Designing a thermoelectrically powered wireless sensor network for monitoring aluminium smelters

M H Schneider[1]**, J W Evans**[2*]**, P K Wright**[1]**,** and **D Ziegler**[3]

[1]Department of Mechanical Engineering, University of California at Berkeley, Berkeley, California, USA

[2]Department of Material Science Engineering, University of California at Berkeley, Berkeley, California, USA

[3]Alcoa Technology Center, Alcoa Center, Pennsylvania, USA

The manuscript was received on 23 March 2005 and was accepted after revision for publication on 3 March 2006.

DOI: 10.1243/09544089JPME67

Abstract: Aluminium production cells, Hall–Héroult 'potlines', are inefficient and inadequately outfitted with sensors, mostly due to safety concerns with sensor wires between pots, possible interference with existing hardware, high installation costs, and the lack of an easily accessible, maintenance-free, continuous power source for the sensors. A tested solution to accurately measure various process parameters via wireless sensing technology, using either the cell's exhaust heat or steel shell as a thermoelectric power source is presented. Early experiments at Eastalco indicated that the motes, with a few modifications, will be able to operate reliably under industrial conditions, successfully transmitting radio packets through the plants' strong magnetic fields at distances of over 30 m. This article describes the successful testing of wireless measurements of cell parameters, discusses the energy-scavenging thermoelectric power sources and their electronics, and describes the future plans. The authors work is being carried out in conjunction with Alcoa in hopes of improving cell efficiency through better instrumentation.

Keywords: Hall–Héroult cells, wireless sensors, plant monitoring, thermoelectricity, energy efficiency, motes

1 INTRODUCTION

With the rapidly increasing technological advances in wireless technology and its subsequently decreasing prices, numerous wireless applications are being developed in industry. CITRIS (http://www.citris.berkeley.edu/about_citris/), a University of California organization, is one of many institutes performing research on various 'civil' applications of information technology, such as wireless systems, in realms of energy efficiency, transportation, and environmental monitoring. However, industrial applications, such as those in the manufacturing industries, also stand to benefit from wireless technology. According to the Energy Information Administration (www.eia.doe.gov), manufacturing is one of the largest consumers of energy in the US, accounting for 22.7 Quads in 2002, the last year for which data have been published (1 Quad $= 10^{15}$ BTU) [**1**]. Hence, any improvements of energy efficiency in these industries would not only assist the nation by lessening its dependence on foreign energy providers, but would also benefit the individual industries by reducing their manufacturing costs through energy conservation. Wireless technology thus provides a low cost and minimally interfering, yet powerful, resource for conserving energy in manufacturing operations through its ability to measure various process parameters, transmit these values to a central computer for logging, and provide a gateway for automated control. For a comprehensive overview of wireless sensor network technology and mesh technology, the reader is directed to Akyildiz, 2002 and Akyildiz, 2005, and Stankovic and Sinopoli for an introduction to control with wireless sensor networks [**2–5**].

Corresponding author: Department of Material Science and Engineering, University of California at Berkeley, 316 Heart Mining Memorial Building, Mail Stop #1760, Berkeley, CA 94720, USA. email: evans@berkeley.edu

2 BACKGROUND

Primary aluminium production is carried out in Hall–Héroult cells, which have steel shells, with refractory linings, that measure about 3 m by 10 m. The cells enclose a bath of molten salt electrolyte at 950–960°C through which a direct current (DC) current, on the order of several hundred kiloamperes, is passed between blocks of carbon anodes (there are about 20 anodes per cell) and a pool of molten aluminium beneath the molten salt. The voltage across each cell is around 4 V, and with about 100 of these cells connected in series to form a 'potline' and about 2–4 potlines per typical plant, a single aluminium factory can consume more than 150 MW [**6**]. With approximately twenty of these factories nationwide, aluminium production consumes a significant amount of the electricity generated in the United States [**7**]. Worldwide, the production of aluminium now requires more electrical power than is consumed by the whole of France [**8**].

Hall–Héroult cells are notoriously energy inefficient (40–45 per cent efficiency, when compared to the thermodynamically required energy), in part because of limited instrumentation and control at many plants. At most plants, the only variables that are continuously measured are an individual cell voltage and current, with many plants intermittently measuring the molten salt temperature and the weight of the aluminium produced. However, the control of these variables is quite poor and cell disturbances are commonplace. For example, optimal cell operation occurs when each of a cell's anodes carries approximately the same amount of current. However, when an anode is replaced (they must be replaced biweekly as they are consumed by the reaction), the distribution of current among the anodes becomes unknown and the cell voltage is increased to bring the new anode to its operating temperature [**1**].

