5845	7.86
JUN 88	1619	71	803	343	81	6	8	7796	4922	5783	8.03
JLY 88	437	30	287	73	72	5	16	8581	6749	7084	9.52
AUG 88	1686	66	788	354	0	0	0	8394	5818	6606	8.88
SEP 88	381	25	237	63	0	0	0	8958	6589	6826	9.48
OCT 88	988	31	402	266	45	4	0	9080	6729	7149	9.61
NOV 88	893	30	358	254	45	4	0	8972	6458	6834	9.49
TOTAL	16393	834	8707	3214	1720	108	251	99180	67746	77437	
DEC 88	836	29	339	285	52	5	0	9911	7315	7675	10.32
JAN 89	2080	65	844	554	0	0	0	9434	6346	7190	9.66
FEB 89	1143	38	465	180	0	0	0	8563	6448	6913	10.29

Table XV - C White Cliffs Battery Operation, Solar station Feed and Cooling Water used, Diesel Fuel used.

DATE	Battery Efficiency %	Overall Storage System Efficiency %	Distilled Water used by battery litres	Steam system Feed-water used litres	Cooling water used litres	Diesel fuel used litres
DEC 83			80	320	50000	2806
JAN 84			0	430	0	1239
FEB 84			0	410	0	867
MAR 84			80	90	25000	1950
APL 84			0	70	0	1724
MAY 84			0	100	0	1571
JUN 84	60		0	150	50000	1756
JLY 84	58		0	160	0	1936
AUG 84	53		0	190	0	1791
SEP 84	64	35	0	180	130000	1870
OCT 84	64	33	60	400	0	1508
NOV 84	62	32	0	600	0	1608
TOTAL			220	3100	255000	20626
DEC 84	64	38	40	150	30000	1107
JAN 85	63	38	0	150	0	1178
FEB 85	63	37	0	90	0	1521
MAR 85	64	38	0	150	80000	1808
APL 85	64	41	60	140	0	1701
MAY 85	63	37	0	150	0	2177
JUN 85	62	41	0	150	0	2080
JLY 85	63	40	0	160	0	2245
AUG 85	63	40	30	160	0	2180
SEP 85	63	40	0	200	36000	1661
OCT 85	63	39	0	280	0	1906
NOV 85	63	40	0	280	0	1676
TOTAL			130	2060	146000	21240
DEC 85	63	41	60	260	54000	2143
JAN 86	60	39	0	200	0	1868
FEB 86	62	40	0	160	0	1900
MAR 86	62	41	60	270	81000	1983
APL 86	61	39	0	190	0	1902
MAY 86	62	39	0	150	0	2230
JUN 86	61	40	60	250	40000	2401
JLY 86	62	41	0	200	0	2524
AUG 86	62	41	0	220	0	2534
SEP 86	62	40	90	180	40000	1598
OCT 86	63	42	0	200	0	4271
NOV 86	62	38	0	180	0	5180
TOTAL			270	2460	215000	30534

Table XV - C ctd. White Cliffs Battery Operation, Solar station Feed and Cooling Water used, Diesel Fuel used.

DATE	Battery Efficiency %	Overall Storage System Efficiency %	Distilled Water used by battery litres	Steam system Feed-water used litres	Cooling water used litres	Diesel fuel used litres
DEC 86	62	39	45	220	136000	5906
JAN 87	61	38	0	280	0	5905
FEB 87	61	40	0	200	0	5515
MAR 87	62	39	20	210	20000	5810
APL 87	62	40	20	320	0	4990
MAY 87	61	39	20	260	0	5410
JUN 87	62	40	20	60	0	5850
JLY 87	61	39	20	210	0	5400
AUG 87	62	40	20	160	0	5459
SEP 87	62	42	20	220	30000	5213
OCT 87	64	43	20	180	0	5010
NOV 87	63	43	20	80	0	5091
TOTAL			225	2400	186000	65559
DEC 87	64	44	20	230	34000	5156
JAN 88	64	43	20	250	0	5527
FEB 88	64	44	20	240	0	5343
MAR 88	64	44	20	150	0	5410
APL 88	61	41	20	120	0	5257
MAY 88	61	40	20	180	0	5559
JUN 88	64	45	20	160	0	5234
JLY 88	64	43	20	40	0	6295
AUG 88	63	43	20	160	0	6211
SEP 88	64	43	20	30	50000	6394
OCT 88	61	40	20	120	0	6065
NOV 88	60	40	20	120	0	5970
TOTAL			240	1800	84000	68421
DEC 88	60	40	20	180	23000	
JAN 89	60	40	20	240	0	
FEB 89	60	40	20	105	0	

to revise the whole arrangement in later years but funds were not then available and the arrangement was not changed.

Table XVD indicates in detail where all the generated energy from both diesel and solar generation was used and reveals the overall situation. This throws a much better light on the solar results than might be gained from a superficial analysis of the gross energy flows without an awareness of the detailed practice.

As a consequence of the above, about one-half of the solar electrical energy generated was lost (2000 kWh/month) ie about as much as was sent out. This is a matter of system arrangement, not solar output limitations.

During the summer of 1983/84, town load could be maintained continuously from purely solar input without diesel support overnight, so long as each succeeding day was sunny. With ageing of receivers and the intrusion of other factors, such as the appearance of longer term problems not checked out earlier, nett ouput was reduced, then increased again as overall reliability was improved.

During a year of average insolation, the system ought to produce some 42 000 kWh nett with the achieved efficiency. The lower than average insolation in 1984, 1985 and 1986 produced 22 000 kWh (instead of 40 000 kWh), 25 000 kWh (instead of 35 000 kWh) and 20 000 kWh (instead of 34 000 kWh) respectively. Reasons for these lower outputs include:

- The non-linear relation between insolation and output.
- With low town load, all electrical units (and the diesel backup unit) were working very inefficiently at below 1/6 rated output much of the time.
- The low overall storage efficiency (some 50%) causing additional losses.
- System down time due mainly to waiting time for components to be replaced, largely commercial components — see Table XVI.

Almost all the operating days indicated as lost in Table XVI can be obviated as a result of action which follows from this experience. It is anticipated that 'prospective' outputs can be approached closely in the light of lessons learned, particularly since the problems encountered are not actual 'solar' problems.

7. Some Obvious Improvements

System performance may be improved in a number of ways (some of which are ongoing as described in Section 7) including:

- The establishment of a new set of spares adjusted to the experience over the past 4 years.
- Carrying out maintenance — where practicable — outside of sunshine hours.
- Reduction of auxiliary power.
- Addition of a fuel-fired superheater to allow low quality solar heat to be used.
- Generally introducing simplification and improving reliability.
- Introduce intermediate heat storage between the array and engine.

5.5.6 Solar System Costs

Since this is an experimental unit built on a one-off basis, conventional commercial cost assessments and comparisons are hardly appropriate; but they are included as a means for

(b) Response to Insolation Changes

System output follows insolation changes with time delays caused by the various time constants involved in components — absorbers, duct system and engine, as illustrated in Figure 77.

During operation in intermittent cloud, the system will continue providing energy even after a cloud has obscured the sun, drawing on the heat stored in various components. Eventually, if cloud persists, engine speed will fall below synchronous and the engine will coast along at successively lower speeds until it runs out of steam, when it will stop — power for the auxiliaries and the load being provided from the battery. When adequate steam conditions are re-established, the engine will start automatically and take over supply of the load from the battery.

In the afternoon cloud conditions often met at White Cliffs (see Section 2), this mode of operation — continual starting and stopping — may continue for several hours.

Decisions have to be taken as to whether or not it is worthwhile to run in the period between clouds and what to do during the passage of clouds. If the system is allowed to run on in such circumstances, the nett energy gained should be worthwhile in relation to the auxiliary power used during the cloudy patches; actual insolation level plays a part in this decision. During haze, for example as in Figures 8 and 9 in which insolation does not fall to zero, the conditions are somewhat different since the engine does not stop, but the overall generation efficiency is low; again the total useful energy gathered during the day should be worthwhile.

Operating strategies have been developed for various insolation conditions to allow decisions to be taken more readily; usually it is deemed not worthwhile to operate in heavy rapidly varying intermittent cloud and the system may be closed down for a time. The occurence of such conditions can usually be predicted by experience.

(c) Load Change Effects

The general problems of load on the system are illustrated in Section 5.4 and daily load curves are shown in Figures 69–72. While average system loads may be relatively uniform over a period, due to the small number of users and their varying individual use patterns, quite substantial load changes can occur on the system. There are few, if any, problems associated with such changes since the engine/battery-store combination permits a continuous sharing of load between the two sources. If engine output is inadequate to meet load demands at any moment, the automatic torque balance system causes the DC machine to draw energy from the battery to assist in supplying the load; at other times the same control system causes excess energy to be stored in the battery. These transient changes are largely unnoticed by users beyond a very small frequency variation (better than $\pm 1\%$).

(d) Load Transfer Between Solar and Diesel Systems

More-drastic transients occur when changing over supply from diesel to solar or vice versa, when operating conditions as in Section 5.5.3(1) and Figure 45(b) may occur, resulting in larger frequency swings for a few seconds.

(e) Overload Responses

Various overload conditions can occur to cause the system to discontinue supply, when the diesel set can take over. Such operation is discussed in Sections 3.1.5, 3.3.6, 3.3.15, 3.5.2, 3.5.5, 3.10, 5.5.3, but in practice, shutdown from overload has been extremely rare and has not been due to overheating of the AC or DC machines or batteries, nor due to limitations in supply. On one occasion, a DC machine over-current trip has followed a non-tripping of the main station breaker (set at 25 kW) when a town load of probably well over 30 kW has been in place, possibly due to user action to circumvent operation of the individual breaker. Such an overload condition has also put the diesel unit out of action on occasion.

(f) Useful Transient Operating Strategies

The most productive strategy to be employed during any transient condition is one which reduces duration of the transient to a minimum and/or maximises integrated output over the period, or at least minimises auxiliary energy used in the event of no nett output being available.

It is not convenient to have individual automatic controls for the various steam system auxiliaries, otherwise a fine tuning of auxiliary power could be based on a switching on or off of particular auxiliaries. It is also basically imprudent to switch off the feedwater pump (and consequently the vacuum pump) during periods of cloud on the supposition that no feedwater needs to circulate in the absorbers when the sun is not shining, since not all absorbers are necessarily out of the sun together and would therefore have only their overheat/offsteer protection. Moreover, proper feedwater flow would be re-established somewhat after the onset of sunshine again, causing undue heating.

On the other hand, it is beneficial to reduce feedwater flow in accordance with reduced insolation on the grounds that during intermittent cloud the general operating temperatures in the array, ducts and engine, are thereby maintained at a higher level than they would be if too high a feedwater flow during cloudy periods were retained. This strategy ensures that the whole system becomes operational more rapidly when the sun shines again and so minimises auxiliary energy and increases useful output.

In this mode, general array offsteer (in the event that the insolation monitor is shaded by cloud but more than one dish is not) is prevented by increasing absorber temperatures causing increasing feedwater flow as a result of the automatic control system function overriding the insolation monitor signal.

Significant auxiliary energy is used during early morning starting, particularly in winter when insolation levels are low, so requiring a relatively long time for the various parts of the system to reach operating temperatures. There is consequently an optimum time for initiation of the start. Unfortunately, any but an approximate best start time requires accurate prediction of the insolation variation from sunrise, clearly an extremely difficult requirement. Nevertheless it has proved useful to decide on the previous evening whether or not to allow the solar system to start at the normally set clock time, a decision taken on the basis of the weather predictions and on local weather conditions. It is not often that a mistake is made to disable the system on a particular day but, if such a mistake is made, the system can be allowed to start later, in which case the transient starting period is much shorter than it otherwise would have been for an earlier start since a later start occurs in the presence of a high insolation level.

Except in the summers of the earlier operating years (when town loads were low), the solar system usually starts at a time when the town load comes from the diesel set (the battery having been 'discharged'), and the solar system auxiliaries are arranged (as indicated in Sections 3.5.5. and 3.10) to be supplied also from the diesel set. This strategy is advantageous in that the battery is not run down by the start cycle unless there is adequate charge stored; it also allows the solar generator to charge up the battery quickly to the voltage (approximately 327 V) which causes the diesel set to cut out but with still a reasonable battery charge to prevent the diesel set from having to start again soon in the event of cloud obscuring the sun, and to prevent frequent diesel stops and starts in intermittent cloud. A further advantage arises from the direct generation and supply of auxiliary power without the inefficiency resulting from the use of battery storage.

The situation regarding starting and operation at other times is illustrated in Figure 54, which shows typical conditions involving solar operation during the day, followed by battery supply to the load, then diesel operation prior to further solar generation. If the solar output is adequate, the battery continues to supply the load until the solar system starts the next day (otherwise the diesel takes over early in the morning, as illustrated).

Auxiliary power used when the solar system stops can be effectively reduced to zero on initiation of a stop sequence either on fault conditions (involving offsteer) or on clock command at the end of a generating day. This is not currently the strategy used because of the perceived advantage in clearing oil from the feedwater by allowing the auxiliaries to run on for about 10 minutes or so, the time taken for the array to park in the south-east orientation ready for the next day. Energy so lost from the batteries amounts to some 0.5 kWh during the stopping sequence.

This mode of stopping differs from that involving operation during intermittent cloud when the auxiliaries do not stop, not even if the cloud lasts for tens of minutes; no stop signal is given, the engine running down due to lack of steam and starting again when adequate steam quality is re-established. In this case the system may not be inactive for very long during the cloudy periods (the engine may not even stop) and it would be inappropriate in many or most cases to stop auxiliaries.

However, when cloudy periods are relatively long, say more than 20 minutes at a time, a decision has to be taken about the nett energy generated and the benefits of operation at all, since long cloud spaced by short sunshine periods results in little nett generation gain. In such cases, however, it can be worth switching off auxiliaries. This is difficult to achieve by automatic control systems which have no sunshine predictive properties. The strategy currently used is to allow the system to run when sunny periods are relatively longer than cloud but when both are of not long duration (upto 20 minutes). For cloud of long duration with short bursts of sunshine, the system is not run; for long periods of both cloud and sun the system is switched off during the cloud and switched on for the sunshine, so long as insolation levels are reasonable.

The development of transient operating strategies is dependent on the actual installed capabilities for automatic control; this is an area of study which still has much potential for improved understanding and development as regards practical application.

5. Non-Linear Input-Output Relationship

Figures 81 and 82 and Table X well illustrate the essentially non-linear relationship between solar system input and output, reasons for which are discussed in Sections 5.5.5(2) and 5.5.5(3); but briefly follow from the fact that the system thermal losses depend mainly on temperature and that mechanical losses depend on engine speed, while efficiency depends on throughput and losses. With fixed temperatures and engine speed, efficiency tends to improve with throughput (insolation). A consequence of the array and engine characteristics is that whereas efficiency of all components improves with throughput, the efficiency of absorbers and heat transport ducts increase with decrease of temperature, while engine efficiency increases with temperature; as a result, overall optimum output and efficiency of the system is a compromise between array, duct and engine, contributing to the non-linear behaviour.

