The development and impact of an outdoor solar thermal test facility

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Abstract
A recently established programme of solar thermal energy research at the Mangosuthu Technikon has benefited from the development of an outdoor test facility. STARlab provides a secure and productive environment for conducting equipment tests. A brief description of the facility's development is given together with its impact on various solar thermal projects, including the characterisation of a solar collector's performance.

Keywords: solar thermal, parabolic trough collector, radiometry, solar cookers

Introduction
With a growing economy and expanding electricity grid, South Africa faces a potential shortfall in power-generating capacity. To help meet future energy needs in an environmentally responsible manner, the government has endorsed renewable energy and committed the country to producing 4% of its anticipated power requirements from renewable sources by 2013 (DME, 2003). For their part, South African tertiary institutions will be required to increase the output of scientists, technicians and engineers, with relevant skills as well as increase renewable energy research capacity and output.

In this regard, Mangosuthu Technikon has developed a renewable energy research programme focusing on solar thermal technologies. A parabolic trough collector module has been designed and constructed and research is being conducted into tracking and control systems, radiometric monitoring and solar cookers for rural application. As part of the programme, the institution has constructed an outdoor test facility on its Durban campus. This paper describes the development of the Solar Thermal Applications Research Laboratory (STARlab) and how it has positively affected individual projects within the Technikon's research programme.

Development of the STARlab facility
Access to a dedicated testing facility is essential to workers in a solar thermal energy research programme. Apart from providing space to conduct performance tests on equipment, weather conditions must be monitored and solar irradiance data continuously recorded so that an accurate profile of the solar resource can be built up over time. Examples of high-profile facilities include Sandia Laboratories' National Solar Thermal Test Facility in the USA, and the Plataforma Solar de Almeria (PSA) in Spain. Smaller university test sites include a 100 m^2 outdoor facility in northern Greece described by Bakos et al. (1999) and rooftop laboratories at the universities of Stellenbosch (US) and KwaZulu-Natal (UKZN). Big or small, the facilities aim to provide a secure, functional and productive environment in which equipment test data may be acquired, processed and integrated with weather and solar data to present a comprehensive picture of performance.

With the need for such a test facility, STARlab was developed at Mangosuthu Technikon between July 2002 and February 2003. A vacant rooftop site atop a three-story lecture theatre complex was identified as suitable. Key criteria for the selection of a site included good accessibility to staff and equipment, good exposure to solar radiation, minimal exposure to wind, adequate floor-space and a stable, flat base with good load-bearing capacity. Requirements identified for development of the site included adequate safety and security measures for personnel, provision of power and water, provision of a control room for housing computers, Local Area Network (LAN) and Internet connectivity, provision of comprehensive radiometric and meteorological monitoring equipment on site and adequate lightning and power surge protection. The layout of the completed rooftop site is given in Figure 1.

The suite of radiometric and meteorological instruments installed includes a tracked Normal Incidence Pyrheliometer (NIP) for measuring direct normal irradiance (G_{DN}), and Precision Spectral Pyranometer (PSP) for measuring either diffuse or total global irradiance (G_d and G_t respectively). Voltage signals from the radiometers and test thermocouples are scanned by a data acquisition unit and logged using custom-designed LabVIEW applications running on a workstation computer in the

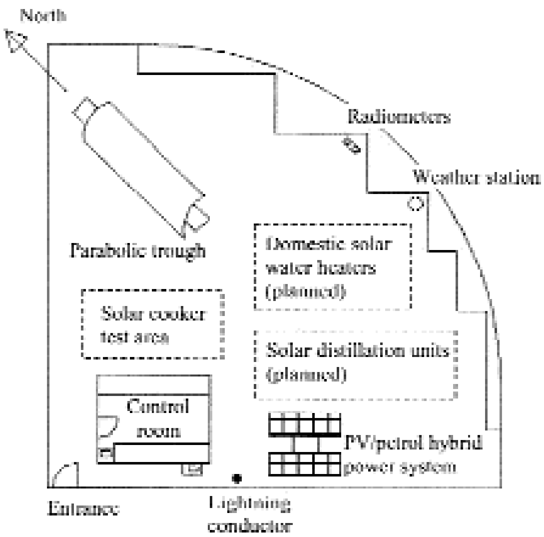

Figure 1: Layout plan of STARlab facility

STARlab control room. A commercial weather station connected to a logging computer provides temperature, atmospheric pressure, wind, rainfall, and related information in support of equipment tests and for continuing analysis. Together with the radiometers, the data acquisition system also allows for ongoing measurement and analysis of the solar resource. Table 1 presents key features of the test facility.

