PLATO Power—a robust, low environmental impact power generation system for the Antarctic plateau

Shane Hengst*[a], Graham R. Allen[b], Michael C.B. Ashley[a], Jon R. Everett[a], Jon S. Lawrence[a], Daniel M. Luong-Van[a], John W.V. Storey[a]

[a]School of Physics, University of New South Wales, Sydney, NSW, Australia 2052;
[b]Solar Mobility Pty Ltd, PO Box 951, Epping, NSW, Australia 2121

ABSTRACT

PLATO (PLATeau Observatory) is the third-generation astronomical site-testing laboratory designed by the University of New South Wales. This facility is operating autonomously to collect both scientific and site-testing data from Dome A, the highest point on the Antarctic plateau, at an elevation of 4093m. We describe the power generation and management system of PLATO. Two redundant arrays of solar panels and a multiply-redundant set of small diesel engines are intended to provide 1–2kW of electrical power for a full year without refueling or other intervention. An environmental chamber has been constructed to study the high-altitude performance of the diesel engines, and suitable cold-starting procedures and engine lubrication techniques have been developed. PLATO's power system is an innovative solution with wide applicability to small astronomical facilities on the Antarctic plateau, offering minimum environmental impact and requiring minimal human intervention.

Keywords: Diesel engine, remote power generation, Antarctica, Dome A

1. INTRODUCTION

PLATO (PLATeau Observatory)[1] is a remote facility that has been successfully deployed to Dome A, Antarctica (see Fig. 1) in January 2008 by an expedition of the Polar Research Institute of China. PLATO was designed and built at the University of New South Wales to provide heat, power and communications for a suite of site-testing instrumentation. The UNSW Antarctic Group has previously developed remote facilities for the South Pole (AASTO, or Automated Astrophysical Site-Testing Observatory), and for Dome C (AASTINO, or Automated Astrophysical Site-Testing InterNational Observatory). Fig. 1 shows the locations of these sites.

The AASTO[2] was built by Lockheed and was based closely on the US Automated Geophysical Observatory. It used a propane-fuelled thermoelectric generator, producing some 50W of electrical power and 2.5kW of heat.

AASTINO[3] was powered by a pair of WhisperGen PPS16 24VDC[4] Stirling engines burning Jet A-1 fuel. The two engines were cooled with a glycol loop that fed directly into large heat exchangers, keeping the AASTINO warm via the waste engine heat. At sea level the WhisperGen engines produced 750W of electrical power but, as with any naturally-aspirated combustion engine, they produce less power as the altitude increases. At Dome C each engine was able to produce about 500W. AASTINO also used two solar panels to provide additional power during summer.

In developing PLATO, several new factors had to be taken into account, building upon the experience from the earlier AASTO and AASTINO facilities. New challenges to be faced at Dome A include:

- **No preferred wind direction.** Unlike at Dome C and the South Pole, the wind at Dome A has almost no preferred direction[5]. This means that it is impossible to protect the astronomical instruments from the exhaust stream by simply placing them upwind of the engines, as was done with the AASTINO. Instead, a separate engine and instrument module are required, spaced at a sufficient distance that the exhaust stream is less likely to intrude into the atmosphere through which the instruments are observing. The disadvantage of this approach is that it is then no longer possible to use waste engine heat to keep the instrument module warm, unless the engine coolant is plumbed between the two units. This option was, however, considered to be impractical, leading us to a solution in which the instrument module is heated purely by electrical power.

* shane@phys.unsw.edu.au; phone 61 2 9385 6695; fax 61 2 9385 6060

Ground-based and Airborne Telescopes II, edited by Larry M. Stepp, Roberto Gilmozzi,
Proc. of SPIE Vol. 7012, 70124E, (2008) · 0277-786X/08/$18 · doi: 10.1117/12.788478

- **Higher altitude.** The physical altitude of Dome A is 4093m. However, the cold air above Antarctica results in a smaller scale height for the atmosphere, resulting in a pressure altitude at Dome A of typically 4500m. The engines must be able to start reliably at this altitude, and their power output must be sufficient even with the thinner air they will be breathing. In practice, this means choosing an engine of a significantly larger displacement than would be required at sea level.

- **Colder.** Dome A is almost certainly the coldest place on earth, although this is not yet firmly established as meteorological records are only recognized if made by a human observer! Nevertheless, temperatures as low as –90°C appear possible. This is well below "dry ice" temperature, emphasizing the need for extremely well-insulated structures and very efficient use of energy.

- **More remote.** The greater difficultly of bringing materials to Dome A makes it even more important that the power solution be optimized in terms of fuel type, fuel efficiency, and power management.

In addition, increasingly sophisticated astronomical instruments require ever greater amounts of electrical power. The PLATO power solution is therefore designed to be both adaptable and scalable—that is, it can provide additional power for short periods when required, and future versions can be built to provide higher base loads if necessary.