Because engine mechanical losses must be supplied and some of the generated energy must drive the station auxiliaries, a further non-linear feature is introduced, leading to the fact that system operation for low insolation levels much below 400 W/m^2 is not profitable, as little or no nett energy is generated.

As is evident from the curves of Figure 82, output rises increasingly more rapidly as insolation increases from 400 W/m^2 for the present White Cliffs configuration and it is a matter of careful perceptive design as to what collection areas and other parameters are chosen to get the most from a given system on an annual basis.

These aspects have an important bearing on the insolation levels chosen to provide 'rated output', as discussed in Section 5.5.7.

6. Annual Energy Generated

Table XV lists the energy generated by the solar station for each of the years 1984, 1985, 1986 and allows comparison between insolation and output. 'Prospective' values are also indicated, that is, those outputs which would be achieved if the hardware systems are all working with no impediments for a whole year of 'average' insolation.

The metering diagram is shown in Figure 83, setup in accordance with contractual arrangements for the project.

Tables XVA to XVC summarize the station energy flow, water use, etc as reported in the various Quarterly Progress Reports presented since December 1983.

Table XVD details the energy flows specifically for 1985 to identify the 'missing energy' in the overall system, which has sometimes been misunderstood and held against the solar system. In fact, by a simple rearrangement of connections and operating strategy, the solar system can provide nearly 100% more useful energy when assessed on a load supply basis.

On the Solar Output

The information in Tables XVA to XVC summarizes the operation and performance integrated quantitites for the station over the period 1983 to 1989.

An analysis is presented of the year 1985 as an illustration of some of the features of the system and some of the imperfections which depend not on the solar component, but on the way the operating strategies were organized.

Suffice to say that the objective was to cause the station to operate effectively in the first instance before attempting optimization or considering the installation more than an experiment but rather commercial-like equipment (which it was never intended to be — that was the task of later developments).

In the process, a number of loads were connected to the system which depended on the particular way the diesel set was connected: Essentially the solar electrical machines have have been run 24 hours a day irrespective of whether the solar system was running or not. Other loads, such as array battery chargers, also ran continuously as did some loads not related to the solar station at all.

As a consequence, the auxiliary power apparently used by the solar station appeared to be extremely large, whereas the real situation was quite different. We had plans

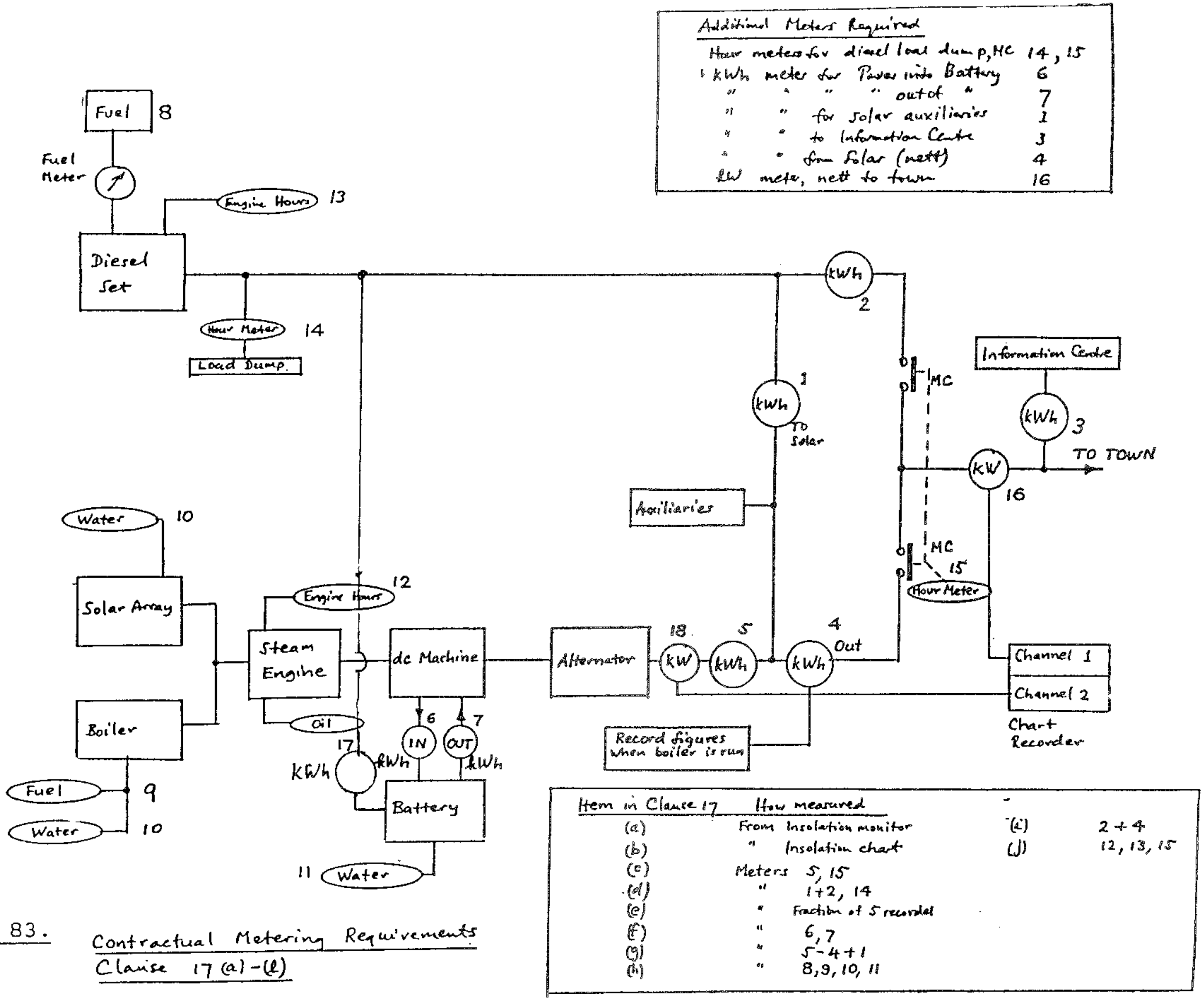


Figure 83. Contractual Metering Requirements Clause 17 (a)-(l)

TABLE XV — WHITE CLIFFS SOLAR kWh GENERATED AND GENERATION COSTS

SOLAR	1984	1985	1986	PROSPECTIVE
Equipment and Expendable Materials \$	2 659	2 048	3 467	1 000
Local Contractors \$	15 312	12 296	9 196	5 000
Communications \$	810	922	541	100
Travel \$	1 334	625	384	—
Total O&M Costs \$	20 115	15 891	13 588	6 100
Solar Station Availability	70%	93%	86%	100%
Insolation — Total kWh/m^2	2 282	2 091	2 120	2 380
Insolation — Total above 700 (W/m^2 kWh/m^2)	1 828	1 588	1 557	1 900
(1) Electrical Energy Generated kWh (Solar-generated incl. auxiliaries)	20 500	25 187	19 620	38 000
Costs of Generated Energy:				
O&M Costs ¢/kWh	91	63	69	16
10% Capital Costs ¢/kWh(2)	141	124	159	82
Total Costs ¢/kWh	232	187	228	98
(1) Nett Energy to Town kWh (including through battery)	10 193	12 461	10 140	30 000
Costs of Energy to Town:				
O&M Costs ¢/kWh	197	128	134	20
10% Capital Costs ¢/kWh(2)	306	250	308	104
Total Costs ¢/kWh	503	378	442	124

(1) In 1986, continuing diesel problems prevented solar system from operating at times; waiting for replacement parts (commercial) to arrive also put solar supply out of action for 46 days on items not expected to be troublesome. Output was consequently low.

(2) On Capital Cost of \$312 000 (1981).

Table XV-A - White Cliffs Insolation, Operational State, Cloud, Diesel-only operation

DATE	Total Insolation kWh	Total Insolation above 700 W/m^2 kWh	No. of days worth operating on Solar	No. of days actual operation on Solar	No. of completely cloudy days	No. of days of Diesel Only operation
DEC 83	57800	48400				
JAN 84	59700	49200				
FEB 84	71500	57500				
MAR 84	58850	51200				
APL 84	36360	30090				
MAY 84	46830	35750				
JUN 84	47180	34600	23	14	7	12
JLY 84	28660	20220	14	15	17	7
AUG 84	44870	34450	21	18	10	10
SEP 84	47465	35800	26	26	1	3
OCT 84	57310	47740	26	22	3	9
NOV 84	55770	48250	27	26	2	4
TOTAL	612295	493200	137	121	40	45
DEC 84	66450	52310	29	29	2	2
JAN 85	63780	49930	29	26	2	5
FEB 85	49940	36940	23	13	5	15
MAR 85	57080	45760	30	24	2	7
APL 85	47530	35940	24	29	6	1
MAY 85	35170	23220	20	13	11	16
JUN 85	32800	25310	17	18	13	12
JLY 85	38420	27710	22	24	8	7
AUG 85	39880	31560	22	22	9	9
SEP 85	51190	39740	25	25	5	5
OCT 85	46410	32570	20	15	11	16
NOV 85	50780	39360	23	21	7	8
TOTAL	579430	440350	284	259	81	103
DEC 85	61600	48620	28	20	3	11
JAN 86	69100	50100	26	20	5	11
FEB 86	60200	47400	26	20	2	8
MAR 86	61080	46240	30	31	1	0
APL 86	42160	30540	25	27	3	3
MAY 86	38240	25580	23	23	7	8
JUN 86	30920	19200	20	20	10	6
JLY 86	36100	25400	24	20	7	3
AUG 86	37120	25800	20	20	11	11
SEP 86	47280	33680	23	13	6	18
OCT 86	47580	33870	24	23	7	8
NOV 86	51380	39630	21	13	7	17
TOTAL	582760	426060	290	250	69	104

Table XV - A ctd. White Cliffs Insolation, Operational State, Cloud, Diesel Only Operation.

DATE	Total Insol-ation kWh	Total Insolation above 700 W/m^2 kWh	No. of days worth operat-ing on Solar	No.of days actual operat-ion on Solar	No. of complet-ely cloudy days	No. of days of Diesel Only operat-ion
DEC 86	61690	50790	24	18	7	13
JAN 87	59660	48260	25	21	6	10
FEB 87	45030	34360	21	14	7	14
MAR 87	50800	41270	25	10	6	17
APL 87	49290	37160	27	24	3	6
MAY 87	44960	35080	22	20	9	11
JUN 87	29300	21100	14	12	16	18
JLY 87	48300	38130	26	26	5	3
AUG 87	34380	24900	16	9	15	15
SEP 87	55390	43920	24	22	6	7
OCT 87	49460	38280	23	19	8	10
NOV 87	50280	40890	22	9	8	14
TOTAL	578540	454140	269	204	96	138
DEC 87	56100	44300	23	17	8	8
JAN 88	74430	61900	29	21	2	10
FEB 88	64490	55630	27	18	2	11
MAR 88	46950	36140	24	16	7	15
APL 88	35590	26710	20	12	10	12
MAY 88	32500	20580	22	19	9	12
JUN 88	39300	31130	24	24	6	5
JLY 88	37070	26670	22	6	9	24
AUG 88	47100	36030	24	22	7	9
SEP 88	40080	29690	22	7	8	23
OCT 88	46550	34610	27	19	4	12
NOV 88	55770	46350	26	20	4	10
TOTAL	575930	449740	290	201	76	151
DEC 88	41470	33770	20	20	11	10
JAN 89	61810	53250	28	28	3	3
FEB 89	52500	43610	25	11	3	17

Table XV-B White Cliffs Solar Generation details, Auxiliary Energy, Boiler and Diesel Operation and Generation, Nett energy supplied to town.

DATE	Total energy generated by solar kWh	Total hours town suppld by solar power hrs	Total solar power to town kWh	Aux power reqd by solar station kWh	Total boiler Gen power kWh	Totl hrs boiler supp town hrs	Aux power req by boiler kWh	Total power gen by diesel kWh	Total power diesel to town kWh	Nett elec energy to town kWh	Average continuous power to town kW
DEC 83	1088	277			760	57		1320	1320	1160	
JAN 84	1700	426			232	16		1368	1368	984	
FEB 84	2176	483			48	3		1041	1041	1476	
MAR 84	951	288		873	53	3	45	1732		1408	
APL 84	649	258		536	19	1	14	1899		1292	
MAY 84	0	287		795	1184	58	795	1588		1676	
JUN 84	1370	82	545	870	290	18	60	3113	840	1720	
JLY 84	1070	69	455	930	560	40	140	3610	1145	1988	
AUG 84	2060	118	925	1175	270	19	70	3623	990	2232	
SEP 84	2387	255	1080	1550	69	5	8	3574	1100	2208	3.07
OCT 84	2554	314	1111	1405	128	8	23	3251	923	2084	2.80
NOV 84	2386	287	1050	1325	184	12	36	3125	850	1972	2.74
TOTAL	18391	3144	5166	9459	3797	240	1191	29244	9577	20200	
DEC 84	3197	436	1495	1380	19	1	5	2397	598	2100	2.82
JAN 85	2985	403	1355	1350	19	1	5	2730	677	2040	2.74
FEB 85	1877	236	910	1060	38	2	10	3376	1263	2190	3.26
MAR 85	2740	290	1438	1390	0	0	0	3948	1327	2730	3.67
APL 85	2800	302	1508	1250	18	1	5	3821	1558	3069	4.26
MAY 85	1350	184	766	1020	251	21	70	4635	2060	2933	3.94
JUN 85	1850	222	956	1120	0	0	0	4460	2004	2960	4.11
JLY 85	1650	217	837	1300	0	0	0	4654	2013	2850	3.83
AUG 85	1770	228	880	1160	0	0	0	4621	2040	2920	3.92
SEP 85	2170	272	1010	1240	0	0	0	3546	1365	2375	3.30
OCT 85	1810	230	828	1030	0	0	0	3523	1302	2129	2.86
NOV 85	2010	243	897	1130	0	0	0	3601	1278	2175	3.02
TOTAL	26209	3263	12880	14430	345	26	95	45312	17485	30471	
DEC 85	2175	224	1076	1245	0	0	0	4277	1681	2757	3.71
JAN 86	2140	240	1018	1010	0	0	0	4193	1738	2756	3.70
FEB 86	1566	166	714	775	0	0	0	4392	1923	2637	3.92
MAR 86	2525	259	1361	1645	0	0	0	4242	1719	3079	4.14
APL 86	2048	225	1053	1345	0	0	0	3714	1512	2565	3.56
MAY 86	1546	181	796	1066	0	0	0	4829	2281	3077	4.14
JUN 86	1627	168	855	1280	150	16	40	5729	3342	4307	5.98
JLY 86	1716	145	970	870	170	12	40	6144	3510	4610	6.20
AUG 86	1709	150	982	1040	0	0	0	4935	3248	4410	5.93
SEP 86	858	85	451	600	0	0	0	3531	2482	2933	4.07
OCT 86	1510	155	750	1250	120	6	25	4255	2243	3049	4.10
NOV 86	895	79	500	880	0	0	0	4656	2760	3261	4.53
TOTAL	20315	2077	10526	13006	440	34	105	54897	28439	39441	

Table XV-B (ctd) White Cliffs Solar Generation details, Auxiliary Energy, Boiler and Diesel Operation and Generation. Nett energy supplied to town.