Impact on solar thermal energy research

To date, the development of STARlab has positively impacted on four research projects. These relate to performance testing of solar cookers, tracking systems for concentrating collectors, radiometric monitoring and analysis, and the testing of a locally developed parabolic trough solar collector (PTSC).

Solar cooker tests

Pilot-trials have been conducted at STARlab in anticipation of a full-scale test programme for commercial solar cookers in 2005. During the trials, a comparison was made between the performance of a Sunstove cooker in tracked and untracked configurations. This was to fine-tune future testing procedures. Tests were also run to compare the performance of two different types of cookers.

Use of STARlab and its measurement equipment was key to establishing a comprehensive test plan for the forthcoming programme, which aims to apply a recognised testing standard to characterise the performance of cookers under a variety of conditions. Results will be used to improve their design.

Table 1: Key features of STARlab

Location	Latitude 29° 58.214' S Longitude 30° 54.901' E
Elevation	105.5 m (AMSL)
Area	257 m^2 (total floor area) 16 m^2 (control room)
Construction materials	*Floor:* raised platform of galvanised steel mentis grid panels on waterproofed concrete roof *Nett load-bearing capacity:* 175 kg/m^2 *Control room:* steel framework with aluminium cladding
Services	Municipal water supply, geyser, 220 VAC and 3-phase electrical power
Internal temperature control	Air conditioner, low-transmittance window film, ceiling insulation, shading overhangs
Connectivity	Four fire-wall protected connections to Technikon server
Security	Closed-circuit camera, motion-detecting alarm with radio link to campus security
Weather monitoring	Davis Vantage Pro weather station, sensor suite and display console with on-board memory and battery back-up Weatherlink software for display, logging and report generation
Radiometric monitoring	*Eppley Laboratories:* PSP (Serial # 33583F3) NIP (Serial # 31955E6) ST-1 motorised tracker
Data acquisition and processing	*Hardware:* Agilent Technologies 34970A data acquisition/switch unit with 34901A 20-channel multiplexer module and 34907A multifunction module Two desktop computers with uninterruptible power supply unit *Software:* MATLAB, Microsoft Office, Autodesk Inventor, LabVIEW, Benchlink

Tracking systems for concentrating collectors

Since the latter part of 2003, STARlab has been successfully used to test tracking and control systems for concentrating solar collectors. A PLC-based system using the PSA Algorithm (Blanco Muriel et al., 2003) to locate the solar vector has been developed by Naidoo (2005) and implemented on the Technikon's parabolic trough test-bed. This work is being expanded to include intelligent control methodologies.

Radiometric monitoring and analysis

Although maps of averaged solar radiation data are available for South Africa, Duffie and Beckman (1991) assert that calculating the dynamic behaviour of solar energy equipment requires more detailed information. For example, solar collector testing standards such as ASHRAE 93-1986 (RA 91), hereafter ASHRAE 93, require real-time irradiance values to establish the energy input to the equipment under test (ASHRAE, 1991). After STARlab's completion in February 2003, a programme of daily radiometric monitoring was started at the facility. Figure 2 shows typical G_{DN} and G_t values collected as part of the programme over a week in March 2003, with most of the days reflecting partly cloudy or completely overcast conditions. The 17th and 21st show curves typical of clear days.

Although not yet fully developed, the monitoring programme is now an ongoing research project in its own right and has three aims; to supply information in support of equipment tests, to test new monitoring techniques and to make solar data available to researchers locally and abroad via the World Wide Web. Further work is required to ensure that logging techniques and reporting methods conform to the standards of the World Meteorological Organisation (WMO).

Parabolic trough solar collector

To date, STARlab's greatest impact has been in facilitating a test programme to determine performance of a PTSC according to the ASHRAE 93 standard. Between December 2003 and July 2004, tests were conducted on a 5-metre collector module to characterise thermal efficiency, incidence angle modifier, collector acceptance angle and collector time constant (Brooks et al., 2005). While the PTSC was under construction in 2003, meteorological and radiometric monitoring programmes were run to provide data used in preparing test procedures and scheduling tests.