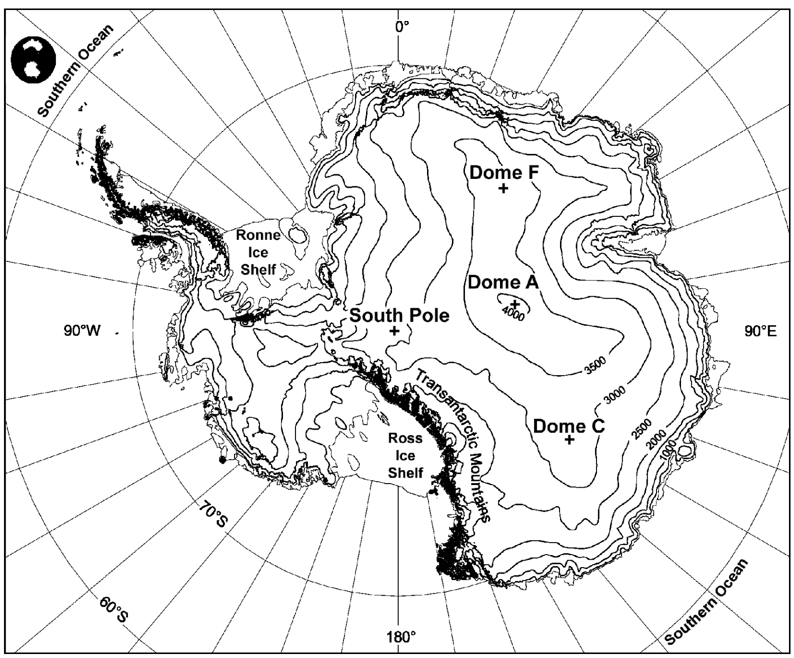

Fig. 1: Contour map of Antarctica (courtesy of AAD)

2. POWER GENERATION AND THERMAL MANAGEMENT

Fig. 2 shows that, during the course of a year, the Sun is continuously above the horizon at Dome A for approximately four and a half months, rises and sets each day for three months and is continuously below the horizon for four and a half months The ideal power system will therefore be one that uses solar power during the summer, short-term electrical storage in the form of batteries, and uses a high energy-density fuel in an efficient manner during the dark winter months. PLATO therefore uses a hybrid solar/diesel power solution, burns Jet A-1, and has lead-acid batteries for energy storage.

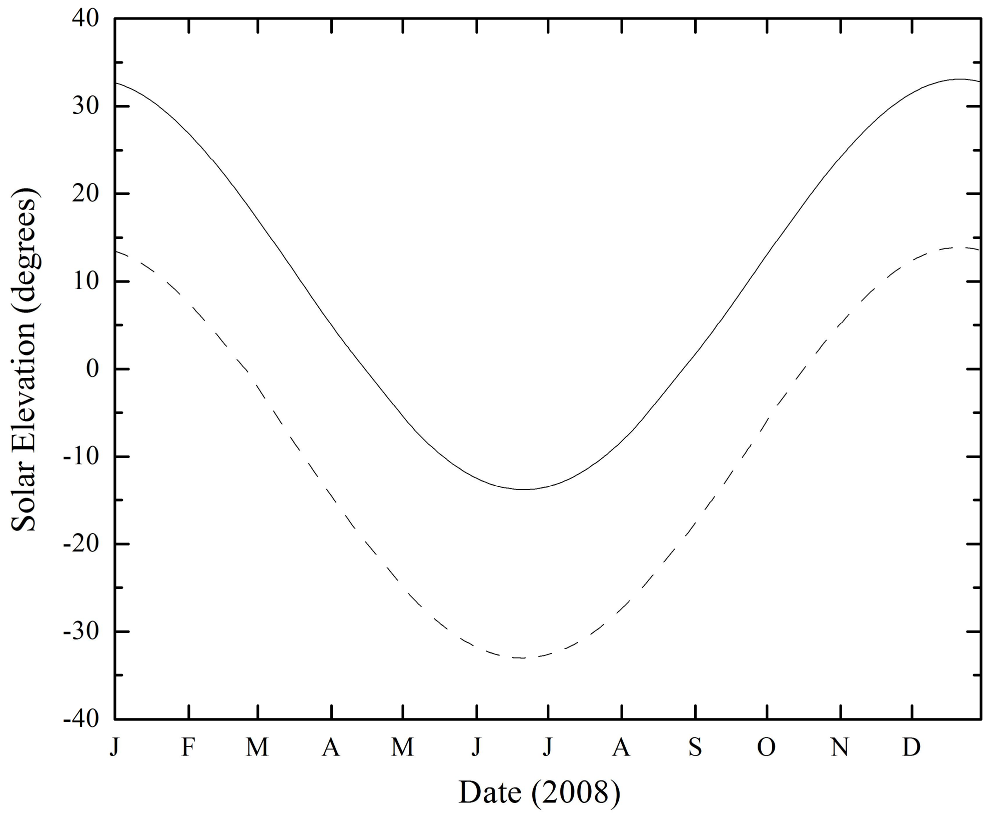

Fig. 2 Maximum and minimum daily solar elevation at Dome A for 2008.