DATE	Total energy generated by solar kWh	Total hours town suppld by solar power hrs	Total solar power to town kWh	Aux power reqd by solar station kWh	Total boiler Gen power kWh	Totl hrs boiler supp town hrs	Aux power reqd by boiler kWh	Total power gen by diesel kWh	Total power diesel to town kWh	Nett elec energy to town kWh	Average continuous power to town kW
DEC 86	1480	157	690	1190	0	0	0	5077	2514	3204	4.31
JAN 87	1738	157	1032	1280	0	0	0	6015	3287	4319	5.81
FEB 87	1459	114	816	890	0	0	0	5206	2853	3669	5.46
MAR 87	1466	138	721	286	357	25	82	5552	2806	3709	4.99
APL 87	1848	170	858	592	0	0	0	6723	4057	4915	6.83
MAY 87	1625	147	742	473	0	0	0	6836	4770	5512	7.41
JUN 87	763	63	390	182	0	0	0	7913	5560	5950	8.26
JLY 87	1437	132	730	322	126	9	30	7835	5410	6214	8.35
AUG 87	712	55	426	560	787	102	147	7438	4846	5780	7.77
SEP 87	2075	103	1050	440	143	11	20	7035	4274	5504	7.64
OCT 87	1663	94	963	233	134	10	24	7573	4588	5624	7.56
NOV 87	1144	83	668	224	616	42	104	7503	4794	5818	8.08
TOTAL	17410	1413	9086	6672	2163	199	407	80706	49759	60218	
DEC 87	2011	126	1289	364	837	44	167	7499	4789	6587	8.85
JAN 88	2296	157	1457	383	0	0	0	8290	5098	6555	8.81
FEB 88	2090	88	920	348	0	0	0	7766	5088	6008	8.63
MAR 88	1653	94	989	265	0	0	0	8207	5314	6303	8.47
APL 88	1164	64	647	283	640	45	60	7450	4877	5857	8.13
MAY 88	1175	52	530	218	0	0	0	8187	5315	5845	7.86
JUN 88	1619	71	803	343	81	6	8	7796	4922	5783	8.03
JLY 88	437	30	287	73	72	5	16	8581	6749	7084	9.52
AUG 88	1686	66	788	354	0	0	0	8394	5818	6606	8.88
SEP 88	381	25	237	63	0	0	0	8958	6589	6826	9.48
OCT 88	988	31	402	266	45	4	0	9080	6729	7149	9.61
NOV 88	893	30	358	254	45	4	0	8972	6458	6834	9.49
TOTAL	16393	834	8707	3214	1720	108	251	99180	67746	77437	
DEC 88	836	29	339	285	52	5	0	9911	7315	7675	10.32
JAN 89	2080	65	844	554	0	0	0	9434	6346	7190	9.66
FEB 89	1143	38	465	180	0	0	0	8563	6448	6913	10.29

Table XV - C White Cliffs Battery Operation, Solar station Feed and Cooling Water used, Diesel Fuel used.

DATE	Battery Effic- iency %	Overall Storage System Effic- iency %	Dist- illed Water used by battery litres	Steam system Feed- water used litres	Cooling water used litres	Diesel fuel used litres
DEC 83			80	320	50000	2806
JAN 84			0	430	0	1239
FEB 84			0	410	0	867
MAR 84			80	90	25000	1950
APL 84			0	70	0	1724
MAY 84			0	100	0	1571
JUN 84	60		0	150	50000	1756
JLY 84	58		0	160	0	1936
AUG 84	53		0	190	0	1791
SEP 84	64	35	0	180	130000	1870
OCT 84	64	33	60	400	0	1508
NOV 84	62	32	0	600	0	1608
TOTAL			220	3100	255000	20626
DEC 84	64	38	40	150	30000	1107
JAN 85	63	38	0	150	0	1178
FEB 85	63	37	0	90	0	1521
MAR 85	64	38	0	150	80000	1808
APL 85	64	41	60	140	0	1701
MAY 85	63	37	0	150	0	2177
JUN 85	62	41	0	150	0	2080
JLY 85	63	40	0	160	0	2245
AUG 85	63	40	30	160	0	2180
SEP 85	63	40	0	200	36000	1661
OCT 85	63	39	0	280	0	1906
NOV 85	63	40	0	280	0	1676
TOTAL			130	2060	146000	21240
DEC 85	63	41	60	260	54000	2143
JAN 86	60	39	0	200	0	1868
FEB 86	62	40	0	160	0	1900
MAR 86	62	41	60	270	81000	1983
APL 86	61	39	0	190	0	1902
MAY 86	62	39	0	150	0	2230
JUN 86	61	40	60	250	40000	2401
JLY 86	62	41	0	200	0	2524
AUG 86	62	41	0	220	0	2534
SEP 86	62	40	90	180	40000	1598
OCT 86	63	42	0	200	0	4271
NOV 86	62	38	0	180	0	5180
TOTAL			270	2460	215000	30534

Table XV - C ctd. White Cliffs Battery Operation, Solar station Feed and Cooling Water used, Diesel Fuel used.

DATE	Battery Efficiency %	Overall Storage System Efficiency %	Distilled Water used by battery litres	Steam system Feed-water used litres	Cooling water used litres	Diesel fuel used litres
DEC 86	62	39	45	220	136000	5906
JAN 87	61	38	0	280	0	5905
FEB 87	61	40	0	200	0	5515
MAR 87	62	39	20	210	20000	5810
APL 87	62	40	20	320	0	4990
MAY 87	61	39	20	260	0	5410
JUN 87	62	40	20	60	0	5850
JLY 87	61	39	20	210	0	5400
AUG 87	62	40	20	160	0	5459
SEP 87	62	42	20	220	30000	5213
OCT 87	64	43	20	180	0	5010
NOV 87	63	43	20	80	0	5091
TOTAL			225	2400	186000	65559
DEC 87	64	44	20	230	34000	5156
JAN 88	64	43	20	250	0	5527
FEB 88	64	44	20	240	0	5343
MAR 88	64	44	20	150	0	5410
APL 88	61	41	20	120	0	5257
MAY 88	61	40	20	180	0	5559
JUN 88	64	45	20	160	0	5234
JLY 88	64	43	20	40	0	6295
AUG 88	63	43	20	160	0	6211
SEP 88	64	43	20	30	50000	6394
OCT 88	61	40	20	120	0	6065
NOV 88	60	40	20	120	0	5970
TOTAL			240	1800	84000	68421
DEC 88	60	40	20	180	23000	
JAN 89	60	40	20	240	0	
FEB 89	60	40	20	105	0	

Indeed we conclude that the solar system is extremely reliable; the steam system - after initial problems - is also very reliable; the engine has become reliable as a result of development in the field. The most interesting factor which has emerged is the unreliability of many commercial components - pumps, freewheel clutch and other items 'off the shelf' which have been on the market a long time.

In the context of developing solar collection, concentration and conversion, the array has proved remarkably successful in all aspects over the years.

5.8.2 Lifetime of Components and Maintenance Requirements

Normal mechanical and electrical maintenance procedures are appropriate for most of the station components which, when given such attention, will provide years of service.

The mirrors are cleaned as required, generally once per month or more frequently on some occasions. This process takes only a few minutes per dish.

Recent measurements on reflectivity have shown that the mirror reflectivities have dropped on the average from 0.86 to 0.77-0.79. Interestingly, most of the mirrors have deteriorated but little, the drop in average reflectivity being due to some tiles which have discoloured to a grey tone indicating a deterioration in reflective surface. We rejected some mirrors before assembly in 1980/81 but should have been more critical and selective of imperfect mirroring. On the whole, the mirrors are expected to last many more years.

Absorber life has ben patchy with early designs but with the latest improved designs resulting from a better understanding of the influence of thermal stress and fatigue, lifetime is expected to increase from a year or two to many years - the precise robustness has yet to be determined.

The engine, which has required the most attention, is now robust and reliable. The valve mechanisms should be inspected every 1000 hours and components replaced after several thousand hours, depending on service conditions.

The auxiliary boiler has seen relatively few hours of operation (about 500), but needed refurbishing recently because - apart from the superheater which uses stainless steel tubes (and is still intact) - the low temperature tubes which include the boiling zone, are of mild steel and had corroded. This unit gives a high conversion efficience of some 75-85once a steamline was provided to dislodge soot build-up after every 10 or so hours of operation.

6 ACHIEVEMENTS AND ASSESSMENTS

Much has emerged from the White Cliffs project which has made considerable impact on aspects of solar thermal power.

6.1 Achievements

1. The station supplies White Cliffs with electrical power with an overall reliability not inferior to that applying on the NSW grid. The system overall and its components are improving as remaining outstanding matters are resolved.
2. The station works on a continuous stand-alone basis, the only such installation of which we are aware. Experience now shows a decreasing O&M component; this O&M can be handled by local people.
3. In view of (b), we consider the technology is very suitable for the application.
4. Objectives of the project have been met — the necessary information and scientific, technological and economic data and understanding have been attained.
5. Of its generation, it was by far the cheapest on a per unit basis.
6. Development from conception through the research, development, experimentation and useful supply stages had been achieved largely in one step.
7. Cost potential for the next generation units and the nature of these units have been revealed and appear attractive, pointing to competitive viability with diesel sets in appropriate areas.
8. The concepts selected and the underlying principles have turned out to be very successful and need not be changed.
9. Many parts of the system have involved original development of significance for future work; they have a wider application in their own right. For example,
    - Rotary joints for conveying simultaneously hot and cold fluids via the two axes of rotation.
    - A special skimmer for removing surface (floating) oil from the feedwater.
    - A simple reliable automatic torque balancing system.
    - A simple system for enabling energy flow control between the various parts of the system.
    - And others.
10. We have the most real-world operating hours of any solar thermal system of which we are aware.
11. The technology developed is 'appropriate for relatively unsophisticated production and running'.
12. The project has highlighted the value of going out into the field at an early stage in order to experience and understand the realistic situation and to develop design appropriately.

13. A good awareness (and statistical data) has been developed of the nature, extent and influence of environmental effects. Effect of solar radiation on materials has been most remarkably demonstrated, revealing unexpected weaknesses and strengths which provide valuable lessons for future systems. Good understanding of the approaches necessary to run solar steam systems has been attained.

    Hitherto unavailable design data has been acquired; a set of design strategies as well as O&M consraints and strategies has been assembled; design parameters for effective operation have been revealed.

14. It has been demonstrated that an array of collectors working on a modular basis can be operated successfully, whether for electricity generation or industial process heat; modules can be removed from service for attention without upsetting the rest of the system or its integrity.

    Because of this modularity, although the results have been attained on a relatively small system, they carry over to much larger systems.

15. It has become very clear that dish sizes must be increased greatly (say to 300 m^2 aperture) in order to adequately increase economic viability when economy of size, as in most systems, becomes well apparent. Cost analyses of such dishes appear very attractive, targeting a cost per square metre of $150 Australia. In these circumstances, industrial process heat may become available in sunny areas for some 0.6¢/MJ or 2¢ per kWh thermal.

16. The project has resulted in development of a very successful high performance steam engine whose application areas seem extensive. Such an engine, when combined with a large dish (as in (15) above), may produce electricity at less than 20¢ per kWh on a production basis.

17. The White Cliffs Project is well known overseas;this has produced tangible benefits through the desire for close collaboration, as indicated below.

18. We consider it is now likely that settlements without existing grids can be supplied reliably and economically with solar thermal power, this being a more appropriate approach. Settlements on the grid, but at the end of long lines, might also well benefit from such solar power.

19. The project has already resulted in several 'spinoffs' including:

    - Interest generated in our dishes at the 1982 World's Fair — Energy Expo, Knoxville Tennessee, May to November 1982. The Department of Works built two of our dishes and mounted these in front of the Australian Pavillion.
    - We are collaborating with the University of the South Pacific (Suva) on producing a rural village power supply using our engine and probably dishes/wind enhancement. Crop wastes may be suitable to raise steam.
    - At the request of the Maryborough (VIC) Council, we set up one of our 5 -metre dishes for ascertaining the feasibility of supplying the hospital with low quality steam.
    - At the request of the Lizard Island (northern Australia) Research Station of the Australian Museum,, we established in 1984 a solar/wind monitoring station preparatory to designing a dish/engine system for the island (if climatic conditions prove suitable).

- At the instigation of Allco Steel of Tomago (NSW), we are collaborating with a view to developing large dishes and other technology for the utilization of high temperature solar energy.
- The solar firm Power Kinetics Inc (Troy NY) has been granted a licence to market the ANU engine technology for solar and other applications, recently purchased from us an improved engine which they intend to use
- At the invitation of Power Kinetics Inc, we put in a joint bid to the US Department of Energy for the Molokai Solar Power Station. Our joint bid was successful and the project (engines supplied by us and collectors supplied by Power Kinetics) successfully completed tests at the US Department of Energy test site in Albuquerque (New Mexico) in August 1988.
- The considerable perceived versatility of our engine has also resulted in other projects being considered, taking advantage of its cogeneration possibilities, waste heat, waste crop and fuel utilization, direct solar water pumping and remote area power supply. .

6.2 Lessons and Significance

With proper attention to the level of technological sophistication and detailed design, it is quite practicable, cost-effective and competitive now to supply sunny areas reliably with paraboloidal dish solar thermal power and for local people to operate and maintain such systems.

There is great scope and potential for producing more economical systems which should have more widespread viability.

Practicability, reliability and cost-effectiveness can be achieved without going to exotic systems, conversion cycles or having to rely on massive production runs, although these additional factors may assist in the long term.

White Cliffs has been an effective starting point for further development. Even as a first generation one-off system it compares well with its associated diesel generator operating under the same conditions. While 25 kWe may seem small, because of its 14 dishes and other features characteristic of much larger systems, lessons carry over to such systems. Moreover, the relatively low investment involved allows bolder experiments and concepts to be tried without undue anxiety, so allowing broader and more rapid investigation.

Assessment of the system has been hampered initially by the light town load with consequent low efficiency of all components; the large number of components (and 14 dishes) has needlessly increased O&M costs.

We were responsible for the conception, design, development, construction, installation, commissioning and later the operation, maintenance and updating of the station; this close and continuing association, we believe, has been a major factor in success and in gaining lessons for next generation systems.

6.2.1 The Economy of Size

A useful lesson emerging has been appreciation of the effect of size on cost-effectiveness, a feature in many engineering systems. But what the dimensions of 'large' happen to be depends on many factors. The White Cliffs dish units, in this context, are far too small.

Generally, heat losses depend on temperature, not on throughput of heat. If temperatures are set, systems with greater throughput will (other aspects aside) have much the same losses and therefore higher efficiency. This is well illustrated in Figures 29 and 81 and for the engine in Figure 43. Regarding the latter, mechanical losses depend on speed which in this case is constant; efficiency will therefore be higher at a set temperature if the throughput is higher, as is evident.