ASHRAE 93 requires that ambient test conditions such as temperature, wind speed and irradiance fall within prescribed limits, as given in Table 2.

Table 2: ASHRAE 93 prescribed limits for outdoor solar collector tests

Parameter	*Limits*
Ambient temperature, t_a	$t_a < 30°C$
Wind speed, v_w	$2.2\ m/s = v_w = 4.5\ m/s$
Global irradiance, G_t	$G_t = 790\ W/m^2$

For a concentrating collector the direct normal component of irradiance is of prime importance, thus the irradiance limit condition was taken as $G_{DN} = 790\ W/m^2$ for this programme.

The standard further requires that thermal efficiency tests should be run symmetrically before and after solar noon. The meteorological data shown in Figures 3 to 6 were gathered to evaluate STARlab as a test site ahead of the programme. Figure 3 gives a breakdown of monthly average air temperature from February 2003 to January 2004, for three periods during the day. Expected seasonal variations in temperature are visible. Little variation is seen between the periods, although morning temperatures tended to be slightly lower. The data suggested that STARlab was suitable for conducting tests since, on average, the ASHRAE 93 upper ambient temperature limit was unlikely to be exceeded during any of the time periods.

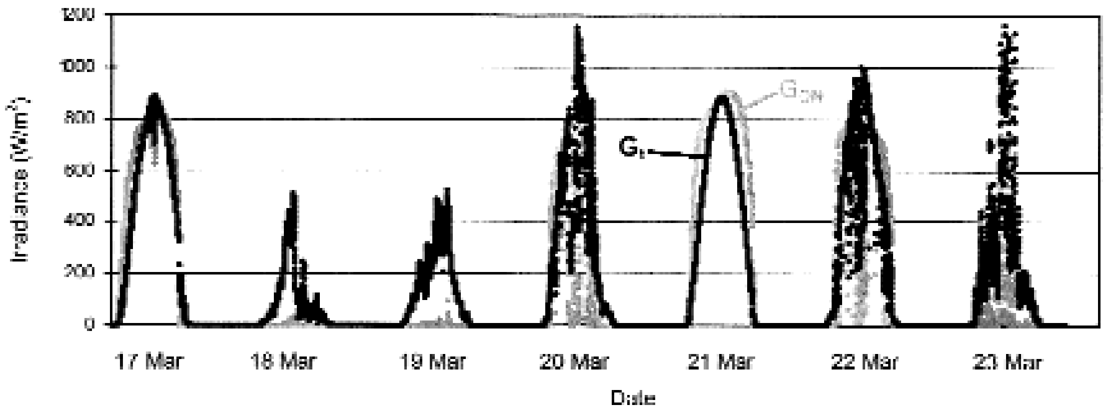

Figure 2: Direct and global irradiance for the week of 17 to 23 March 2003

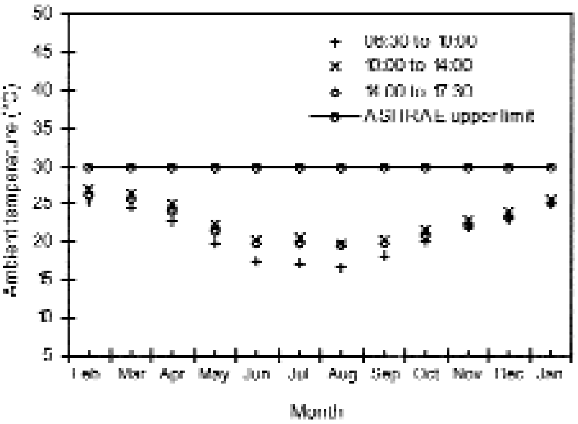

Figure 3: Monthly average air temperature for early morning, midday and afternoon periods

Unlike temperature, the facility experienced higher than allowed average wind speeds over several months, with the ASHRAE 93 violations occurring from 10:00 hours onwards between August and December and during February and March (Figure 4). While these results represented one year's worth of monitoring only, they suggested that high daily wind speeds might interrupt the PTSC test programme.