PLATO consists of a power module and a separate instrumentation module[1]. The two modules are separated by about 50m, and are joined only by the two pairs of high-voltage power cables, a Controller Area Network (CAN) bus cable, and a 28V power bus. Both modules are extremely well insulated: the engine module with 150mm thick polyurethane foam on all six internal surfaces and the instrument module similarly insulated with 200mm of foam.

The engine module is kept warm by the waste heat of the engines. A Eurotherm 3200 PID (Proportional-Integral-Derivative) controller activates two brushless axial-flow fans that exhaust warm air from the module, causing cold air to be drawn in. This maintains the temperature at a steady 20°C. All the fuel required for a year's operation (4000 litres) is also contained within the engine module, where it is kept warm.

The instrument module is kept warm mainly by the waste heat from the electronics. When this is insufficient, up to 1200W of resistive heaters can be switched on. Two anti-stratification fans keep the air within the module well mixed. Should the module become too warm (as can occur during the summer), a Eurotherm 3200 PID controller turns on two exhaust fans, in a manner similar to the thermal management system of the engine module.

The battery bank is a set of six, 4 Volt Sungel 4SG320 sealed lead-acid batteries, giving a nominal power bus of 28V. The batteries have their own 180W heater. Despite their modest energy density (34Wh/kg), sealed lead-acid batteries remain a good choice for short-term energy storage in Antarctica. They have good charge/discharge efficiency, work down to very low temperatures (~ –30°C), can be frozen and re-thawed without serious ill-effect, require only basic charge management, and are remarkably tolerant of accidental abuse.

3. SOLAR POWER

The solar panels are arranged in two arrays of three paralleled panels. Each panel is a polycrystalline silicon Conergy C167P, with a nominal power output of 167W at 25°C; 1.5 air-masses. Fig. 3 shows one array of solar panels that was erected at UNSW for testing.

Each panel is mounted vertically, roughly 1 metre above the snow to allow air to freely flow beneath it, thus minimizing snow accumulation. The two arrays are oriented north-east and north-west respectively, to maximize the amount of energy captured in the late autumn and early spring.

Fig. 3. One of the two solar arrays erected at UNSW for testing.

Each array of three panels is fed to an Apollo Solar T80 maximum-power-point tracker (MPPT)[6]. The two T80 MPPTs are arranged in a master/slave configuration, so that both units will switch from boost charging to float charging and back again at the same time. The master T80 MPPT has its own battery temperature sensor, allowing the output voltage to automatically track the battery's charging requirements.

Solar arrays are remarkably effective in Antarctica, as we have previously noted with the AASTINO[3]. Silicon solar cells are significantly more efficient at low temperatures, producing 5% more power for every 10°C drop in temperature. This, combined with the enhanced solar input from the snow reflection, results in a power output of up to 220W from each 167W panel. The bright reflection from the snow has another advantage: even when the sun is directly behind the panel, it can produce several watts of power.

When the Sun is above the horizon, it also provides a significant amount of useful radiant heat to the modules.

4. DIESEL POWER

Within the engine module are six Hatz 1B30 diesel engines[7] arranged in two banks of three. See Fig. 4. The engines are air-cooled single-cylinder units with a capacity of 350cc and a nominal power output of 5.4kW at 3600rpm at sea level. Generally, only one engine is running at any time, although the possibility exists to run any number of engines simultaneously. This gives a very high degree of redundancy, plus the ability to boost the power output whenever it is required while maintaining a highly efficient "base load" generating capacity.

These engines have a nominal service interval of 200 hours. However, in PLATO they will see no human being for over eleven months. In order to achieve this extended running time, the engine lubrication system has been extensively modified. Each bank of three engines shares a 60 litre external oil tank. Oil is continuously pumped into each engine from the storage tank with a Thomas Magnete LHP27 metering pump at a rate of approximately 11cc/minute at 3Hz. A simple overflow pipe in each crankcase returns the excess oil to the storage tank. Large-area filters are used to clean the oil. The lubricating oil is fully synthetic Delvac 5W-40[8]. Operating the engines at only 2200rpm further enhances engine longevity.