Overall, larger dishes and larger engines will tend to be more cost-effective. It is not just that for the same output smaller units have more total components which reduce reliability and increase O&M, but more important is the fact that small units carry severe cost constraints which do not allow more sophisticated designs and, therefore, more effective units to be produced; efficiency accordingly tends to be inherently lower for smaller units, as an additional factor to the effect on efficiency of throughput.

Probably the most consequential matter emerging from our studies is the economy of size with influence on shape and configuration — this is in agreement with overseas conclusions, and is already having a marked effect on new generation designs, target performance and cost-effectiveness.

6.3 Impact of the Technology

The station has had a significant influence on the development of paraboloidal dish solar thermal systems and on the use of high performance robust inflow steam engines. The White Cliffs derived steam technology is the most developed and cost effective available, pending realisation of several new engine systems. Current applications include:

- Licensing a USA firm to market the engine technology (sizes ranging from kilowatts to megawatts) for solar use, energy conservation and for village power supplies, with involvement of an Australian firm, taking advantage of favourable manufacturing costs in Australia.
- In collaboration with a USA firm, design, construction and installation of the Molokai Solar Thermal Power Station for the US Department of Energy using White Cliffs engine and steam technology and USA dishes. This project resulted from tenders competing with the USA solar power industry and researchers (see Appendix I).
- Development of new generation large dish/engine systems in collaboration with an Australian firm.
- Development of a rural village power supply using the White Cliffs steam technology.
- Influencing the USA Department of Energy to begin establishing dish/steam systems with our participation.
- Development of a range of useful components for solar thermal systems.

6.4 Evolution and 'Spinoffs'

Our work has shown that solar thermal power is now potentially cost-effective both for remote areas and for on-grid connection where insolation is good. We are working on concepts which, when developed, will enable the production of solar thermal (and thermochemical) power systems to be built which are not only environmentally more benign than fossil and nuclear systems, but are more cost effective. One path to such development is via binary and trinary systems with a potential overall efficiency of some 60%. Scope for innovation in this respect is considerable. Target costs as low as $500/kWe installed and generation costs of a few cents/kWh are suggested in preliminary studies.

Concepts employed have so far been unoptimised and selected without substantial investigation due to time limitations. We are now going about placing this work on a sound theoretical footing and generalizing all important concepts, for example,

- As far as we know, there is no adequate analytic formulation of transient behaviour of overall systems using water in its various phases as an energy transport medium. Water is a complex material and equations of state are hard to determine; we are developing an analytic description (valid for transient conditions) for a complete system, whereby water is heated to superheated steam in many absorbers then used to deliver mechanical work via a heat engine, condensed, reheated and so on.
- Investigation, identification and quantification of all loss mechanisms in solar thermal systems.
- Derivation of relationships between insolation, quality of heat produced, losses, output, efficiency and cost-effectiveness of overall systems.
- Derivation of relationships between system configuration, degree of insolation (and losses) and optimum output.
- Study shows there is a considerable economy of size for both components and systems. It is important to ascertain and quantify trends and limitations to optimum size.
- Investigation and determination of optimum heat flow networks for heat transport from arrays of different sizes and configurations to a central plant; comparison with thermochemical energy transport and with modular generation. What is an optimum configuration? How large a thermal system can be built and at what stage does this become inferior to thermochemical energy transport and to modular power generation?
- Overall systems which achieve greater reliability through fault tolerance, self checking, self disconnecting of modules and self repair, as well as failsafe operation, now appear feasible. Concepts and processes for achieving such operation are being studied, as the overall contribution to practicality could be of considerable benefit to system viability.

  In this respect it is worth noting that NASA has been giving consideration to employing two modules of solar thermal (dish/engine) power systems for the next space station, to be operational in the late 1990's, in preference to photovoltaics (which would still be present in small size), indicating a favourable assessment of current system reliability for solar thermal systems.

6.4.1 Thermochemical Systems

Few projects introduced by the department have aroused as much interest and controversy as the thermochemical research, the concepts of which earlier tended to be frankly disbelieved by some scientists who should have known better.

As time passed and theoretical developments and experimental results emerged, all challenges were answered and subsequently the research could be related to other ongoing work elsewhere.

Two independent detailed industrial assessments have been carried out on the basis of our concepts for an ammonia-based thermochemical system by Davy McKee Pacific Pty Ltd (a Davy International Corporation Company, Chemical Engineering Consultants, Plant Designers and Installers especially in the ammonia industry) in 1979 and 1986/87.

The Davy 1979 assessment concluded that ammonia thermochemical systems of 10 MWe in size could be viable compared with diesel power in inland Australia. Their 1987 report, just being compiled, shows that thermochemical systems (taking aboard the various improvements in conception, system and component improvements since 1979) are now attractive in relation to traditional energy sources so long as attention is directed to various identified aspects of these systems (which are amenable to further improvement). This favourable assessment is emerging and further support should follow as a result.

Research directions include:

- Basic theoretical formulation of the thermodynamics of thermochemical systems is an important ongoing study. Generalized work recovery formulations need to be produced, noting the fact that there are certain unique aspects of each system which will have to be separately considered.
- A further vital aspect is research towards the specification and development of catalysts of higher performance than those existing, in order to improve overall system effectiveness; this requires collaboration with physical chemists.
- Detailed studies relating to free energy of reactions and maximum work recovery.
- More-detailed screening of candidate systems.
- Conception and development of solar absorbers which accept the optimum radiation into the catalyst chamber.
- New heat transfer studies.
- Generation of control system options for optimum process control of thermochemical systems.
- The problem of storage, short and long term.

Other problems addressed are:

- What are the limits to size of collector array, size of individual synthesis systems, storage limits and losses?

- What are the limits to overall efficiency for systems which have heat exchanger type synthesisers in comparison to direct work recovery from synthesisers?
- What limits exist to distance between collection array, storage and utilization plant?
- How can losses from the exothermic terminal be reduced, so improving direct work output via a turbo cycle, for example?
- Investigation of systems which can 'breed' the energy transport material, for example ammonia, to be used as an additional product.

6.5 Heat Engine Research and Development

Our White Cliffs Project resulted in development of a robust reliable low-cost reciprocating expander with a heat-to-mechanical work conversion efficiency of up to 23% on steam at 420°C and 60 atmospheres pressure. The technology is appropriate in sizes from a few kW to perhaps 2 MW output, with a target cost of 25¢/watt for an engine system; this is attractive for a number of different areas of application — solar power generation, cogeneration, biomass utilisation for steam production and power supplies for rural villages, as well as the use of steam from forest and municipal wastes.

The technology, although not as potentially efficient as new generation engines (Stirling, Brayton systems for example), is worth developing further because of simplicity and cost effectiveness. Research in this area includes:

- Placing our enhanced steam engine developments on a firm theoretical footing; investigation and reduction of losses, extending limits of input heat quality, and formulating functional relationships between power output and conversion efficiency. What is the quantitative relation between efficiency and size of unit? What is the advantage of employing ceramic valve and piston components?
- A programme investigating various classic converters (thermoelectric, photovoltaic, magneto-hydrodynamic) and thermodynamic systems which rely on separation of ions across membranes (as in the sodium heat engine), and developing formulations of performances; comparing these systems.
- Investigation of concepts which can utilize the low voltage outputs from such devices while retaining the high inherent conversion efficiency; possible AC production directly.
- Generalizing and extending energy conversion theory based on reversible and irreversible thermodynamics.
- Ascertaining the practical limits to efficiency and output improvement in various heat engines, thereby identifying areas of potential improvement.

6.6 Solar Collection and Concentration

Our approach to paraboloidal dish solar collectors has favoured robust units with optical accuracies no greater than is essential for good collection and conversion efficiency, a philosophy which has resulted in cost-effective collectors. There is good reason to believe that, as in many engineering systems, there is an economy and effectiveness of size. We are now in a position to quantify and optimise many of the conceptual advances over the past few years, and our current programmes include:

- Ascertaining the 'optimum' size of collectors for concentrating solar energy, taking into account configuration. The major factor of wind loading presents one limit but configurations can be devised to reduce the effects of such loading. What are these limits? Is there an optimally cost-effective collector?

- Ascertaining 'optimum' shapes for collectors.

- Cavity receivers, from basic physics, might be expected to be the best configuration for use with solar-concentrating collectors. We have found a better arrangement, under certain conditions, involving our concept of semi-cavity absorbers. What is the optimum for this concept in terms of lowest losses and best cost-effectiveness for collectors of specific optical accuracy?

- What effective measures can be taken to reduce the trauma on absorbers resulting from varying insolation, convection and orientation, while retaining high quality heat output?

- Investigations of indirect irradiation of absorbers — practicability, conversion properties and effectiveness.

- Developments involving direct absorption receivers — use of various concepts which can employ practical materials. Limits to conversion efficiency and minimum losses?

7 ON-GOING EXPERIMENTS AT WHITE CLIFFS

Improving the System

The following additions or changes are being implemented or are in progress to improve performance and reliability to lift the present system to deliver annual outputs at generation costs which come near to the 'prospective' values in Table XV.

- General simplification of systems and reduction of auxiliary demands.
- Addition of an automatic oil-fired superheater to improve steam quality at times of low insolation to allow utilizing more of the available solar energy (already working).
- Improved feedwater flow control to each receiver to balance their outputs more effectively.
- Better oil/water separation.
- Installation of air-cooled condensation in place of water cooling.
- Use of improved receivers designed for much longer life and performance.
- Life testing of all components, especially absorbers and steam system.

It is possible to go much further than this by modifications to the technology (as suggested in Kaneff 1983 ISES papers). By better receiver designs, better reflectors, improved engine efficiency, reduced auxiliary power and generally improving generation efficiency, peak efficiency of the system can be more than doubled, with corresponding increase in output. Because the dish design is conservative, further improvement can be effected by bolting on extra mirror area on each dish (4 m^2 per dish) to increase output still further. But such changes to the present station can make little impact on installed cost. Having demonstrated viability (real and potential), the station is continuing to provide valuable experience and data useful in the development of next-generation systems, as well as serving the valuable function of providing power to White Cliffs. As operations continue, advantage is being taken to run the system as an experimental testbed to 'develop' and check out new ideas and approaches; to optimize the present system; and to investigate longer-term problems which only time can bring to light. But to achieve improvements in overall cost-effectiveness, advantage needs to be taken of the economy of size, leading to new design configurations, followed by application of all lessons already learned:

- Improved reliability.
- Minimal operator intervenion.
- Minimal auxiliary power.
- Automatic mechanical regular dish cleaning.
- Improved engine efficiency fossil fuel supplementation at times of low insolation.
- General system simplification and optimization.

There is much scope for improving all these factors which lead to lower installed costs, less O&M and greater annual collection efficiency; as a consequence, overall generation costs can be reduced substantially.

It is hard to overplay the importance of reliability improvement and simplification. The former allows more energy to be collected as well as reducing O&M; the latter leads to lower installed cost and higher reliability. Both factors play key roles in cost-effectiveness and advances; as a consequence, R&D in this field are vital to future system development.

8 FUTURE DIRECTIONS FOR SOLAR THERMAL POWER

That Australia has excellent insolation over most of its land mass is usually well appreciated. But misconceptions and unfounded assumptions regarding the utilization of this solar input for electricity generation via the thermal path have helped cause this asset to be undervalued and its development has been largely unsupported. What support has existed has usually been based on the need and relevance for remote areas with a specific rejection — in the name of (generally unanalysed) 'Australian Conditions' — relating to 'cheap' coal-based electric power. This attitude has relegated its potential applications here to relatively small capacities.

Nonetheless, substantial progress has occurred in the field of solar thermal electric systems due to the dedication of Australian researchers in the field and, especially, to overseas developments which have been greatly facilitated by the opposite approach — that solar thermal electric systems can contribute substantial on-grid electric power.

Solar thermal electric power has been a late starter in the quest for new energy sources but, over the past decade, has advanced in great strides, even surpassing expectations of those working in the field. This trend has become much more evident over the past 5 years and especially over the past 2–3 years, with important studies producing hard evidence of technological and economic viability. These developments are not widely known nor their implications generally appreciated.

8.1 Solar Thermal Technological and Economic Development Trends

Trends over the past few years are highlighted in Table XXI which lists several solar electric power systems selected because they have contributed some noteworthy aspect(s). The selection is not exhaustive nor is any comment implied regarding other systems not mentioned. One reason for listing has been the availability of system costs; a further criterion has been that of continued operation.

Table XXI indicates a substantial drop in installed cost of practical systems by about an order of magnitude over some 5 years — to below A$2 000/kWe — and are now near those of coal-fired electric power systems and generally lower than those of nuclear stations [Kaneff 1985, 1986, 1987]. It is relevant to point out that this new equivalence in installed cost refers to solar thermal systems of up to about 100 MWe and coal or nuclear stations of an order of magnitude or more larger in capacity.

Overall generation costs have also dropped by an order of magnitude over the same period to less than 12¢/kWhe, due to better hardware, higher reliability and more-effective operating strategies.

These trends are ongoing; their ultimate limits are yet to be revealed but the improvement not yet tapped is still very large.

For example, the installed costs of the 334 square metre aperture dish systems are on a one-off unit basis and do not include the benefits of a significant production run; generation

TABLE XXI— SOME NOTEWORTHY SOLAR ELECTRIC SYSTEMS

SYSTEM	LOCATION	WHEN FIRST OPERATING	SIZE	TYPE*	COST $/W (PEAK)
Barstow	California USA	1982	10 MW	CR	$US 14.4/W
White Cliffs	NSW Australia	1982	25 kW	PD	$A 9/W (no backup)
					$A 12/W (storage and backup)
Arco	Hisperia CA	1984	1 MW	PV	$US 12/W
	Carissa Plains CA	1984	6 MW	PV	$US 8/W (?)
LUZ	California USA	1984/86	13 MW	PT	$US 5.5/W
	"	1986	30 MW	PT	$US 4.5/W
	California USA	1987	30 MW	PT	$US 3.2/W
La Jet	California USA	1984/85	5 MW	PD	$US 2.8/W
Power Kinetics		Full Design Study	10 MW	PD+	$US 1.35/W (expected)
ANU	N.S.W.Australia	1991 Experimental	50 kW	PD+	$A 2/W (expected)

* CR = Central Receiver; PD = Paraboloidal Dish; PV = Photovoltaic; PT = Parabolic Trough.

costs for this unit are expected to be about 20¢/kWhe, all costs considered, a figure which would be reduced for a serial run of units.

The benefits of size and scale are illustrated by the LUZ systems, currently 30 MWe each, whose installed costs are tending to $3 000 kWe and generation costs to below 12¢/kWh. LUZ have, by good engineering, been able to make viable the potentially least effective of the three solar thermal technologies — dishes, central receiver and troughs — taking advantage of developments over a period of years in evacuated tube absorbers, in the economies of size in large parabolic trough units, and in the benefits of relatively large-scale production runs.