Aluminium production via Hal–Héroult cells is thus an important test case for the implementation of wireless sensors in monitoring manufacturing processes. This report tests the viability of employing self-powered wireless nodes (called motes because of their miniature size), running TinyOS, to monitor the aforementioned Hall–Héroult cells in hope of improving each cell's efficiency and decreasing the plant's total energy consumption through improved instrumentation. The remainder of the article is organized as follows: first, the wireless motes, the software implemented in them, and the software developed for the central workstation is described; secondly, the thermoelectric generators and the power conditioning electronics used to robustly power the motes from the cells' wasted heat is discussed; next, the sensors used in the trials are shown; then, the results of several tests performed at Alcoa's Eastalco works in Frederick, Maryland are presented; and finally, a number of modifications and future considerations to be implemented in a final system are proposed.

3 WIRELESS DEVICES

The Processor-radios (MPRs) used for this network are called 'mica2 motes', supplied by Crossbow Technology, Inc., model number MPR400 (Fig. 1(a)). The MPR400 comes standard with a 10 bit analog-to-digital converter (ADC) (~3 mV precision), an FM tunable radio (set manually to 916 MHz), flash data logger memory, and a basic whip antenna [**9**]. Without obstructions, the mica2s can transmit data up to 150 m away. No hardware modifications were made directly on the MPR400 (except for removing its standard 2 AA battery holder – see section 4).

In order to utilize the necessary sensors (see section 5), the MTS101CA sensor board (Fig. 1(b)) was used. In addition to its built-in thermistor and photocell, the board's prototyping area allows an additional five connections to the mote's ADCs through a 51 pin expansion connector (allowing for a total of seven input ADC channels) [**10**].

Since the motes will be powered by an external energy scavenging source (see section 4), their peak power draw is of importance. Table 1 below characterizes the mote's power consumption in various modes.

3.1 Software

The software side of this project consists of two components: (a) TinyOS, the operating system of the wireless motes and (b) Java, the programming language of the server, which collects and records each mote's information.

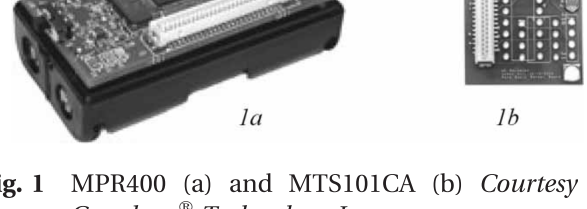

Fig. 1 MPR400 (a) and MTS101CA (b) *Courtesy of Crossbow® Technology Inc.*

Table 1 Mica2 power consumption at 3 V[a]

Mode	Current (mA)	Power (mW)
Processor: full operation	8	24
Radio: receive	8	24
Radio: transmit	12	36
Logger memory: write	15	45
Logger memory: read	4	12
Sensor board: full operation	5	15

Source: www.xbow.com
[a]Since more than one mode may occur simultaneously, experiments have shown that a minimum current of 26 mA is required for full operation.

3.1.1 *TinyOS*

TinyOS is an open-source operating system designed for small embedded platforms [**11**]. TinyOS features a component-based architecture, which enables rapid innovation and implementation while minimizing code size as required by the severe memory constraints inherent in sensor networks. TinyOS's event-driven execution model enables fine-grained power management yet allows the scheduling flexibility made necessary by the unpredictable nature of wireless communication and physical world interfaces.

TinyDB, a query-based processing system developed for extracting information from a network of motes, became the TinyOS program of choice for this project because of the following features.

1. It does not require the programmer to write embedded C code for sensors.
2. It presents a SQL-like language for extracting data.
3. It provides a simple Java API for writing server-side applications.
4. Its ability to autonomously network an ad-hoc assortment of motes and route their data via hopping to a single, central workstation.
5. Its power-efficient algorithms which place the mote automatically into a low-power 'sleep mode' when it is not collecting, transmitting, or receiving data.

Despite its many advantages, TinyDB's network is limited to connecting a maximum of 50 motes to a single, central station. To overcome this limitation, in future work, several servers will be stationed around a single potline, each communicating with a set of ~50 motes that are programmed with a different group ID [**12**].

3.1.2 *Java*

On the server side, the Java language was used to extract data from the motes and display it in a user-friendly format on a PC. The main program, AlcoaSensor, which implements the TinyDB API, executes the following actions.