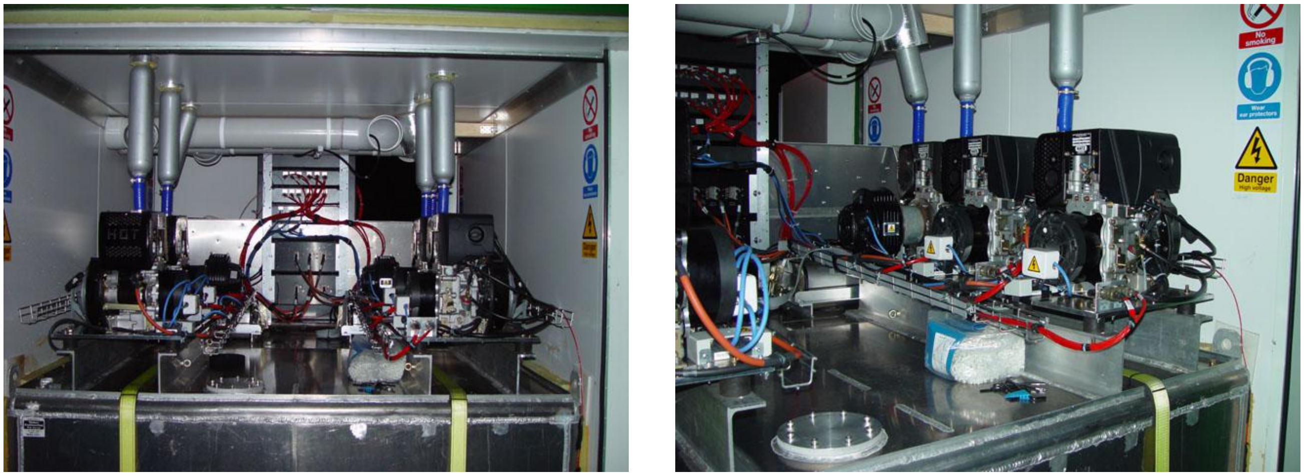

Fig. 4. Left photo: Inside the engine module showing all six engines with electronics mounted on the top of the 4,000 litre fuel tank. Right photo: Inside the engine module showing one bank of the engines. The Mavilor generator is attached to the left-most engine, while the centre and right engines have the eCycle alternators mounted.

The engines sit on top of a 4000 litre aluminum fuel tank. Several thick aluminum webs within the tank provide stiffening and also contribute to the conduction of heat from the engines down to the bottom of the tank. Fuel circulation is further assisted by returning the hot, unused fuel from the injector nozzles back to the vicinity of the pick-up pipe. Fuel is pumped from the bottom of the tank with a Thomas Magnete LHP27 metering pump and passes through a large-area filter on its way to the engine. To help keep the fuel in a liquid state, the fuel pumps on all of the non-running engines are also run continuously, circulating fuel from the bottom of the tank through the warm environment of the engine module before returning it to the vicinity of the pickup lines. If the fuel at the bottom of the tank were to drop much below –40°C, it would freeze and the engines would stop in an unrecoverable state. The fuel tank, when full of fuel, has a thermal time constant of several days, which gives some time to recover from momentary power outages.

The fuel used for the engines is Jet A-1, mixed with ~2% fully synthetic “Racing 2T” 2-stroke oil to provide lubrication for the fuel pumps and injectors.

Two different approaches are used to generate electrical power from the engines: eCycle alternators and Mavilor generators. This was done as a risk-mitigation measure, as neither unit had been tested at this altitude before.

Four of the engines are equipped with brushless alternators made by eCycle[9]. In these units the rotor is mounted directly onto the crankshaft, resulting in an extremely lightweight and compact unit. NdFeB magnets are used to achieve maximum efficiency. The three-phase output of the alternator is rectified with an IR 70MTKB diode bridge to produce 120–150VDC.

The two remaining engines (one on each bank) use MSS 22 axial-flux disc servo motors made by Mavilor[10]. These motors are very efficient (both as motors and as generators) because they have no iron in their armature and hence no hysteresis loss. However, at 16kg they are significantly heavier than the eCycle alternators and, because they have their own bearings, must be coupled to the engine via a flexible shaft coupling. The Mavilor motors produce a DC output of 120–150V. A single IRK166 diode is placed in series with each motor to prevent reverse current flow.

The DC output from each of the three engines in a bank is paralleled after the diode bridges (or blocking diode in the case of the Mavilor) and sent to the instrument module.

4.1 Engine Starting

Each engine has a conventional starter motor that engages with a ring gear on the crankshaft when activated by the starter solenoid. The starter motors draw up to 300A at 12V. At the low temperatures that could be experienced in the engine module, lead-acid batteries lose their ability to deliver high currents. In the interests of reliability, and to ensure that the full starting current would be available at all temperatures, it was decided to instead use a stack of ultracapacitors.

Each bank of engines has its own stack of Maxwell BCAP3000P ultracapacitors[11]. One bank has six paralleled pairs of 3000F capacitors in series, giving 1000F at 12V. This was found to give more than enough capacity for multiple engine start attempts, and so the second bank was constructed with just six 3000F capacitors in series, giving 500F at 12V.

Each ultracapacitor has a voltage clamp across it, to ensure that no capacitor is charged beyond its absolute maximum voltage rating of 2.7V. Additional shunt resistors are used to help distribute the charge equally across the capacitors.

Each capacitor stack is charged from a DC/DC converter that takes its input from the 28V PLATO power bus. The DC/DC converters must be able to deliver their rated current into a short circuit, as this is the load presented to them by a discharged ultracapacitor stack. At a current of 9A it takes 11 minutes to fully charge the 500F stack to 12V, and twice as long as this to charge the 1000F stack.