The position regarding new generation solar dish, central receiver and trough systems is well summarized by Williams and Co-workers [1987]. Figures 84(a) and 84(b) are based on their recent assessment (without calling on tax incentives) which is consistent with many other studies, including our own theoretical and practical research results. It may be noted that installed costs for dish systems are moving to $1 500/kWe and generation costs of 6¢/kWe.

Noting that overall generation costs for New South Wales coal-fired power stations are 4¢/kWe, at the station busbars, indicates that new-generation solar thermal electric systems will be close to competing with fossil stations in their own right, without the benefit of tax or other incentives. Moreover, solar thermal electric systems have yet to take advantage of the real economies of size and scale and of further technological advances.

The 4¢/kWh is in many ways an understatement of actual costs, being arrived at by costing the coal itself at extraction cost, not at market value. No account is being taken of environmental pollution costs in surrounding areas, nor of effects of this pollution, both short and long term; the economic calculations are based on relatively cheap capital. Generally, no attempt is made to include all those costs which are insisted on to be included whenever renewable energy systems are being considered — a very curious anomaly.

Mention is warranted on the two photovoltaic systems listed in Table XXI. The Carissa Plains PV Station was originally intended to be 16 MWe but was stopped at 6 MWe due to inability to reduce installed costs to a lower value. Since this station was built, no further megawatt-size PV units have been built. Photovoltaic-generated electricity carries the attraction of apparent simplicity and reliability, leading many to assume that a solar electric future will be a photovoltaic future. Such assumptions are not supported by evidence of appropriate cost competitiveness in relation to solar thermal systems. Indeed, although convenience and the lower maintenance needs for photovoltaic systems ensure their application for power units in sizes up to kilowatts (and perhaps tens of kilowatts), solar thermal systems are more cost effective in larger sizes, a situation which could well persist indefinitely since the latter are less well developed than PV systems.

8.2 Factors Promoting Solar Thermal Electric System Viability

Contributing to further increase in cost-competitiveness of solar thermal systems in comparison with traditional fossil and nuclear systems are the following factors:

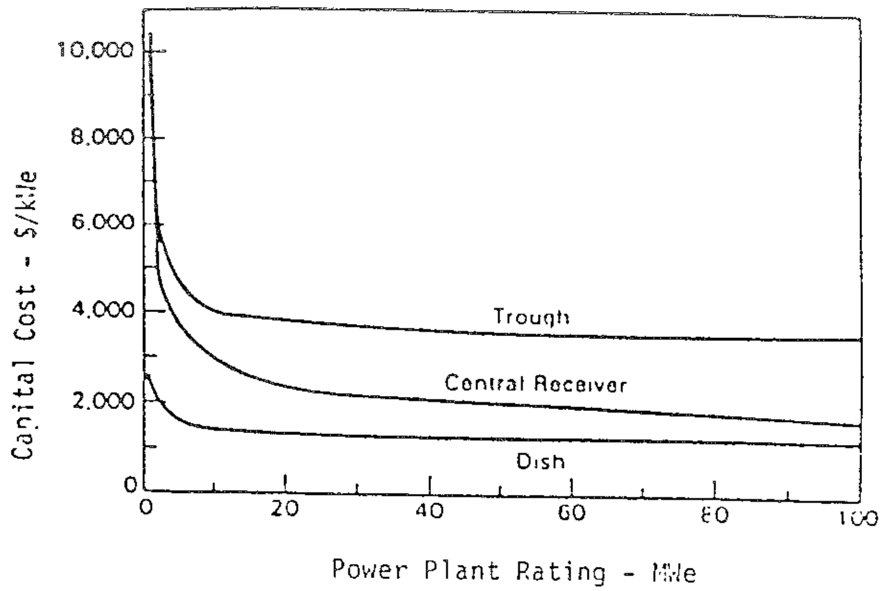


Figure 84 a New Generation Solar Thermal Installed Cost vs. Plant Rating

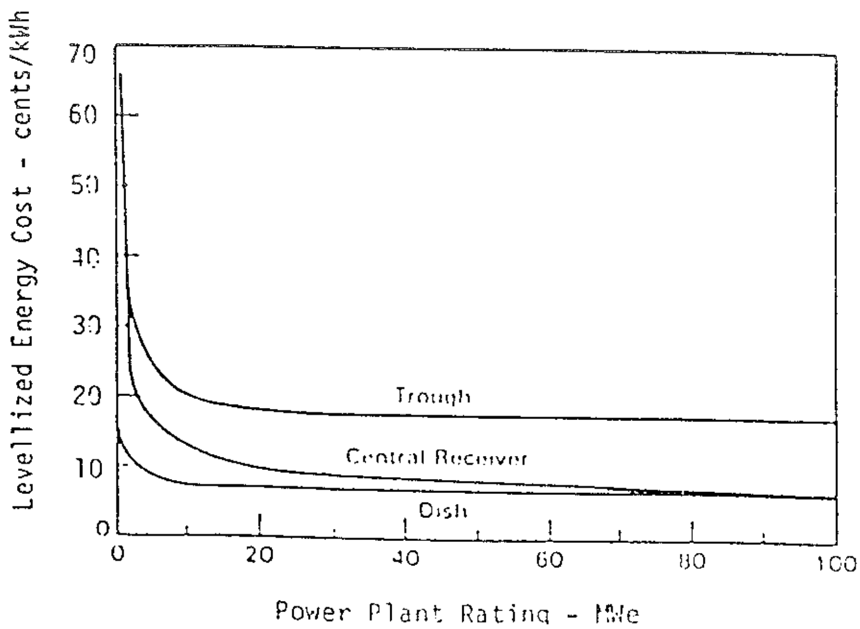


Figure 84 b New Generation Solar Thermal Levellised Energy Cost vs. Plant Rating.

1. A rapid technological development in which systems are becoming cost competitive absolutely in their own right, even without taking account of the uneven means for comparison.

2. The Question of Avoided Cost: Although generation costs at mainline station terminals may be as low as 4¢/kWh, due to the need for transmission and distribution and the associated costs (which include losses, operation and maintenance), actual costs elsewhere will be higher than 4¢/kWh — substantially higher at the more distant locations. At any specific location away from power station terminals, it is possible to assess actual costs which can then serve as a comparison with the costs of generating at that location by whatever other means. When such assessment is made, renewable energy systems can often generate at below the avoided cost, even though the actual generation costs are above 4¢/kWh, a factor which allows such systems to be installed economically even now.

   In this context, the actual price which electricity authorities are willing to pay for another form of grid-connected supply will depend on political as well as economic considerations, and the concept of incremental cost is often involved.

   Nevertheless there are clear-cut situations where avoided cost is easy to determine and accept; for example, the case of Wilcannia NSW, which previously had no grid connection, revealed that connection to the grid would result in power costs of some 23–24*cents*/kWh [Kaneff 1986] from that source. Any renewable energy which can supply generated electricity at below that price would therefore be economically preferable to grid connection. Other similar examples can be given around Australia, indicating an existing scope for renewable energy systems in the 1–10 MWe range.

3. The Application of Modular Units: In times of low load growth, the construction of large central power stations carries a great capital cost penalty since building time is long and the time to achieve full load capacity is also extensive. A more economical approach involves the addition of smaller units more frequently and, even if generation costs for such small units is higher, overall costs can be lower. This aspect is discussed by Mayer [1985, 1987] and is becoming enshrined in policies affecting power utilities in USA (for example PURPA) and some other countries in which utilities are directed to build smaller units more frequently rather than large units occasionally. Effectively any smaller system, whose generation costs may be substantially greater than those of mainline stations, can be cost competitive on this basis. In the event, these developments favour renewable energy systems which can be built in sizes from megawatts to tens of megawatts — especially solar thermal units.

4. Reliability, Operation and Maintenance (O&M)

   Along with very significant reduction in installed costs, continuing improvements are occurring in reliability and, in the consequent reduction in O&M costs due to the availability of more-detailed and authoritative environmental and operational information, permitting better design approaches. Reliability of dish/engine systems has now progressed to the point where the USA Space Station scheduled for operation in the late 1990's may us e dish/engine systems for supplying the greater part of its electric power needs in preference to photovoltaic (PV) supply [Dustin and Co-workers 1987]. The reason for this break with tradition depends on the cheaper, lighter and more efficient dish/engine systems which require less collector area than PV and thereby introduce less drag on the station, which consequently requires less fuel to be placed and kept in orbit; system reliability is considered satisfactory.

Acceptance of the consequences of recent and on-going advances and general developments has been rapid in some quarters. The Southern California Edison Company (SCE) seems to have led power utility acceptance as early as 1982 [Fogarty 1983]. The USA Department of Energy view as presented by Fitzpatrick [1986] is also supportive of the rapidly improving potential of the field. When taken in conjunction with relatively large solar thermal installations in California on the SCE system (Barstow central receiver and LUZ trough instllations), the La Jet dish installation at Warner Springs (California) and the various research programmes (in USA and elsewhere), it is tempting to agree with views expressed that solar thermal power will become a substantial contributor to the total energy budget (in USA) by 2000. Some 200 MWe are already either running or being installed on the SCE system, and a further 300 MWe are to be installed in California in the next 3 or so years. This already represents a billion-dollar industry and has all the hallmarks of a flourishing new technology.

8.3 Some Outstanding Problems

When normal commercial power system approaches are applied to determining costs of solar thermal systems, the intermittent nature of the incoming energy causes considerable cost disadvantage since, on the average, equipment remains idle for about two-thirds of the time. Yet most storage systems are quite expensive, although they are sometimes used to allow generation during peak load periods. A further problem regarding insolation occurs in intermittent cloud which can close down generation of fast-responding systems frequently or the system has, again, to be supported by storage or backup.

Solution of the storage problem is not a trivial matter. Two approaches seem potentially useful:

- The Use of Phase Change Heat Storage

  Latent heat may be used at a suitable temperature to store an appropriate amount of heat either to keep the system going overnight or at least during intermittent cloud. The use of more storage would be dependent on costs [Brandstetter and Kaneff 1987].

- The Use of Thermochemical Storage

  By storing materials at ambient temperature — the heat energy having been concerted to chemical energy — allows potentially seasonal storage and seems in principle attractive for this reason [Carden 1979].

Both forms of storage are as yet in only early stages of development.

8.4 A Solar Thermal Electric-Based Industry

Small dish/engine solar thermal systems (10 kW to several megawatts) are becoming potentially viable in certain parts of Australia (being more than competitive with diesel electric generation [Kaneff 1986, 1987]. For example, rather than connect the grid to Wilcannia (western NSW), it would have been more cost-effective in installed cost and operating cost to install 1 MWe or so of solar thermal power and retain the present diesel station there as a backup [Kaneff 1987]. Even more cost-effective would be the provision of smaller dish/engine systems to the outlying stations in western NSW rather than connect them on-grid. At Broken Hill (Menindee or Wentworth), a larger 10–100 MW solar thermal station could supply power to the grid. This is only one area in Australia which seems ripe for action; there are many similar locations elsewhere.

The only encouragement needed for Australian industry to take advantage of the situation, is to employ common-sense economic considerations, properly assessed. We know of at least one large organisation ready to proceed with such development.

The level of sophistication required is well matched to Australian industry and much of the resources necessary for producing equipment already exist. Collectors rely on steel structures, glass reflectors, and stainless steel or boiler tubes, tube fittings, insulating materials, gearboxes; engine technology depends on reciprocating blocks or turbines, dependent on size; electronic monitoring and control systems employ standard hardware as do most electrical units; advantage is gained by developing high efficiency generators. On the whole, the technology is well suited to Australian conditions and capabilities.

Apart from export potential, such an industry, even in its early stages, will be able to take advantage of the heat-to-mechanical-work conversion systems and electrical developments to provide biomass systems running from steam generated from sawmill wastes, rice husks, bagasse, coconut fibre and shells, and other crop wastes as well as being used in waste heat utilization systems. Applications are then extensive both within Australia and in our near and far neighbours.

There seems to be no compelling reasons, apart from inertia and lack of enterprise, why these advances should not be grasped now for the benefit of industrial development.

9 FUTURE EXPERIMENTS AT WHITE CLIFFS

The foregoing has argued that solar thermal electric systems are progressing rapidly in both efficiency and cost-effectiveness; White Cliffs has contributed to the provision of hard evidence of the potential viability of such systems and has provided lessons and experience which have made an impact overseas. Large 334 square metre dish systems are the next evolutionary development now being pursued, with scope for competing in inland Australia with diesel electric sets; it also should have application for larger modular or central plant systems both off-grid and, in suitable locations, also on-grid.

The case for continuing operation of White Cliffs , beyond the obvious provision of energy to the town and the considerable tourist attraction which supports many of the people in the vicinity, is based on the fact that this going system can be kept operational in order to gain further vital information at a lower cost than by gaining such information by other means. The system is a field laboratory which can accept new experiments readily.

Certain results which can be gained from White Cliffs can be obtained in no other practicable manner: such results relate to life testing under real-world conditions; to the effect of adding additional heat by fossil or other fuel in order to be able to use more of the lower quality solar heat; and to any changes in parameters which affect the essentially non-linear input/output relation for the station.

Specifically, it is of vital importance to test (over a period of a year or more) new generations of absorbers to enable the large 334 square metre collectors to require little if any further absorber development. These elements are the most severely tried components on the system and cost effectiveness is very dependent on absorber characteristics and O&M requirements.

It is also of great importance to simplify and improve the steam system generally, including better oil water treatment, better feedwater control and particularly the reduction of auxiliary power. Reducing auxiliary power by 1 kW not only gains an extra 2000 kWh energy per year usefully, but leads to an even further gain due to the fact that the system can be run longer hours to take advantage of lower insolation. We propose to employ steam ejector vacuum production to reduce auxiliary power further.

Similarly the addition of fossil-fired superheat extends the solar collection regime and produces more nett energy. A superheater is in place but cannot be used effectively until the feedwater flow subdivision has been improved.

Most of the above developments need a significant period of running to establish their effectiveness, including reliability improvement factors.

Those changes which lead to less auxiliary power and more substantial useful generated energy are potentially very cost-effective. We expect, if all are introduced and proved, that some 30% extra energy will be produced per annum which would demonstrate significant progress for next-generation units.

10 CONCLUSIONS

White Cliffs has provided and is providing information which can allow solar thermal paraboloidal dish systems to more than compete with diesel systems in inland areas. The project has resulted in a number of advances in array and engine technology which has influenced R&D directions.

The project has shown that cost-competitive, efficient, robust engines can be built using parts from currently available diesel engines. The highest temperatures at which such engines can operate are limited by the properties of the materials used for the valves and seats, mainly. Currently limits are set at 450°C, but ongoing research to employ ceramic components give potential temperatures of over 800°C. A target efficiency of up to 30% may eventually be achieved.

The engine can be serviced or repaired by any person familiar with the usual internal combustion engine used in vehicles and could be used in any location where superheated steam could be produced by any means including the combustion of waste material or garbage.