1. Presents a setup GUI for the end-user to select and input various variables (i.e. sampling frequency, duct temperature threshold, trial number, etc.) as well as which processes to monitor.
2. Displays the received data from each mote in the command window, including the date and time, the query number, each mote's ID, the selected process parameter's values, the thermoelectric generator's no-load voltage, and the parent node which the mote hopped across to reach the central station.
3. Stores the recorded data (number 2) into a spreadsheet format .txt file,
4. Creates a new file for every 12 h, statistically analyzes the previous file, and emails the files to specified email addresses twice a day.
5. Displays 3 GUIs that a) display the current program's statistics, b) illustrate a real-time network visualization between each mote and the central computer, and c) allows the operator to monitor an individual node's sensed values over a specified period of time.

4 THERMOELECTRIC POWER GENERATION

Aluminium processing is an energy-intensive process, and the associated plants are awash in wasted energy. Hall–Héroult potlines consume more than twice the electrical energy required thermodynamically, causing a heat loss of approximately 8 kWh per kilogram of metal produced [**13**]. This enormous heat loss presents a valuable solution to providing a continuous and safe power source for the motes – thermoelectricity.

Thermoelectricity is generated via the same principles used by temperature-measuring thermocouples. Known as the Seebeck effect, an electrical voltage can be produced when two dissimilar metals, creating a closed circuit, have their junctions heated to different temperatures. However, this voltage is relatively small: a temperature difference of 100°C between 2 ends of a nickel–chromium alloy and a nickel–aluminium wire (K-type thermocouple) will only create a voltage of approximately 4.1 mV [**14**].

4.1 Thermoelectric modules

Commercially available thermoelectric generating modules (TEGs) make use of the aforementioned Seebeck effect, but with some major modifications. A typical module is shown in Fig. 2. It usually consists of p- and n-type semiconductor materials (bismuth

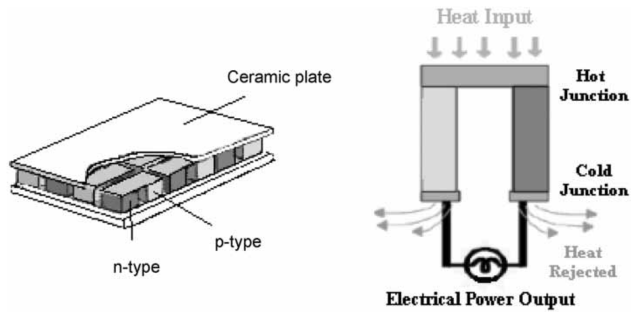

Fig. 2 Typical TEG module with a single element shown on the right *Source: www.thermoelectrics.com*

telluride in the case of the device used in this work) which are optimized for the Seebeck effect (a high thermal resistivity and electrical conductivity). Approximately 100 of these semiconductor 'couples' are connected electrically in series and thermally in parallel to produce voltages at useful levels by simply applying heat to one side of the module and cooling the other (usually with a heat sink). Although inefficient (~5 per cent), a single module can produce up to 19 W when the temperature difference between the two sides is approximately 225°C (HZ-20 http://hi-z.com/). However, in the application, the temperature differences only reached about 20°C, which results in power outputs of around 0.5 W (see section 4.4).

Thermoelectric generation modules were ordered and tested from several major US thermoelectric manufacturers. Main considerations included size and form factor, repeatability, voltage and current outputs at low temperature differences, and resistance to reaching thermal equilibrium. Besides power output, the module's size was the main limiting factor in creating an unobtrusive network and reducing the amount of conduction between the hot plate and heat sink. Detailed experimental results comparing all the modules tested can be found in reference [**15**].

4.2 Heat sink design

One side of the thermoelectric generators must be cooled in order to generate power via the Seebeck effect. The two logical and recommended cooling solutions include a fan-forced heat sink or a water-cooled cold plate. However, due to the lack of a power supply for a fan or a reusable chilled water source available at the cells, these two solutions proved unsatisfactory. Instead, a large, passive heat sink was used to cool the cold interface. But because of the erratic air-flow found within most smelting plants, modifications were made to standard heat sinks to improve their thermal performance for such conditions. One modification that proved valuable was altering a standard heat sink via cross-cuts. Cross-cutting is a manufacturing operation that converts a straight finned extruded heat sink into a pin–fin array by making cuts perpendicular to the original fins. Several tests were performed comparing a cross-cut heat sink to an unmodified extruded heat sink. Some selected results, as in Fig. 3, prove a cross-cut heat sink in an uncontrolled air-flow environment (ambient air ~20°C) is superior. Further details of the heat sink design can be found in reference [**15**].