The 120–150VDC from each engine bank is brought to the instrument module via separate cables. In the instrument module, each bank feeds into a parallel pair of Kepco RKW 28–55K[12] switched-mode power supplies. Although nominally rated at 1500W each, these units (like everything else) must be de-rated to account for the reduced air-cooling from the altitude, and so two are used for each engine bank.

The output voltage from each Kepco pair is set by a feedback loop incorporating a Unitrode UC2906 lead-acid battery charger IC. This automatically tracks the temperature of the batteries with an appropriate compensation. The voltage set-point can also be trimmed by either of two "Supervisor" computers within PLATO over a range of ±5%. Thus, when the sun is up, the set point of the engines can be adjusted below the set point of the solar panels, giving priority to the panels. The UC2906 chip also includes current limiting. This is set to 45A (approx 1400W) so that the engines can never be overloaded.

5. LABORATORY TESTING OF DIESEL ENGINE

Testing of the diesel engine was undertaken in the Internal Combustion Laboratory of the School of Mechanical and Manufacturing Engineering at the University of New South Wales. See Fig. 5.

To simulate the pressure altitude of Dome A at UNSW, an environmental chamber was constructed that can maintain a constant pressure of down to half an atmosphere with the engine running at full power. The chamber consists of a base plate and a bell-jar made from mild steel. The base plate is a circular disk, 30mm thick, with an outer diameter of 1100mm. This is sealed via an O-ring to a 1000mm diameter steel bell jar. The bell-jar has a wall thickness of 5mm, and has a welded dome-shaped head and a welded bottom flange. Two lifting hooks are welded on either side of the bell-jar to accommodate a crane. See Fig. 5.

An 8 cubic metre/minute Roots blower, driven by a 15kW 3-phase electric motor, extracts air from the chamber and discharges it outside the building. The flow rate is chosen to be an order of magnitude greater than the rate at which the engine is consuming air, so that the engine exhaust is well diluted before reaching the Roots blower. Air is continuously introduced into the chamber via an air-filter box and butterfly valve. Manual control of the butterfly valve allows any required pressure to be achieved within the bell-jar.

The engine is attached via rubber isolators to the base plate of the bell-jar. See Fig. 8. A brushless, bearing-less eCycle alternator, similar to those used in the PLATO module, is directly attached to the engine crankshaft. The three-phase electrical output is coupled via a diode bridge to a pair of resistive load banks. The engine breathes the reduced pressure air from inside the bell-jar, and exhausts it via an exhaust diffuser that ensures that the exhaust gases are well mixed with the main airflow before they reach the Roots blower.