Initial cost indications for the first units produced, on a one-off basis, suggest — excluding burner and boiler but including generator and controls — some A$1000 per kWe for sizes of 25–50 kWe, falling to about A$500 per kWe for a small production run. Current simplifications and improvements are expected to lower these costs further, target cost being A$250 per kWe. System sizes up to 2 MW are considered practicable.

The engine technology has aroused great commercial interest overseas and in Australia and is now being actively disseminated by licence and other agreements.

The solar array and associated systems have been very successful. All components, including the glass reflectors, have proved to be robust, reliable and of negligable degradation. This is great encouragement to build very much larger collectors to take advantage of an economy of size. Such collectors are being designed and appear practicable and cost-effective.

All matters considered, we conclude that duct losses (which are already low) and collection, concentration and conversion processes (which can be improved greatly), no real constraint on the use of central plant with large numbers of paraboidal dishes is indicated.

Consequently, one of the major objectives of the White Cliffs Project has been met and resolved, in the demonstration that arrays of collectors operating at high temperature can be effective so long as they are appropriately sized and designed; this applies to electricity generation and by implication also to the provision of industrial process heat.

Overall, the project has contributed invaluable results to the development of solar thermal electric systems, assisting in the development of new perceptions of viability in some situations now and in more widespread areas both on- and off-grid in the next few years. White Cliffs still can contribute much and advantages ought to be taken of this situation by continuation of experimental operation for a further period.

11 REFERENCES

ABBIN J., ANDRASKA C., LUKENS L. and J. MORENO (1987). Liquid metal thermal electric converter. Proc Solar Thermal Technology Conference, Albuquerque NM, August. SAND 87-1258, pp 11-20.

BANSAL P.K. and S. KANEFF (1987). On two-phase flow in solar absorbers. Proc Annual Meeting Australian and New Zealand Solar Energy Society, Canberra, November. Ed Lee, 1:181-190.

BILODEAU E.E., BORTON D.N., ROGERS W.E. and E.K. INALL (1987). Design of the small community program SCSE No 2 at Molokai, Hawaii. Proc Joint ASME-JSME-JSES Thermal Engineering Conference, Honolulu, 22-27 March. In Solar Engineering 1987, Eds Goswami, Watanabe and Healey, American Society of Mechanical Engineers, New York, 2:810-814.

CANTOR H.P. (1979). Accurate suntracking for instruments or mirrors. IREECON International, 17th International Electroncis Convention and Exhibition, 27-31 August, University of NSW, Sydney. 308-311.

CANTOR H.P. (1982). The White Cliffs mirror tracking system handbook. Dept Engineering Physics Report, January, 91 pages.

CANTOR H.P. (1983). Low cost failsafe tracking units for concentrating collectors. Proc 8th International Solar Energy Society World Congress, Perth, August. Ed Szokolay, Pergamon Press, Oxford, 2:1046-1050.

CANTOR H.P. (1983). Design, economics and life of parabolic concentrating collectors. Proc 8th International Solar Energy Society World Congress, Perth, August. Ed Szokolay, Pergamon Press, Oxford 1984, 2:1317-1321.

CARDEN P.O. (1979). Solar power for remote areas — chemical heat pipes. Progress Report, Dept Engineering Physics Publication, July, 18 pages.

CARDEN P.O. (1979). Solar power for remote areas — fluid heating 200°C and above. Progress Report, Dept Engineering Physics Publication, July 25 pages.

CARDEN P.O. (1980). Demonstration of a paraboloidal mirror collector. Dept Engineering Physics Report, December, 32 pages.

CARDEN P.O. and P.K. BANSAL (1987). Computer software for optimum energy transport layouts for distributed solar systems. Proc Annual Meeting Australian and New Zealand Solar Energy Society, Canberra, November, pp 143-152.

COLEMAN C.C. and J.E. RAETZ (1986). Field performance of dish Stirling solar electric systems. Proc Solar Thermal Technology Conference, Albuquerque NM, June. SAND 86-0536, pp 316-325.

DOCHAT G. (1986). Free piston Stirling engines for terrestrial solar electric power conversion. Proc Solar Thermal Technology Conference, Albuquerque NM, SAND 86-0536, UC-62, pp 143-152.

EDWARDS B.P. (1980). Collector deflections due to wind gusts and control scheme design. Solar Energy 25(3):231-234.

FITZPATRICK D. (1986). Solar thermal technology. Keynote Address, Proc Central and Distributed Review Annual Conference, US Dept of Energy, Sandia National Laboratories, Albuquerque NM, June, pp 1-10.

FOGARTY D.J. (1983). Commercial realities of solar power generation. Keynote Paper 6B, International Solar Energy Society World Congress, Perth, August. Abstracts pp 553-557. Also in Proc of Congress, Pergamon Press, 1984, 4:2443-2551.

FULTON K.G., KANEFF S., INALL E.K., THOMAS K., WHELAN R.E. and H.P. CANTOR (1983). The operation and maintenance manual for the White Cliffs solar power station. ANUTECH Publication, November.

INALL E.K. (1983). The White Cliffs solar power station steam engine air condensate treatment system. Proc 8th International Solar Energy Society World Congress, Perth, August. Ed Szokolay, Pergamon Press, Oxford 1984, 3:1478-1482.

INALL E.K. (1983). The economics of the addition of a wind-driven generator to the solar power station at White Cliffs. Proc 8th International Solar Energy Society World Congress,

Perth, August. Ed Szokolay, Pergamon Press, Oxford 1984, 4:2390-2394.
JAFFE D., FRIEDLANDER S. and D. KEARNEY (1987). The LUZ solar electric generating systems: technical and economic review. Proc International Solar Energy Society World Congress, Hamburg, 13-18 September. Paper 2W3.02, Pergamon Press, Oxford (in press).
KANEFF S. (1979). Country towns — solar energy resources hope for local economies. Royal Australian Planning Institute Journal 17(3):182-185.
KANEFF S. (1979). Alternative sources of energy for farming. Proc 55th Annual Conference, Agricultural Bureau of NSW, Orange, July, pp 19-34.
KANEFF S. (1979). The Australian National University solar energy programme. 1st National Conference on Applied Physics, Australian Institute of Physics, Rockhampton, July.
KANEFF S. (1979). Solar energy has potential for rural industries and decentralisation. Agricultural Gazette of New South Wales, October, pp 44-49.
KANEFF S. (1979). Some potential applications of concentrating paraboloidal solar systems. Proc 1979 Country Convention, The Institution of Engineers Australia, Bendigo, October, pp 7-18.
KANEFF S. (1980a). Design of a 5m diameter altitude-azimuth-tracking paraboloidal dish collector system for generating high quality steam. Dept Engineering Physics Report, August, 42 pages.
KANEFF S. (1980b). DC machine/battery storage system. Dept Engineering Physics Report, August, 15 pages.
KANEFF S. (l980c). Realisation of an efficient dc motoring-generating machine for use with battery storage. Dept Engineering Physics Report, September, 23 pages.
KANEFF S. (1980d). Progress Report on 25 kWe solar power station for White Cliffs. Dept Engineering Physics Report, September, 39 pages.
KANEFF S. (1981). Towards inland and remote area development. Paper prepared for Dept of Industrialisation and Development, NSW, Western Region, July, 41 pages.
KANEFF S. (1982). Operating the White Cliffs solar power station. Proc 21st International Solar Energy Society (ANZ Section) Conference, University of Queensland, 10-12 November, pp 183-189.
KANEFF S. (1982). The White Cliffs solar power station. Proc 4th Parabolic Dish Solar Thermal Power Program Review, US Dept of Energy/Jet Propulsion Laboratory, Pasadena CA, 30 November–2 December. Publication DOE/JPL 1060-58, JPL 83-2, March 1983, pp 299-317.
KANEFF S. (1983). Solar thermal electric power — the White Cliffs solar power station. Guest Editorial, Solar Energy Bulletin of Solar Energy Industries Association of Australia, January, 12:1-7.
KANEFF S. (1983). White Cliffs — operating experience. Proc 5th Parabolic Dish Solar Thermal Power Program Annual Review, Indian Wells CA, 6-8 December. US Dept of Energy/Jet Propulsion Laboratory Publication DOE/JPL-1060-69, JPL 84-13, March 1984, pp 146-158.
KANEFF S. (1983). White Cliffs and beyond. Proc Remote Area Power Supply Workshop, Canberra, 9-10 May, Dept of Resources and Energy/National Energy Research, Development and Demonstration Council, pp 324-345.
KANEFF S. (1983). The design of viable paraboloidal collectors for high quality heat production. Proc 8th International Solar Energy Society World Congress, Perth, August. Ed Szokolay, Pergamon Press, Oxford 1984, 4:2762-2766.
KANEFF S. (1983). On the practical and potential viability of paraboloidal dish solar thermal electric power systems. Proc 8th International Solar Energy Society World Congress, Perth, August. Ed Szokolay, Pergamon Press, Oxford 1984, 4:2767-2771.
KANEFF S. (1983). The White Cliffs solar power station. Proc 8th International Solar Energy Society World Congress, Perth, August. Ed Szokolay, Pergamon Press, Oxford 1984, 4:2772-2776.
KANEFF S. (1984). Fourteen dish community electric system — White Cliffs. Proc International Energy Agency Workshop on Large Solar Thermal Arrays, San Diego, June. IEA Publication, Paper Session 2, 44 pages.

KANEFF S. (1985). High temperature solar technology — potential and reality. Proc Annual Conference of International Solar Energy Society (ANZ Section), Sydney, 14-15 November, pp 147-160.
KANEFF S. (1985). Fourteen dish community electric system, White Cliffs: collector system performance. In Design and Performance of Large Solar Thermal Collector Arrays, Solar Energy Research Institute, Golden CO USA, Ed Bankstown, UC-62, March, pp 328-356.
KANEFF S. (1985). Interim report on the operation and performance of the White Cliffs experimental solar power station — analytic comments. Dept Engineering Physics Report, July, 17 pages.
KANEFF S. (1985). On the feasibility of high temperature solar thermal electric systems — a critique. Dept Engineering Physics Report, December, 48 pages.
KANEFF S. (1986). On the commercial reality, scope and potential of solar thermal power. Proc Annual Meeting Australian and New Zealand Solar Energy Society, Adelaide, 13-15 November, pp 3-16.
KANEFF S., INALL E.K. and R.E. WHELAN (1986). Evolution of concepts for low loss receivers for relatively deep paraboloidal dishes. Dept Engineering Physics Report ER-RR-45.
KANEFF S. (1987). The White Cliffs solar thermal electric power systems. Proc Joint ASME-JSME-JSES Thermal Engineering Conference, Honolulu, 22-27 March. In Solar Engineering 1987, Eds Goswami, Watanabe and Healey, American Society of Mechanical Engineers, New York, March, 2:815-820.
KANEFF S. (1987). A viable role for solar thermal power in remote areas. Proc Engineering Conference 'Developing Remote Areas', Darwin, 11-15 May, The Institution of Engineers Australia, pp 192-198.
KANEFF S. (1987). Grid connected renewable-energy-based electricity generation. Proc Annual Meeting Australian and New Zealand Solar Energy Society, Canberra, November. Ed Lee, 1:227-236.
KANEFF S. (1987). On the economy of size in solar thermal systems. Proc International Solar Energy Society World Congress, Hamburg, 13-18 September. Paper 10.1.06, Pergamon Press, Oxford, 5 pages (in press).
KANEFF S. (1987). White Cliffs — the first seven years. Proc International Solar Energy Society World Congress, Hamburg, 13-18 September. Paper 2.18.01, Pergamon Press, Oxford, 5 pages (in press).
KANEFF S. (1987). On the rapidly improving cost effectiveness of solar thermal electric systems. Proc International Solar Energy Society World Congress, Hamburg, 13-18 September, Paper 10.1.05, Pergamon Press, Oxford, 5 pages (in press).
KANEFF S., INALL E.K. and R.E. WHELAN (1987). A range of high performance uniflow reciprocating steam engines powered by solar, biomass and other sources of steam. Proc International Solar Energy Society World Congress, Hamburg, 13-18 September, Paper 2.13.14, Pergamon Press, Oxford, 5 pages (in press).
KANEFF S. and N.D. KAUSHIKA (1987). Semi-cavity receivers for paraboloidal dish solar collectors. Solar Energy (paper submitted).
KANEFF S. and N.D. KAUSHIKA (1987). On the design of viable paraboloidal dish solar collector systems. Energy Conversion and Management (paper submitted).
KAUSHIKA N.D. and S. KANEFF (1987). Flux distribution and intercept factors in the focal region of a faceted paraboloidal dish concentrator. Proc International Solar Energy Society World Congress, Hamburg, 13-18 September, Paper 2.18.07, Pergamon Press, Oxford, 5 pages (in press).
KEARNEY D.W. (1986). 1985 Operation performance of SEGS-I. Proc Solar Thermal Technology Conference, Albuquerque NM, June. SAND 87-0536, pp 296-305.
KREPCHIN I.P., TORBIN R.N., ANDREPONT J.S. and T.K. SHAH (1987). Design and testing of a solar powered freeze distillation plant. Proc Joint ASME-JSME-JSES Thermal Engineering Conference, Honolulu, 22-27 March. In Solar Engineering 1987, Eds Goswami, Watanabe and Healey, American Society of Mechanical Engineers, New York, 1:12-19.
LEONARD J.A., DIVER R.B. and T.R. MANCINI (1987). Proc of the Concentrating Solar