4.3 Power conditioning

Although the thermoelectric modules supply a sufficient amount of power, their power composition is unacceptable. Laboratory tests have shown that the motes require 2.35–3.3 V and approximately 26 mA for full power operation (it has been shown experimentally that once the mote's voltage drops below 2.35 V, they shut off). However, the tested thermoelectric generators, with temperature differences of approximately 20°C (as expected at a plant), can only supply 0.9–1.6 V, but up to 300–650 mA (~0.3–1.1 W) at matched loads. Additionally, the module's have a variable internal resistance which fluctuates as a function of temperature and the connected electrical load. This means that when more current is drawn by the electrical load, more power is dissipated within the module. Thus, in higher current drawing modes (i.e. unmatched loads) such as radio transmission (see Table 1), less useable power is made available to the mote. Therefore, a passive power conditioning circuit must be introduced into the system to increase and stabilize the TEG's output voltage despite electrical load and temperature gradient fluctuations, while still supplying sufficient current.

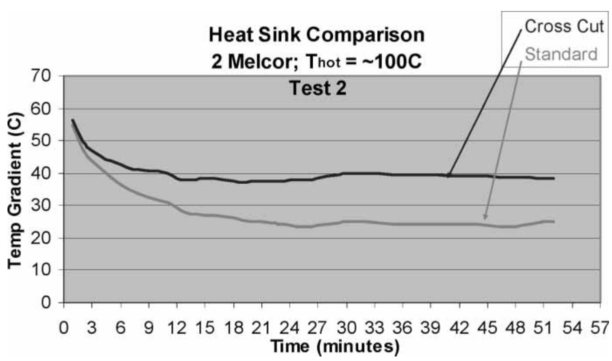

Fig. 3 Time-dependent heat sink temperature-gradient comparison between a standard extrusion heat sink and a modified cross-cut heat sink

A straightforward solution involves the implementation of a step-up (boost) DC–DC converter. A step-up DC–DC converter is a highly efficient (>90 per cent) passive device that outputs a constant, higher-than-input voltage, through a combination of inductors, capacitors, diodes, and transistors. Maxim IC's MAX1760 step-up DC–DC converter was well within the specifications needed to power the motes: a 0.7–5.5 V input range, a fixed 3.3 V output (as long as the input voltage is ⩽3.3 V), and a maximum output of 800 mA.

4.4 Experimental results

Several experiments with the thermoelectric modules were performed in a laboratory setting to determine the following characteristics.

1. How different modules' temperature differences fluctuate over time when a constant hot-side temperature is applied to one interface, and how their associated no-load power output changes.
2. The minimum temperature differences needed across the TEGs to switch on the DC/DC converter.
3. The effect of varying the module's hot side temperature on the mote's successful transmission rate.
4. The performance of the thermoelectrically powered motes at different sampling frequencies.
5. A comparison of several thermoelectric modules steady state temperature gradients and power outputs while powering the motes.

The results of these experiments can be found in reference [**15**], whereas a selected result of part 5 is shown below. Various TE modules were tested in a straightforward manner by bolting each one between a heat sink and an aluminium plate, which was heated by an electrical hot plate. The power output was conditioned via a DC/DC converter and fed into the mote's power inputs. As displayed in Fig. 4, a single Tellurex CZ1-1.4-219-1.14 provided robust results, and was tested at Alcoa because of its consistent output voltage despite large fluctuations in temperature difference (because a TE module is an unregulated power-source, if too little power is supplied to the mote, the voltage input will be pulled down accordingly).

5 SENSORS

Fluorinated hydrocarbon, a significant greenhouse gas, is emitted during the aluminium smelting process, primarily when the aluminium oxide content of the molten fluoride electrolyte falls below critical levels required for electrolysis. The resulting phenomena are known as an 'anode effect'. According to federal regulations, these harmful gases must