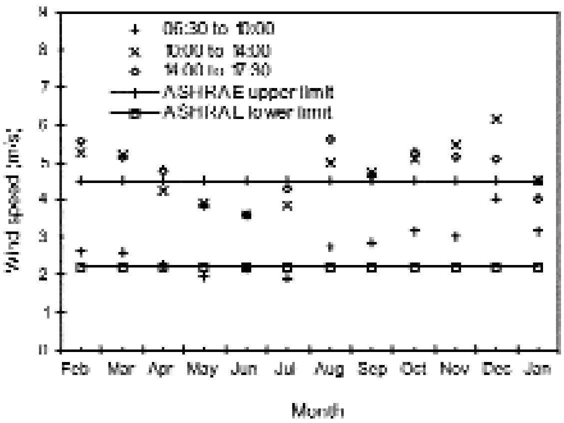

Figure 4: Monthly average wind speeds for early morning, midday and afternoon periods

While peak temperatures remained within limits over the monitoring period, the daily peak wind speed exceeded the ASHRAE limit in every month (Figure 5). This data prepared researchers for a disrupted test programme with repeated aborts and restarts and spurred development of a real-time PTSC monitoring application, using LabVIEW software, to enable rapid configuring of the test rig.

In ten out of twelve months, more rain fell overnight than during the day at the facility, with total night rainfall for the year at 464 mm (Figure 6). During the monitoring period, there was no significant difference between mornings and afternoons, with total morning rain for the year at 129 mm and afternoon rain at 126 mm. While of interest, these results were secondary to the output from the

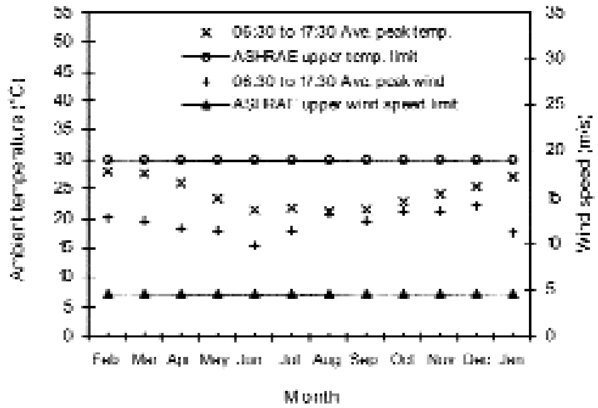

Figure 5: Monthly-averaged daily peak wind speeds and temperatures between February 2003 and January 2004

radiometers, which better describe the presence of cloud. Nevertheless, the data suggested there would be little difference between mornings and afternoons as far as disruption of testing due to rain was concerned.

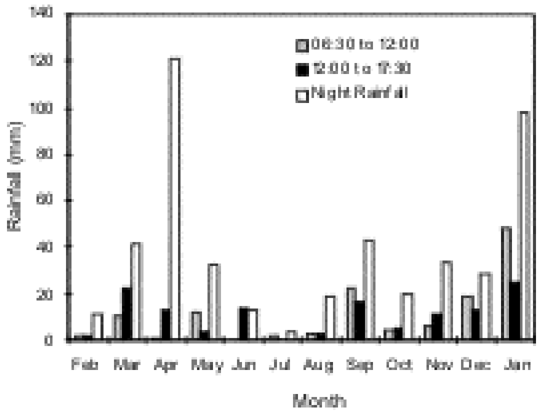

Figure 6: Monthly rainfall by time period between February 2003 and January 2004

In the initial monitoring phase, data from the STARlab radiometers was logged from February to September 2003, where after the programme was terminated while software applications were developed and tested. To expand the monitoring window, additional readings from a nearby station at the University of KwaZulu-Natal (UKZN) covering December and January 2002/2003 were used to augment the Technikon data (SELFRAD, 2004).

The aim was to determine G_{DN} as a function of the month, as well as the daily time at which the threshold value of 790 W/m^2 was first recorded (T_{THRESH}). This was to enable researchers to meet ASHRAE 93 requirements regarding minimum irradiance (Table 2) as well as to ensure that the correct angles of incidence (θ_i) could be obtained for the collector, without violating the related ASHRAE 93 limits.