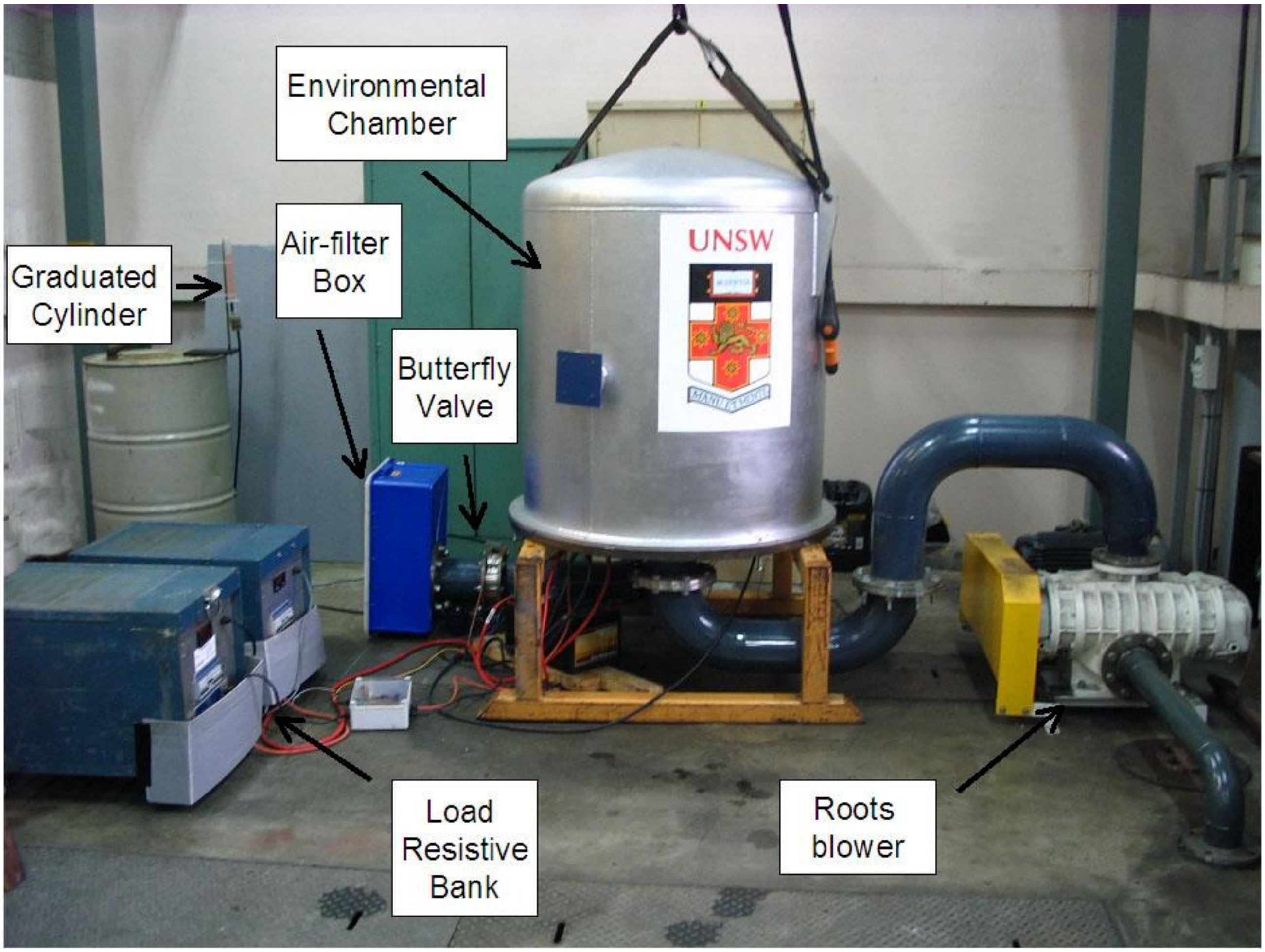

Fig. 5 Engine test rig. Air flows through the air-filter box to the environmental chamber. The rate of airflow is controlled by the butterfly valve. The Roots blower runs at constant speed, pumping air from the environmental chamber.

Fuel consumption is measured using an externally-mounted graduated cylinder, which delivers fuel via a fuel line that leads through the base plate to the engine. By having the fuel-feed system mounted externally to the pressure chamber, there is less vibration coupled to the graduated cylinder, thus allowing a more accurate reading of the fuel level.

To control the speed of the engine, a motor-drive lead screw is attached to the engine governor lever. The actuator is mounted on the engine plate and is electronically controlled via a switch that is external to the chamber.

K-type thermocouple sensors measure the temperatures of the ambient air, oil sump, cylinder head, exhaust gas, alternator/generator and the intake air. The exhaust gas temperature (EGT) is a particularly important indicator of engine performance. The other temperatures are monitored largely to ensure that none of the engine components is overheating.

Readings from the thermocouple sensors, pressure sensors and load bank are all monitored via ADAM modules. ADAM modules are input/output devices that both execute commands and receive voltage signals. The received voltage signals can be calibrated to the desired output of a sensor. A LabVIEW application monitors all systems and records all measurements.