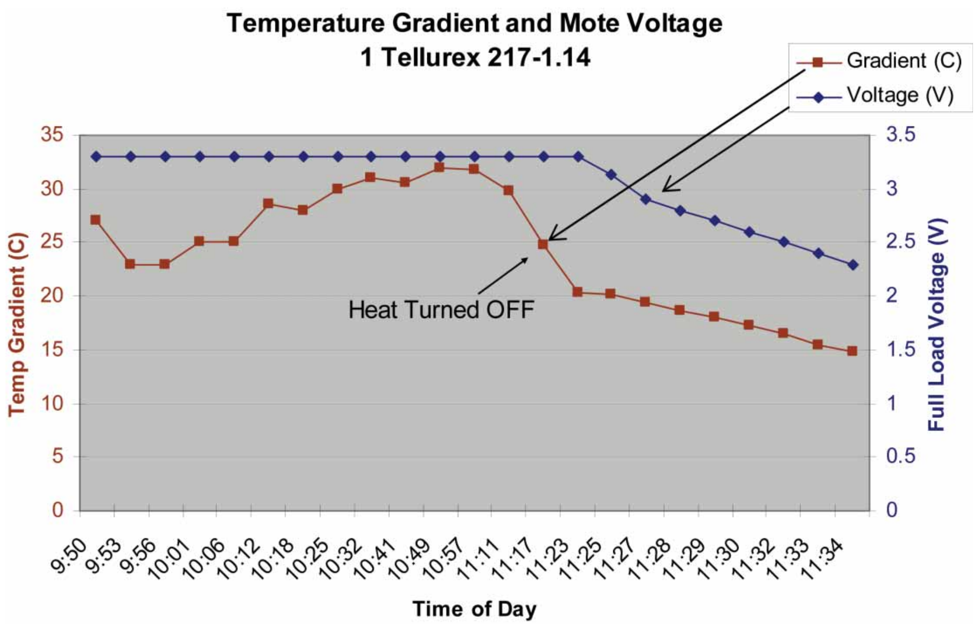

Fig. 4 The graph above reflects a mote's measured input voltage during its maximum current drawing mode while being powered by a Tellurex 219 TEG. Despite the large temperature difference fluctuations measured across the TEG throughout the test, the mote consistently received enough power. Once the heat source was turned off, it can be seen that too little power was supplied to the mote, and thus, the mote, as expected, pulls down the measured voltage

be removed from the air stream before it is released into the environment. Thus, each cell's emissions are directed towards a wet scrubber via a negatively pressurized exhaust duct (a few centimeters of water below one atmosphere) to remove the fluoride containing gases.

Tests performed in september and october of 2002 by Dando of Alcoa revealed that individual gas exhaust duct temperatures may vary by more than 60°C in a single potline, with the highest gas temperatures (~160°C) corresponding to smelting pots with vapor-phase fluoride (HF) evolution rates 2–3 times higher than those of smelting cells with the lowest exhaust duct temperatures (~100°C) [**16**]. Additionally, the pots with higher exhaust duct temperatures exhibited visible open holes in the crust of frozen electrolyte/ore that normally covers the molten salt electrolyte, while the lowest exhaust duct temperature pots did not exhibit any visible crust holes. As suggested by Dando, duct temperature monitoring provides a 'relatively low cost means for identifying inadequately covered pots' as well as lowering the 'overall HF evolution rates at aluminium smelters'. Because of the ducts' accessibility, their pre-existing monitoring holes, and the environmental implications, measuring the duct's exhaust temperature became the first sensing objective for the wireless devices during the development campaign.

By utilizing the mote's ADC, a simple voltage divider with a thermistor functioning as one of its main resistors can be used to measure the temperature of the duct. A glass-encapsulated NTC thermistor, part number A4196-2 from advanced thermal products, was embedded inside a stainless steel housing to protect it from the corrosive duct gases as well as provide an attachment mechanism to the entire thermoelectric housing (Fig. 6). The thermistor ranges from 98 KΩ at 25°C to 343.3 Ω at 225°C. Placed in series with a 1 and 10 K resistor, the overall power draw at 150°C is on the order of 10^{-4} W, ensuring a 'zero-power' sensor [**17**].

By using three known resistance–temperature values and the mote's ADC6 output, we determined the duct temperature (in Kelvin) by solving the Steinhart–Hart equation (1)

$$\frac{1}{T} = A + B \cdot \ln(R_{\text{threm}}) + C \cdot (\ln(R_{\text{therm}}))^3 \qquad (1)$$

6 FIELD RESULTS

6.1 Mote functionality and preliminary measurements

A first series of tests were performed in early 2004 at Alcoa's eastalco works in Frederick, Maryland. Because of the enormous magnetic fields created by the large currents required for the electrolytic process (at a radial distance of 0.5 m from a busbar carrying 200 kA, $B = \mu_o I/2\pi r = 800$ gauss), these trials' main objective was to determine the feasibility and functionality of this project. Not only are RF signals disturbed by EM radiation, but previous tests have proven that at a specific orientation to a strong magnetic field, the MPRs tend to power off automatically and must be reset manually.