Collector Workshop: Key Technical Issues. Sandia National Laboratories, Albuquerque NM, SAND-0131, UC-55a, June, 58 pages.
LINKER K.L. (1986). Heat engine development for solar thermal dish — electric power plants. Sandia National Laboratories, Albuquerque NM, SAND-0289, UC-63, November, 27 pages.
MANCINI T.R. (1986). Sandia stretched-membrane concentrating solar collector development project. Proc Solar Thermal Technology Conference, Albuquerque NM, SAND 86-0536, UC-62, June, pp 287-296.
McGLAUN M.A. (1986). Innovative concentrator detailed design. Proc Solar Thermal Technology Conference, Albuquerque NM, June. SAND 86-0536, UC-62, pp 246-257.
McGLAUN M.A. (1987). La-Jet Energy Company update on SOLARPLANT I. Proc Solar Thermal Technology Conference, Albuquerque NM, Sandia National Laboratories. SAND-1258, UC-62, pp 142-150.
MOUSTAFA S., EL-MANSY H., ELIMAN A. and H. ZEWEN (1984). Operational strategies for Kuwait's 100 kWe/0.7 MW_{th} solar power plant. Proc Solar World Congress, Perth, August. Ed Szokolay, Pergamon Press 1984, 3:1333-1449.
NEY E.J. and J. WILLARD KING (1984). Performance of 114-dish array at Shenandoah. Proc International Energy Agency Workshop 'Design and Performance of Large Solar Thermal Collector Arrays', San Diego, June. SERI (Golden CO) Publication IEA/SERI, UC-62, March 1985, 319-327.
OVERLY P. (1986). Acurex innovative point focus solar concentrator. Proc Solar Thermal Technology Conference, Albuquerque NM. SAND 86-0536, UC-62, June, pp 258-268.
PRASAD S. (1987). Reciprocating steam engine: theoretical performance. Dept Engineering Physics Report, March, 30 pages.
PRASAD S. (1987). Electricity from biomass fuels, rural power for Fiji. Proc Annual Conference Australian and New Zealand Solar Energy Society, Canberra, November. Ed Lee, 1:171-180.
ROGERS W.E., BORTON D.N., BILODEAU E.A. and E.K. INALL (1988). Design of a solar/oil hybrid plant for the small community solar experiment (SCSE No 2) at Molokai, Hawaii. Proc ASME Solar Energy Division Conference, Golden CO, 10-14 April, 6 pages.
QUARTERLY PROGRESS REPORTS (1983–1987). Quarterly reports listing progress; problems; data acquired and performance calculations; daily insolation characteristics for periods December–February; March–May; June–August; September–November in each year. Dept Engineering Physics Reports prepared by S. Kaneff.
ROSENBERG L.S. and W.R. REVERE (1981). A comparative assessment of solar thermal electric power plants in the 1–10 MWe range. US Dept of Energy/Jet Propulsion Laboratory, DOE/JPL-1060-21 JPL Publication 81-53, June, 92 pages.
SCHERTZ P. (1986). Design of a point-focus concentrator. Proc Solar Thermal Technology Conference, Albuquerque NM, SAND 86-0536, UC-62, June, pp 235-245.
SCHEFTER J. (1985). Solar power cheaper than coal, oil, gas. Popular Science, February, pp 77-80.
SLABY J.G. (1987). Overview of free-piston Stirling engine technology for space power application. Proc Joint ASME-JSME-JSES Thermal Engineering Conference, Honolulu, 22-27 March. In Solar Engineering 1987, Eds Goswami, Watanabe and Healey, American Society of Mechanical Engineers, New York, 2:686-696.
THOMAS K. and R.E. WHELAN (1981). Assessing solar flux distribution in the focal region of a paraboloidal dish by moonshots. Dept Engineering Physics Report ER-RR-44, ANU, February.
WEST P.T. (1982). The White Chiffs solar power station dc machine control system. Dept Engineering Physics Report, February, 80 pages. [Major revision by E.K. INALL, June 1982.]
WHELAN R.E. (1979). A miniature low flow rate turbine flowmeter for high pressure. Journal of Physics Engineering: Scientific Instruments, 12:553-556.
WHELAN R.E. (1986). Rotating joints for high temperature fluids and their application to tracking solar concentrators. ANZAAS-AIST Conference on Science Technology, Macquarie University, 15-16 July, 23 pages.
WHELAN R.E. (1986). Accurately machining paraboloidal surfaces in concave shells, the cutting path determined by simple mechanical linkages. ANZAAS-AIST Conference on Science

Technology, Macquarie University, 15-16 July.
WHELAN R.E. (1987). A dual-flow force-balanced rotating joint for high temperatures and pressures. Proc International Solar Energy Society World Congress, Hamburg, 13-18 September. Pergamon Press, Oxford, 5 pages (in press).
WILLIAMS O.M. (1980). Evaluation of wall temperature difference profiles for heat absorption tubes exposed non-uniformly to solar radiation. Solar Energy 24:597-600.
WILLIAMS O.M. (1980). Design of a low-loss absorber for a relatively deep paraboloidal dish. Dept Engineering Physics Report, February.
WILLIAMS T.A., BROWN D.R., DIRKS J.H. and M.K. DROST (1987). Analysis of solar thermal concepts for electricity generation. Proc Joint ASME-JSME-JSES Thermal Engineering Conference, Honolulu, 22-27 March. In Solar Engineering 1987, Eds Goswami, Watanabe and Healey, American Society of Mechanical Engineers, New York, 2:779-785.
WILLIAMSON H.W. (1987). Exploring dependence of reciprocating steam engine performance on controllable parameters. Dept of Engineering Physics Report, November.
ZEWEN H., SCHMIDT G. and S. MOUSTAFA (1983). The Kuwait solar thermal power station: operational experiences with the station and the agricultural application. Proc Solar World Congress, Perth, August. Ed Szokolay, Pergamon Press 1984, 3:1527-1532.

From: Solar Engineering - 1987
Proceedings of the ASME-JSME-JSES Solar Energy Conference
Honolulu, 22-27 March 1987
Ed D. Yogi Goswami; K. Watanabe; H.M. Healey
American Society of Mechanical Engineers.

DESIGN OF THE SMALL COMMUNITY PROGRAM (SCSE #2) AT MOLOKAI, HAWAII

E. A. Bilodeau, D. N. Borton and W. E. Rogers
Power Kinetics, Inc.
Troy, New York

E. K. Inall
Australian National University
Canberra, Australia

Abstract

Power Kinetics, Inc. (PKI) is building a solar power station to be installed on the island of Molokai, Hawaii under a contract with the U.S. Department of Energy. The station will consist of five modules to produce 50 kW each. These consist of a 306m^2 point focus collector with polar axis tracking, a ground mounted steam engine driving an induction generator via a cam clutch, an oil fired boiler and superheater, and a water cooled condenser. The steam system will produce 363 kgm of steam per hour at 6.89 MPa. The temperature at the exit of the solar receiver will be 280°C and at the outlet of the superheater, 450°C. The boiler can produce the steam when there is no sun.

Key words: solar thermal power station, solar collector, solar boiler, steam engine.

INTRODUCTION

The US Department of Energy has two projects under the Small Community Solar Experiment (SCSE); one at Osage City, Kansas, the other at Molokai, Hawaii. PKI bid under both programs and was successful with both bids. The orientation in design, however, is quite different for each project.

In Kansas, the site is in rural America but has ready access to cities and technical services. That projetct will provide experience with a four unit 100 kW system, to determine operational characteristics in such an environment. In Molokai on the other hand, the system is exposed to a corrosive ocean atmosphere in a relatively remote site. Additionally, this five unit 250 kWe system produces a significant (6%) addition to the existing electrical output of the Molokai Electric Company (MOECO). This paper describes that project at Molokai.

The Power Kinetics Square Dish solar collector design avoids the structural limitations inherent in fixed parabolic dish shapes, as will be explained later. The reduction of the design constraint has resulted in a unit size growth from 80m^2 of mirror surface in the 1984 SOLERAS desalination project in Yanbu, Saudi Arabia to the 300m^2 unit size being implemented at Molokai. This scale up has brought about a significant weight reduction, a lowered maintenance profile, decreased parasitic losses, and has simplified the system. This has brought about a major reduction in the costs of the collection of solar energy.

An Australian National University (ANU) engine is aptly chosen for the Molokai project because it addresses the design philosophy for a remote site. A similar engine has operated for over 6000 hours in a solar power station which will be described in another paper. Although it operates in the moderate efficiency range, it is inexpensive and has a very low maintenance requirement. Additionally, the use of a fossil fuel superheater system stabilizes output and increases capacity. This affords the utility a firm 250 kWe addition to its own 4 MWe output.

The system is currently undergoing tests at Sandia National Laboratory in Albuquerque, NM. and is scheduled for installation on Molokai in the fall of 1987.

A parabolic dish configuration was required by the Small Community Program because of the assessment years earlier, that this design could provide more than twice the integrated energy output of a parabolic trough configurations or central receiver. The SCSE program also stipulated that each solar collector in the system have its own electric generator, a requirement that was intended to avoid the energy losses inherent in the pipe collection network of a centralized generation system. PKI has implemented both of these requirements at Molokai with a five dish, 50 kWe reciprocating steam engine design. We would have preferred to use a single similar but larger 250 kWe generator because it would be more efficient and cost much less. The existing design will furnish baseline information, however, from which the characteristics of the larger engine system can be extrapolated.

The addition of an oil fired steam generator and superheater provides stability and firm capacity to the system. Because of the large penetration of the grid, however, this seemed a necessary precaution to minimize any deletorious effects from a 6% solar contribution. Additionally, this benefits MOECO because the firm capacity allows them to use the system as a peaking supply between 5PM and 7PM when the solar input is low or non existant.

SYSTEM DESCRIPTION

The solar collector field will use two acres of land adjacent to the Molokai Electric Company's current operations located about 1/2 mile from the sea. Water is obtained from nearby wells to supply cooling water. The plant is to be operated when the solar input is sufficient for the combined input of solar and oil to produce more output than a diesel engine would when using the same amount of oil as the burner.

A central plant control turns on and off each of the five identical modules and monitors their status. Each module consists of a series connected solar collector and fossil fired boiler and superheater, a steam engine, condenser and a heat rejection loop, condensate conditioning unit, and integrating controls. Water supply, cooling pond, and fuel oil storage are shared by the individual power modules while the solar collectors and the engines have individual controls which enable their automatic operation and fault detection. When a module is turned on, the solar collector concentrates the available energy to produce steam. The oil burner then brings this wet steam to the conditions required by the engine. Without the sun, the boiler can produce all the steam. The steam engine can operate with wet steam but it is much more efficient when running on superheated steam. This flexibility allows continuous stable operation through clouds and variable weather conditions with the use of simple controls.

SQUARE DISH SOLAR COLLECTOR

The PKI Square Dish Solar Collector (Figure 1) consists of 392 mirrors, 0.6m (25") x 1.2m (48"), mounted on 28 identical open web triangular shaped mirror support beams, each of which supports 14 facets. The dish is aligned parallel to the earth's axis to simplify tracking. The rotating frame consists of three main girders extending from a central beam which is supported so that the girders clear the ground at all orientations. A 2-member boom extends from the frame to support the receiver (Figure 2) 15m (50 ft) from the mirrors. The collector can operate in an 18 m/s (40 mph) wind.

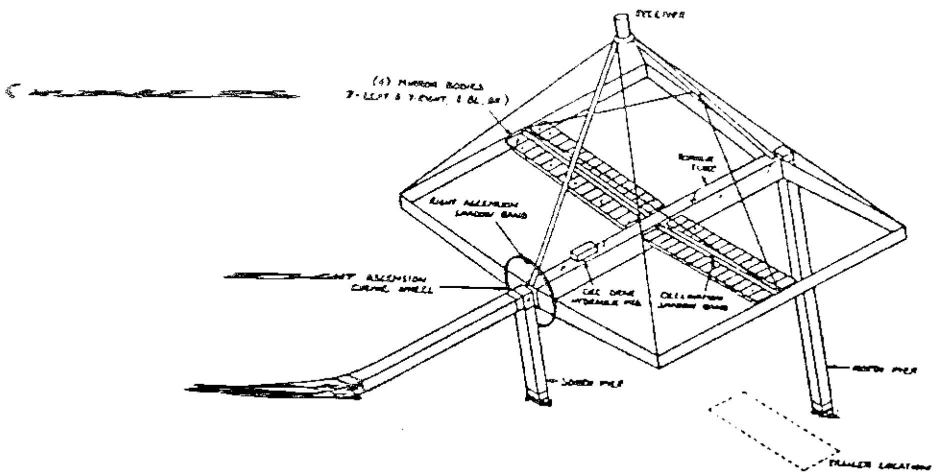


FIGURE 1 The Square Dish collector structure

The mirror supports shape
approximate paraboloid which
sun0.25m (10") in diameter at 1
each beam are aligned to proj
15 m (50 ft) away. Each fac
aligned independently by mear
which is locked after alignment
adjusted, the images remain wit
point (i.e, the point where the co

The collector has dual-axis
of sunlight throughout the day.
accomplished by rotation of th
west polar sweep, about its ce
tracking is accomplished by sim
support assemblies, also around

The collector control subsy
Active feedback control of the
shadowband sensors mounted
controller keeps track of sunrise
sun in Right Ascension withou
sunlight is blocked by clouds.
inverted position whenever the s
The module controller provide
rainwash command, etc.) that ar
provide common safety and conv

Except during operation, m
in a stowed position. This pro
hail, or dirt build-up. The over
safe operation. Except during p
manual override for rainwash, th

FOSSIL BOILER AND SOLAR

The boiler was designed to
steam/hr at 450°C (850°F) and
consists of four sections: an
receiver, a saturated boiler, and
consist of only coiled pipe an
headers or pressure containing p
inch pipe. The boiler has been de
and Pressure Vessel Code.

The economizer, the solar re
sections, since they are water we
be made of low alloy steel; b
stainless steel. To insure con
operational flexibility, the ratin
allowable working pressure) will
though code allows different pr
water-steam flow. In operation
economizer will see the upper pr
psi) and these will be at a temp
The superheater will be at the l
MPa (850 psi) at the higher
(850°F). This design is appropri
nature of the application and all
below the set points of the pressu

The receiver (Figure 2) is
aperture coil opening to a diame
about 1.5 meters deep. The foc
meters from the concentrator.
cavity has been kept below 12
insure long life of the absorbe
receiver is estimated at 5.7 kW
a wind of 10 m/s. When the in
input to the steam is estimated to

POWER CONVERSION SUBSYSTEM

Most of the engine is made from parts of two diesel engines which are on the market. The crankcase, sump, crankshaft, flywheel, connecting rods and starter are from a Lister Diesel. The cylinder liners and pistons are from a GM diesel. The engine is started by a standard electric starting motor. Steam is admitted to each cylinder through ball valves which are opened by fingers attached to the crown of the pistons. The steam expands until the piston exposes the exhaust ports in the cylinder liner, which was made for a two stroke diesel engine. The engine is started automatically when the incoming steam is hotter than 180°C and the pressure reaches 2.74 MPa (400 psi). The full supply of steam being produced by the collector is used whenever the engine is running. When the power from the collector drops due to lack of sunshine, the engine stops and the starting circuits are reset to monitor the steam and await the starting conditions. The engine is not sensitive to water in the steam , it gives partial output from wet low temperature steam when the sun is attenuated and not supplemented by the oil fired boiler, and a maximum net output of 53 kWe when the insolation is 1 kW/m^2 and the superheater is supplying 40 kW.

The engine configuration is as follows:

Bore	98.4 mm
Stroke	114.3 mm
Number of cylinders	4
Max. steam press.	6.89 MPa (1,000 psi)
Max. steam temp.	450°C (850°F)
Condenser press.	24.5 kPa (abs)
Expansion ratio	25
Lubrication	as in Lister engine
Lubricant	Mobil oil XRN 1301C

Initial water treatment will be done on a plant basis providing deionized water to each module. Each module will utilize a closed loop steam Rankine cycle with only incidental evaporation from the oil skimming tank and occasional boiler blowdown having to be made up. Water supply at the site will be required for both boiler feed and cooling.