Towards the end of the PTSC test programme, it was planned to repeat certain tests for a second receiver type. The PTSC is tracked about a single axis only, however, and from February onwards, it begins to experience angles of incidence which exceed the ASHRAE 93 limits. This requires tests to be conducted earlier in the morning or late in the afternoon when more favourable angles prevail.

The problem is that sun strength gradually falls through autumn into winter, reducing G_{DN}. This reduction is exaggerated in the mornings and afternoons, leading to a dilemma for the test operator – how to run tests with appropriate solar angles, while maintaining minimum allowable irradiance levels. The solution lies in intelligent scheduling of collector tests to optimise the time available, but this requires knowledge of the sun's anticipated strength and position.

To this end, the data from STARlab and UKZN were integrated to produce Figure 7, which shows the seasonal change in peak direct normal irradiance and T_{THRESH}. Best-fit curves obtained by regression analysis are also shown. The graph covers the anticipated test period of December to September and the data was gathered in 2002/2003 for application during the PTSC test programme in 2004.

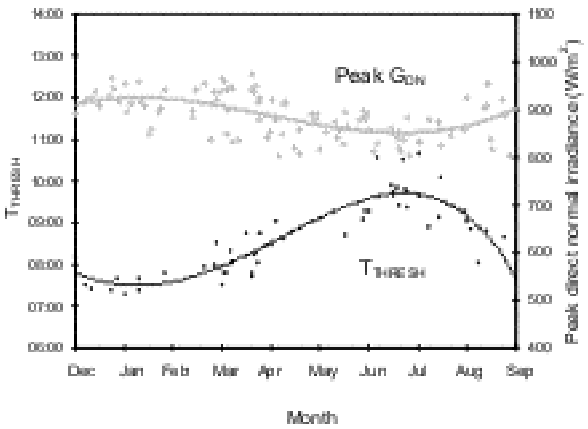

Figure 7: Peak G_{DN} and morning T_{THRESH} values for December 2002 to September 2003 obtained from merged STARlab and SELFRAD data

Having noted and characterised seasonal trends in the irradiance data of Figure 7, it was possible to schedule four sets of PTSC tests for two receiver types, with confidence that minimum irradiance levels and incidence angle criteria would be met. Thermal efficiency tests for were scheduled so as to ensure minimum incidence angles, as required by ASHRAE 93, while incidence angle modifier tests were scheduled for when the necessary set-point values of θ_i could be obtained.

Although some violations of ASHRAE 93 criteria occurred during efficiency testing with respect to excessive angles of incidence, these were limited. The minimum irradiance criterion was upheld throughout. Figure 8 shows each test from the completed programme superimposed on a solar map for the STARlab facility, which gives daily changes in solar angle of incidence over a six month period, coinciding with the collector test programme (Brooks, 2005). The map was obtained by implementing the PSA Algorithm for a north-south aligned parabolic trough at STARlab's location. The morning and afternoon T_{THRESH} limits were obtained from the regression curve fitted to the data in Figure 7.

During the PTSC test programme, which ended successfully in July 2004, approximately 30 000 lines of processed spreadsheet data were generated over 130 hours of testing. STARlab's role in this programme cannot be overstated. The facility enabled and sustained the test programme from the planning stage through to completion.

Conclusion

Many factors influence the quality of results from solar energy equipment tests, including weather conditions, instrumentation, measurement techniques and testing methodology. The environment in which the tests take place is also of crucial importance. Mangosuthu Technikon has developed the Solar Thermal Applications Research Laboratory to provide a fit-for-purpose space in which outdoor testing can take place. The key criteria governing development of the facility, the nature of the site's conversion and an inventory of equipment have been provided.

Since January 2003, the decision to develop STARlab has been validated by the successful hosting of a series of research test projects. Performance tests on a parabolic trough collector and its tracking system as well as a radiometric monitoring project could not have taken place without access to STARlab and its data acquisition systems. Furthermore, the comprehensive meteorology and radiometry studies conducted before the start of PTSC testing streamlined the test programme, ensuring it was completed on time and with due regard for the requirements of an international testing standard.

Now that STARlab has demonstrated its potential, researchers are expanding data acquisition capabilities at the site and further projects are planned, including studies into solar thermal water distillation and certification of domestic solar water heaters.

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