A multitude of tests gave promising results. Although the magnetic fields limited the successful packet relay between two motes, the tests showed that motes can effectively communicate with each other despite the plant's strong electromagnetic fields. A linear network between three remote nodes and a central computer, with two motes directly communicating (i.e. no hopping) with each other at distances greater than 30 m was successfully created. Figure 5 portrays the successful transmission rate between three nodes and the central workstation. As expected, the successful transmission of packets decreased as the node's distance from the central computer increased. Additionally, the successfully received packets were observed to both hop along adjacent motes as well as directly communicate with the central node, depending on which method provided a stronger broadcasting line during transmission [**18**].

6.2 Preliminary prototyping test

A second series of tests performed in the latter half of 2004 were designed to demonstrate a complete working prototype. Figure 6 shows a CAD drawing

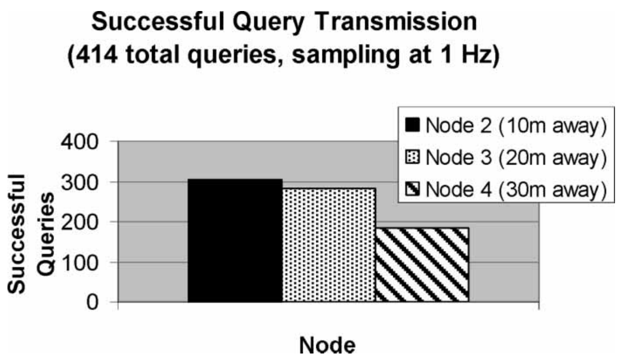

Fig. 5 Basic hopping capability test performed at Eastalco Works in May, 2004. The successful queries represent the number of successful packets received by a centeral laptop for each mote. Each node was placed on a different cell's exhaust duct; distance from the central server are specified in the legend

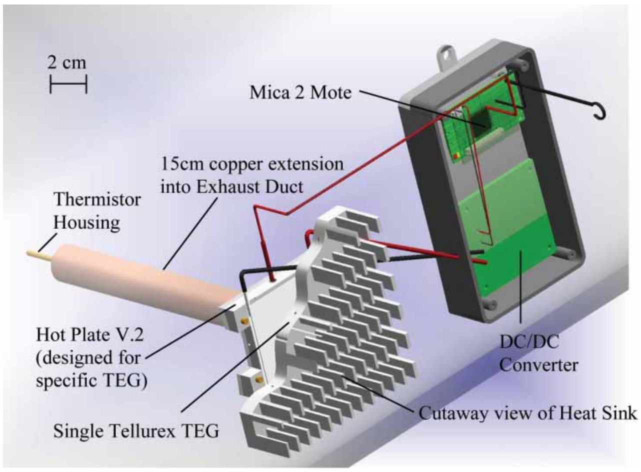

Fig. 6 CAD drawing of the final duct temperature measurement device and TEG housing used at Alcoa

of the complete setup used in this prototyping test. The TEG is sandwiched between a cross-cut heat sink and a hot plate, which is flat on one side for the TEG but rounded on the other side to match the curvature of the duct which it will be placed against. A 17 cm copper extension is bolted to the hot plate and is inserted into the duct through a pre-existing monitoring hole to (a) place the thermistor into the centre of the duct, (b) create a channel for the thermistor's wires, and (c) conduct the heat of the hot gas to the hot plate.

This housing was then inserted into a cell's exhaust duct (as shown in Fig. 6), the internal gas temperature of which was measured at 120°C, while the ambient air temperature outside the duct was around 30°C. After reaching its steady-state temperature (the hot side temperature reached 71°C while the cold side stayed constant at 46°C), the TEG module provided a minimum voltage (i.e. when the mote was in its maximum current drawing stage) of 3.29 V.

After successfully powering a mote via thermoelectricity, our second objective was to accurately monitor duct gas temperatures via the motes. These trials were performed successfully, with the motes transmitting temperature values that were within 1 per cent of a nearby thermocouple. Table 2 compares some temperature measurements taken by both the ATP thermistor and a thermocouple. The data in Table 2 also serve to address any issue of the TEG abstracting sufficient heat from the duct to lower the gas temperature. The duct and the gas flow through it are so large that any heat flow through the TEG has negligible effect on the temperature. The authors have also assumed that the commercial thermistor and associated electronics were free from calibration error and drift over the period of the project. Table 2 provides some justification for that assumption.

Table 2 Thermistor and nearby thermocouple measurements of selected cell's

Cell	Thermocouple (C)	Mote thermistor (C)	% error
1	150	149.0	0.6%
6 (not operational)	41.0	41.54	1.3%
11	161	162.0	0.6%

The next objectives included the testing of a complex network of 10+ motes in the plant and running a networking application for 20+ hours to determine mote functionality and TEG fluctuations over prolonged time periods. Two extensive tests were performed: one during the day with the battery-powered central computer inside the potroom, and another at night, with the computer placed inside a nearby trailer for security reasons and the availability of a 120 VAC supply to power the laptop. A group of 11 motes, 2 of which were powered off the temperature difference between the inside and outside of the exhaust duct, successfully networked their data to a central computer for logging In order to receive data from the potroom during the night setup, several nodes were removed from the day setup's cells and placed in a linear fashion to create a transmission line to the trailer.