Figure 5 shows the interconnections between the components of the steam system. The exhaust steam line enters the upper end of a cylindrical vortex chamber tangentially . Oil and water droplets are stopped by a gauze sleeve on the inner surface and drain to the bottom of the chamber, the steam passes up through the top plate of the vortex chamber to the condenser. The smallest oil drops pass into the condenser with the steam, and the condensate carries these as a very fine suspension to compartment 1 of the feedwater tank. This dispersion of oil in the condensate must be removed before the water is returned to the boilers. It cannot be removed by conventional filters or the centrifuge. The method used is to pump water from compartment 1 of the feedwater tank and deliver it to a 5u filter bag which is packed with non-absorbent cotton wool and mounted in compartment 2 of the feedwater tank. The oil coalesces on the cotton wool and the partly cleared water passes over a weir into compartment 1 from where it is recirculated through the filters. The filter pump delivers about 180 ml/s while the feedwater pump draws 90 ml/s from compartment 2 of the feedwater tank. Beads of oil form on the non-absorbent cotton wool and float to the surface in compartment 2 from where they are carried over the weir into compartment 1.

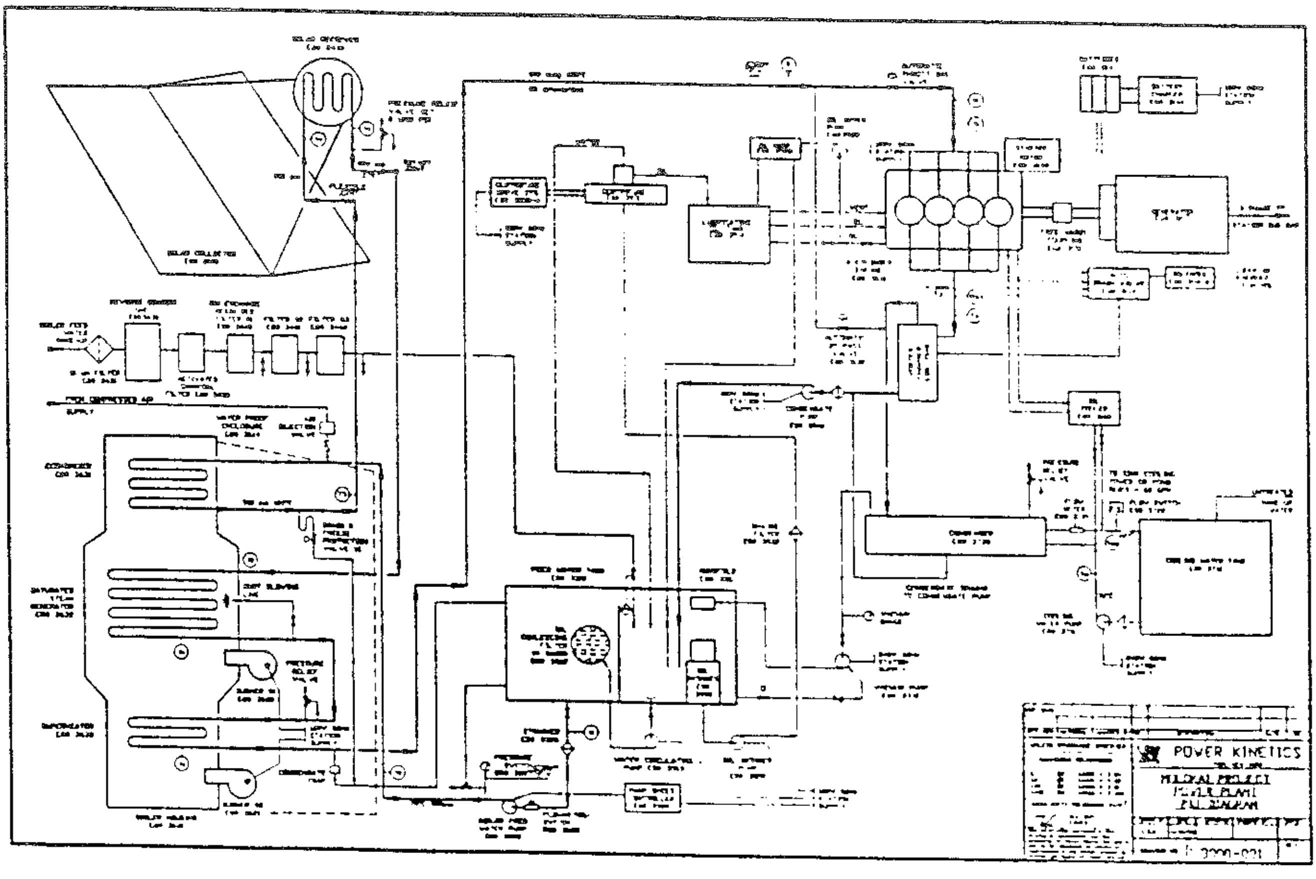


FIGURE 5 The interconnection of components of the power plant

POWER CONVERSION SUBSYSTEM

Most of the engine is made from parts of two diesel engines which are on the market. The crankcase, sump, crankshaft, flywheel, connecting rods and starter are from a Lister Diesel. The cylinder liners and pistons are from a GM diesel. The engine is started by a standard electric starting motor. Steam is admitted to each cylinder through ball valves which are opened by fingers attached to the crown of the pistons. The steam expands until the piston exposes the exhaust ports in the cylinder liner, which was made for a two stroke diesel engine. The engine is started automatically when the incoming steam is hotter than 180°C and the pressure reaches 2.74 MPa (400 psi). The full supply of steam being produced by the collector is used whenever the engine is running. When the power from the collector drops due to lack of sunshine, the engine stops and the starting circuits are reset to monitor the steam and await the starting conditions. The engine is not sensitive to water in the steam, it gives partial output from wet low temperature steam when the sun is attenuated and not supplemented by the oil fired boiler, and a maximum net output of 53 kWe when the insolation is 1 kW/m^2 and the superheater is supplying 40 kW.

The engine configuration is as follows:

Bore	98.4 mm
Stroke	114.3 mm
Number of cylinders	4
Max. steam press.	6.89 MPa (1,000 psi)
Max. steam temp.	450°C (850°F)
Condenser press.	24.5 kPa (abs)
Expansion ratio	25
Lubrication	as in Lister engine
Lubricant	Mobil oil XRN 1301C

Initial water treatment will be done on a plant basis providing deionized water to each module. Each module will utilize a closed loop steam Rankine cycle with only incidental evaporation from the oil skimming tank and occasional boiler blowdown having to be made up. Water supply at the site will be required for both boiler feed and cooling.

Figure 5 shows the interconnections between the components of the steam system. The exhaust steam line enters the upper end of a cylindrical vortex chamber tangentially. Oil and water droplets are stopped by a gauze sleeve on the inner surface and drain to the bottom of the chamber, the steam passes up through the top plate of the vortex chamber to the condenser. The smallest oil drops pass into the condenser with the steam, and the condensate carries these as a very fine suspension to compartment 1 of the feedwater tank. This dispersion of oil in the condensate must be removed before the water is returned to the boilers. It cannot be removed by conventional filters or the centrifuge. The method used is to pump water from compartment 1 of the feedwater tank and deliver it to a 5u filter bag which is packed with non-absorbent cotton wool and mounted in compartment 2 of the feedwater tank. The oil coalesces on the cotton wool and the partly cleared water passes over a weir into compartment 1 from where it is recirculated through the filters. The filter pump delivers about 180 ml/s while the feedwater pump draws 90 ml/s from compartment 2 of the feedwater tank. Beads of oil form on the non-absorbent cotton wool and float to the surface in compartment 2 from where they are carried over the weir into compartment 1.

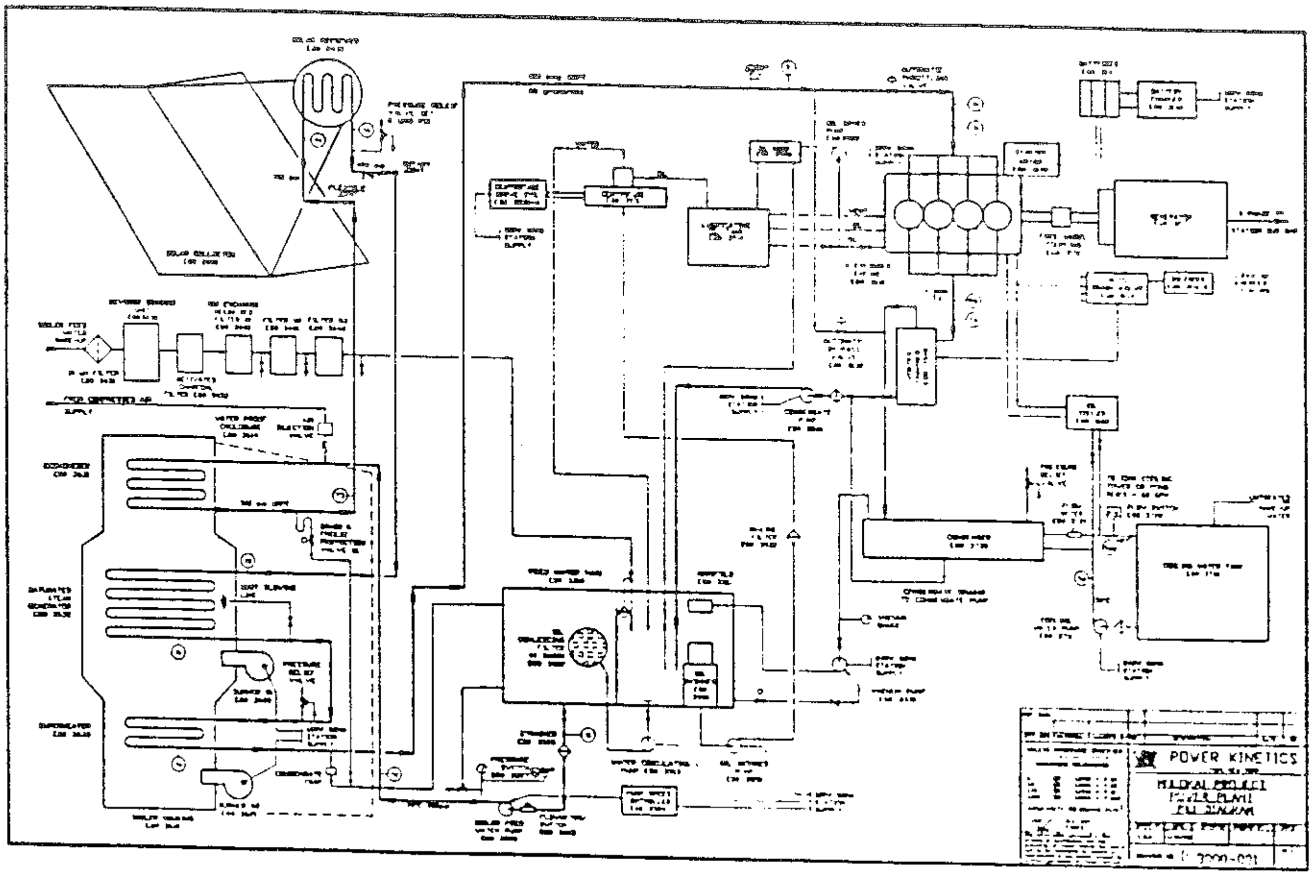


FIGURE 5 The interconnection of components of the power plant

Level switches in the vortex chamber control the operation of the condensate pump which delivers the oil-water mixture to compartment 1. There the oil collects on the surface of the water which varies in level depending upon the amount of water or steam in the return line from the collector. A special skimmer, which floats to the level needed to skim at the rate determined by the flow into the skimmer pump, is used to collect the oil with water. The skimmer pump delivers this mixture to the centrifuge. About 2 ml/s of oil is recovered from the engine exhaust with the complete condensate treatment. The oil is washed and cleaned by this process, leaving solids in the various filters and the centrifuge chamber.

A small quantity of steam leaks to the engine crankcase and condenses. This water must be removed from the lubricating oil in the sump. The wet oil is pumped at 35 ml/s from the sump and through filters to remove the water. It then returns to the oil tank. Oil cooling is also required to remove the heat conducted to the sump oil by the crankcase.

Engine operation starts when the module controller sends an enable signal to the engine controller. This signals the central plant controller and the module's concentrator both to allow operation. As in all cases, a manual shutdown can override the enable signal.

While the engine is stopped, each cylinder is drained of water and steam by a valve. Interlocks prevent the starter from functioning unless the drain is open. As soon as the engine starts, the drain valve is closed by a signal based on engine speed. When the engine is running, any water in the steam is diverted via a steam separator and trap.

The engine controller monitors fluid temperatures, pressures and levels to detect out of limit conditions. The out of limit signal shuts down the whole module at the module controller level and a light signals the reason for the shutdown.. The module controller relays the shutdown status of the module to the central plant controller without affecting the other modules. The independent engine controller allows the module to safely produce electric power as long as there is steam and no shutdown condition.

An induction generator is specified for delivering the electrical power to the utility. It is driven from the engine via a cam clutch which allows the generator to run as a motor when the engine stops due to a passing cloud. At sunset or when continuous clouds develop, the generator is disconnected from the bus after the engine has stopped. When compared to a synchronous generator, the induction generator offered several advantages to the project:

- No voltage regulator is required. Voltage and frequency are controlled by the utility
- Simple construction; no brushes or collector rings
- No synchronizing circuit for paralleling to the utility
- Lower maintenance costs
- Large power swings do not pull the generator out of synchronization with the system.

The generator chosen for the project obtains a high efficiency through use of heavy rotor bars, a close tolerance rotor, extra copper in the stator windings, and an efficient fan. It is a 240/480 VAC, 3-phase, 60 kW/90 HP size at 1800 RPM nominal speed. Actual operating speed is 5% faster with an expected efficiency in the .95-.96 range.

HEAT REJECTION SYSTEM

The condenser of the power conversion subsystem is designed to be cooled by water from a holding tank. On a sunny summer day, heat can be transferred to the water increasing the temperature about 10°C. The heat is lost from the tank by evaporation and some convection to the air at the surface. Evaporation is enhanced by spraying the return water into the pond. At night the heat gained during the day is lost and the temperature drops to a few degrees above that of the air temperature.

The condenser is a shell and tube design with the water in the tubes. The condensate drains from the shell to the vortex chamber and condensate pump. The vacuum pump is a liquidring sealed rotary vane pump for which the flow of cooling and sealing water required is 33 ml/s which is circulated from the feed water tank.

When the engine is not operating, a bypass valve allows water or steam from the solar collectors to pass to the condenser until the steam conditions are correct for the engine to start.

STATUS OF PROJECT

The system design for the Molokai Small Community Program optimizes flexibility. The heavy requirement for reliability because of the remote nature of the site, added significant engineering challenges, but most hurdles have been surmounted under the design phase of the program. Although the 306 m^2 Square Dish has not been approved for manufacture at this time, engineering prototypes indicate that the large size can be produced economically with great gain to system economics. This planned gain permitted the inclusion of fossil hybrid operations.

A pre-production engine similar to the one in operation at White Cliffs in Australia has already been run with a prototype boiler for more than 600 hours. The large risks have been engineered out of the program through suitable equipment design, leaving the more routine risks related to responding effectively with a remote site.

ACKNOWLEDGEMENT

The information presented is the result of the design effort funded by the U.S. Department of Energy under contract DE-FC04-85AL32887 Small Community Solar Experiment -- Molokai, Hawaii. Sandia Laboratories, Albuquerque, NM, provided technical management.