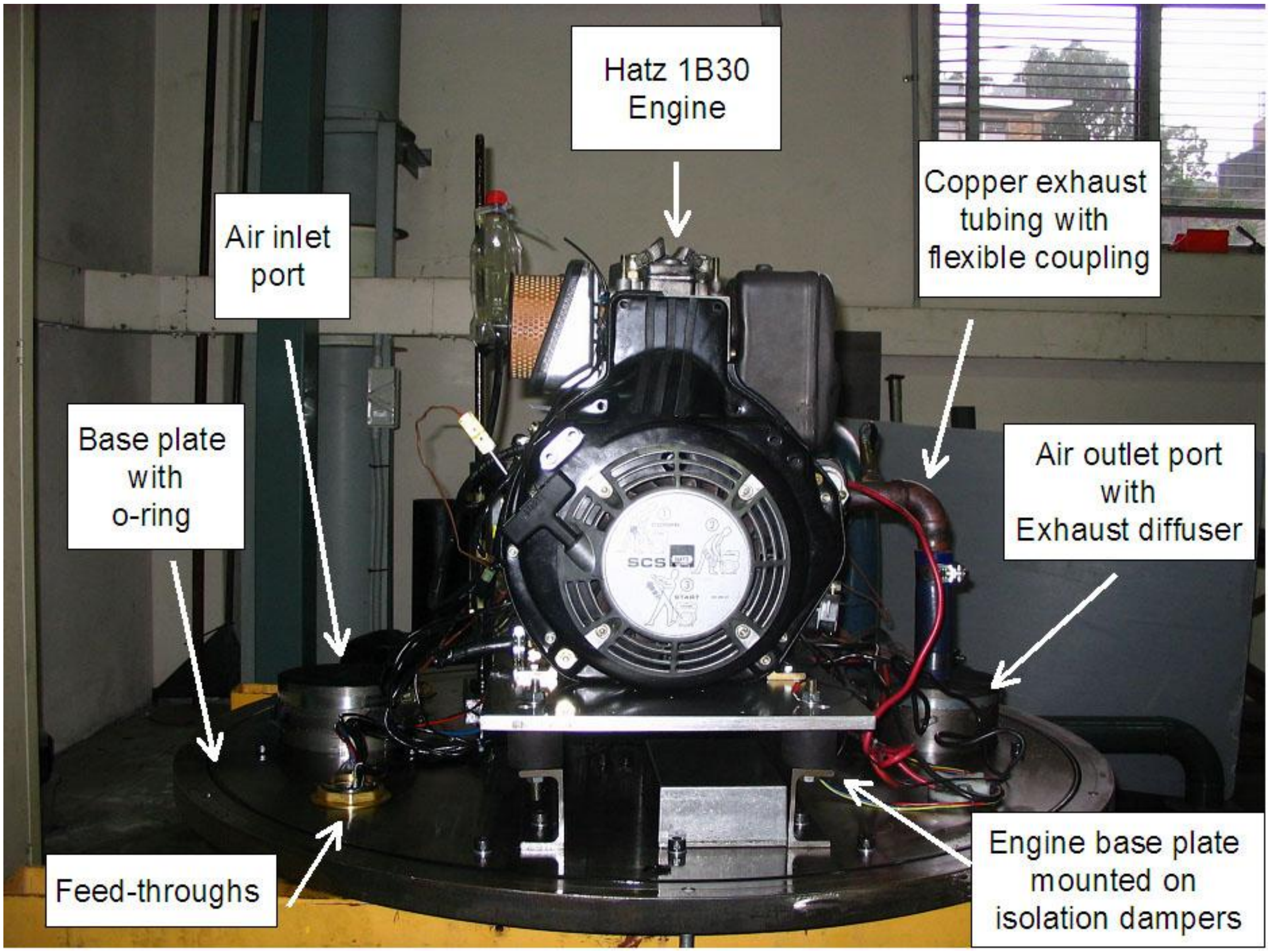

Fig. 6 Hatz test engine mounted on the base plate with peripherals.

5.1 Laboratory test results

The engine was started and stopped at a variety of simulated altitudes. It was found to start reliably, from cold (typically ~ 25°C), at altitudes of more than 5000m. The engine was then run for approximately ten minutes at each speed and load, at both sea-level atmospheric pressure (1000hPa) and at a pressure of about 540hPa, which is well below the typical pressure at Dome A of 575hPa. At each setting, the following parameters were recorded:

- Fuel consumed
- Engine run time
- Load-bank voltage and current
- Exhaust gas temperature

From these data points, a set of engine maps can be constructed for each altitude. We present two examples of this data in Fig. 7, for an engine speed of 2200rpm. In these plots, the power recorded is the electrical output power from the alternator, and thus includes the alternator and rectifier losses. The brake specific fuel consumption figure is therefore an overall fuel-to-electricity efficiency.

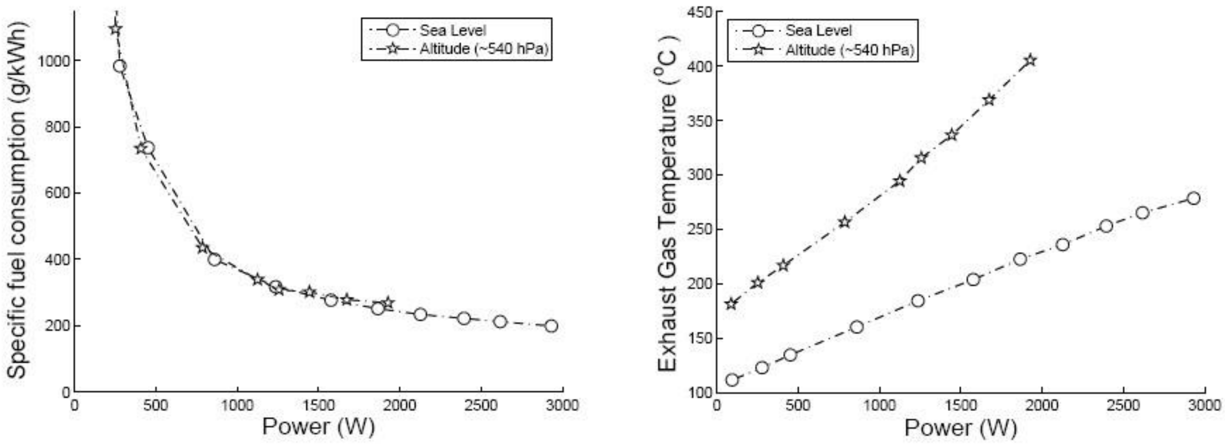

Fig. 7 Left: Brake specific fuel consumption versus power output at 2200rpm. Right: Exhaust gas temperature versus power output at 2200rpm.

The increased exhaust temperature at high altitude observed in the right-hand plot of Fig. 9 agrees with theoretical expectations. As similar amounts of heat must be generated to produce a given power, but only 0.54 times the mass of air is present in the cylinder, the combustion will raise the temperature of the gas by almost twice as much.