Data were collected every 12 s during the day, and once a minute during the night (to conserve the batteries of the nodes being powered from them). Figure 7 shows the successfully received queries over time for both setups. Note that node one worked properly, but once removed from the cell to measure gas temperatures with a thermocouple, electrical problems made it inoperable. Additionally, the second TE-powered node (node 3) was placed adjacent to node 11 because node 11 was using the TEG housing setup's thermistor to monitor duct temperatures. Although every query from each mote did not reach the central station, the worst-case scenario had approximately a 35 per cent successful transmission rate, suggesting that the inputted sampling rate should be ~3× the originally preferred rate if the high valid measurement rate (for this application) of once per minute is necessary.

These extensive tests illustrated that the motes can survive the harsh environment of the plant as well as the robustness of the TE modules in terms of providing enough continuous power for a mote over an entire day (although node 3 stopped communicating around hour 14, its temperature difference remained steady throughout the night). It must also be noted that the night setup's linear network (i.e. nodes 11, 6, and 8) was not optimal. If node 11, 6, or 8 failed,

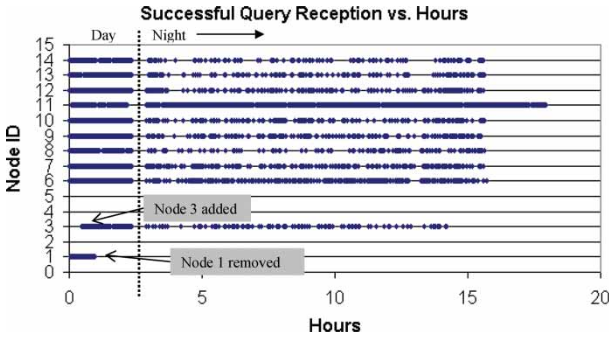

Fig. 7 A prolonged period of tests, in which data was sampled at 1/12 Hz during the day (left hand side) and 1/60 Hz at night. Each data point represents a successfully received query

as one did in Fig. 7 at the 16th hour, all other queries will not be received by the central server (in a real scenario, a mesh network would resolve this problem). However, due to the lack of a 120 VAC source at the cells, this proved the only feasible way of monitoring process parameters over long time periods at Eastalco. However, once the computer was placed back inside of the potroom in the morning, all nodes again commenced to send and receive data.

The 5th objective was to monitor an exhaust duct for several hours before and after the creation of a crust hole. A thermoelectrically powered node was placed on a single cell and sampled its duct temperature every 12 s. After about 2 h of sampling, a plant-operated jackhammer created a $2.5\,\text{m} \times 0.25\,\text{m}$ crust hole around 3 anodes in the middle of a cell. The exhaust temperatures were continuously monitored for another 2 h (Fig. 8). As found by Dando [**16**], the exhaust gas temperatures rose about 14°C in the present case, before returning to their steady-state values.

14°C is lower than the largest temperature excursion reported by Dando but the size of the temperature fluctuation can be expected to depend on how large the crust hole is, as well as on other factors such as the rate of gas flow along the duct. It should be noted that this application is undemanding of reliability or fast data transfer. As shown in Fig. 8, the duct exhibits temperatures, which vary with a time scale of tens of minutes. Operators can take even longer times to address problems. Consequently measurements that are delayed by a few seconds or even minutes are acceptable. It is also acceptable if the measuring device is queried only every several second and if only a fraction of those queries result in a response from the measuring device.

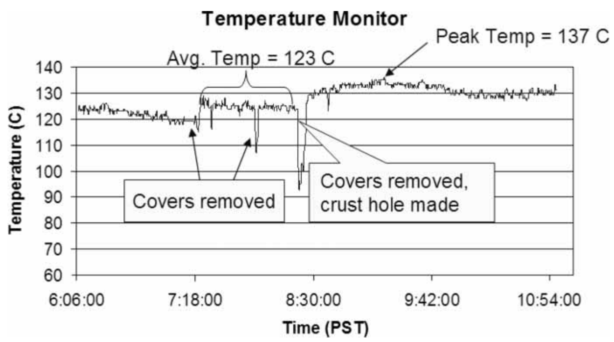

Fig. 8 Temperature signature of a cell before and after crust breaking. The horizontal axis is in hours

The final objective was to find other suitable sites where energy scavenging techniques might be used to power motes in aluminium plants. Although measuring duct temperatures is useful, the final goal lies in measuring several process parameters, some of which are many metres away from ducts. Because it is unacceptable to have wires strung across a cell to act as 'power lines', new sources of energy are required near these new sensing locations.