The high altitude plots end at 1900W, as this is the maximum power that the engine can produce at 540hPa, no more air being available for combustion.

6. CONCLUSION

Little modification to the engines is required for them to run satisfactorily at an altitude of up to 5,000 m. This is as expected: assuming adiabatic compression, the air in the cylinder will reach the same temperature regardless of altitude (ignoring cylinder wall losses), and will be sufficient to ignite the fuel at each injection stroke. However, the maximum power output at a given speed is reduced in direct proportion to the air pressure, and so the maximum fuel delivery must also be correspondingly reduced. Most importantly, because the air is less dense, there is less working fluid available to do the thermodynamic work and less cooling is available, so the temperature rise (cylinder head, exhaust gas etc.) is greatly increased for a given power output.

At high altitude, the mixture is expected to burn slower than at sea level. To partially compensate for this, the engines are run with an injection timing appropriate for a speed of 3600rpm, even though the actual running speed is 2200rpm.

Allowing for an alternator efficiency of around 85%, we find that the brake specific fuel consumption of the engine at sea level is consistent with published data. Furthermore, little loss of efficiency, if any, is encountered when the engine is run at high altitude.

At the time of writing (May 2008), PLATO has run unattended for 4 months. All engines are still functional, although one is becoming difficult to start and some will not run for more than a few hours without having to be restarted. Power has been continuously available to the instrument module since PLATO was switched on.

7. ACKNOWLEDGEMENTS

This research is supported by the Australian Research Council. We thank the UNSW School of Mechanical and Manufacturing Engineering for access to the Internal Combustion Laboratory. Hatz Australia, and in particular Sami Almogawish, Ian O'Callaghan and Tissa Pathiratna, provided us with invaluable assistance and generously shared their deep understanding of diesel engines with us. Apollo Solar kindly provided us with information on the T80 Maximum Power Point Trackers that was vital to the development of our remote monitoring scheme. Jason Allen was responsible for many of the refinements to the oil circulation system that proved essential to the longevity of the engines. One of the electrical load banks was generously lent to us by Graeme Arnold and Bob Bell from Switchgear Commissioning & Maintenance Pty Ltd and the other by Ian Davis from Eaton Electric Systems Pty Ltd. The Astronomical Society of Australia provided partial funding for SH to attend the SPIE meeting.

REFERENCES

[1] Lawrence, J. S., Allen. G.R., Ashley, M. C. B., Bonner, C., Bradley, S., Cui, X., Everett, J. R., Feng, X., Hengst, S., Hu, J., Jian, Z., Kulesa, C. A., Li, Y., Luong-Van, D., Moore, A. M., Pennypacker, C., Qin, W., Riddle, R., Shang, Z., Sun, B., Suntzeff, N., Tothill, N. F. H., Travouillon, T., Walker, C. K., Wang, L., Yan, J., Yang, J., Yang, H., York, D., Yuan, X., Zhang, X., Zhang, Z., Zhou, X., Zhu, Z., "The PLATO Antarctic site testing observatory", Proc. SPIE Astronomical and Telescopes conference paper, *this volume*

[2] Storey, J.W.V., Ashley, M.C.B. Burton, M.G., "An automated astrophysical observatory for Antarctica", PASA, 13, 35 – 38 (1996)

[3] Lawrence, J.S., Ashley, M.C.B. and Storey, J.W.V., "A remote, autonomous laboratory for Antarctica with hybrid power generation. " Aust. Journal Elec. Electronics Engineering, 2(1), 1-12 (2004)

[4] WhisperTech Limited. Whispergen Personnel Power Station Users Manual: PPS16 marine and land version. Christchurch, New Zealand (2003)

[5] Tothill, N. F.H., Kulesa, C. A., Walker, C. K., Ashley M. C., Bonner, C., Cui, X., Everett, J., Feng. L., Hengst, S., Hu., J., Jiang, Z., Lawrence, J. S., Li, Y., Luong-Van, D., Moore, A. M., Pennypacker, C., Qin, W., Riddle, R., Storey J. W. V., Shang, Z., Sun, B., Travouillon, T., Wang, L., Xu, Z., Yang, H., Yan., J., York, D., Yuan, X., and Zhu, Z., "Astrophysics from Dome A", EDP Sciences, EAS Publications, *in press*

[6] http://www.apollow-solar.net/T80-turbocharger.htm, (May, 2008)

[7] http://www.hatz.com.au/products/b-series/index.html, (May, 2008)

[8] http://www.mobil.com/USA-English/Lubes/PDS/GLXXENCVLMOMobil_Delvac_1_5W-40.asp, (May, 2008)

[9] http://www.ecycle.com/APU.html, (May, 2008)

[10] http://www.mavilor.es/pdf_products/mss_series_sc.pdf, (May, 2008)

[11] http://www.maxwell.com/ultracapacitors/products/large-cell/bcap3000.asp, (May, 2008)

[12] http://www.kepcopower.com/specs/rkw-progspecs.pdf, (May, 2008)