In order to test the feasibility of one of these locations, a magnetic TEG housing was developed for attaching a TEG setup to a warm steel surface. As shown in Fig. 9, four samarium-cobalt 12 mm diameter magnets are embedded into an aluminium housing. 0.64 mm of aluminium is left underneath the magnets to hold them in place and minimize their distance from the ferromagnetic steel to maximize their holding force. An aluminium sheet is then placed on top of the magnets to hold their position, and the TEG and heat sink are positioned as usual.

This assembly was placed on the 'belly-band' reinforcement structure of a cell's end wall. After

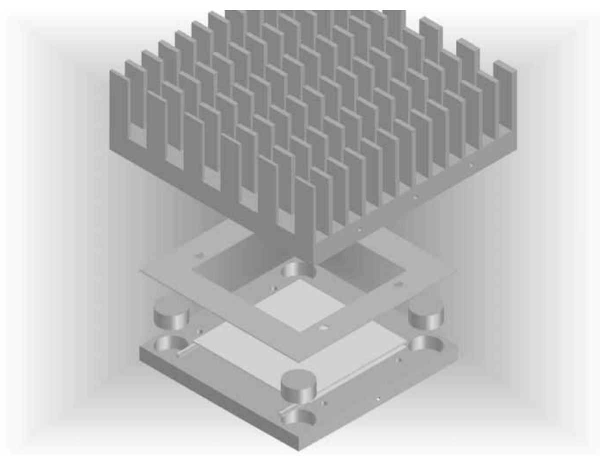

Fig. 9 CAD drawing of the magnetic TEG housing. Four—12 mm diameter, 5 mm thick samarium-cobalt disc magnets are placed inside of the aluminium housing

reaching its steady state temperature, a temperature difference of ~50°C formed across the TEG, enabling it to output approximately 1.5 W of power ($T_{hot} = 126°C$ and $T_{cold} = 76°C$), which is more than enough to power several motes from a single TEG.

7 FUTURE WORK

Although several initial tests have been successful in monitoring aluminium smelting process parameters, there is still much work to be done. While measurements of duct temperatures provide valuable information to the cell operator, self-powered wireless motes extend to other worthwhile measurements. These include measuring the heat flux through a cell's steel shell, measuring the pressure under a cell hood, determining individual anode currents by either hall-effect sensors [**19**] or monitoring the alternate current (AC) noise in the DC current, as well as various other process measurements deemed valuable by the industry.

Additionally, improvements in the mote's power input are a necessity. Even though acceptable temperature differences were found during our final experiments, further power source improvements should increase the packet transmission reliability. This could include increasing the temperature differences found across a TEG module via improved heat sinks, either by adding an internal duct heat sink or employing a new design [**20**], or by using other power sources, such as energy-scavenging vibrations, in series with thermoelectricity [**21**]. Moreover, a secondary storage device could also be used to supply additional power when the TEG output proves insufficient (i.e. a cell becomes inoperable or the temperature differences drop too low). Research is currently being carried out for such storage devices to be used with wireless nodes [**22**, **23**].

On the computer side, there is still much work to be done. Because this is intended to be a fully automated application with as little human interaction as possible, the program's software must have several modifications. The first major alteration may be the implementation of Maté. Maté is a software program developed for TinyOS that would allow wireless reprogramming of motes should the need for additional sensors arise after the motes are placed permanently in the plant [**24**]. Second, there should be further automated data analysis that would correlate the sensed values with what steps would be necessary to take to fix a problem. This might involve automatically generating files that would inform plant operators of these steps, or just using the mote's six 3 volt PWM on/off channels to autonomously trigger an automated solution to improve a cell's performance.

Moreover, further on-site testing must be performed before a full scale implementation would take place. This should include:

(a) creating a larger network where all nodes are powered via energy-scavenging;
(b) creating several networks on top of each other, each programmed with a unique group ID;
(c) running tests for several weeks to determine the motes' durability.

Additionally, if this project is to be fully implemented, technical issues, such as streamlining the manufacturing of these devices, are necessities.

Finally some speculation about the application of wireless devices elsewhere in manufacturing is appropriate. Application would seem most worthwhile where there are:

(a) many manufacturing units in a plant (e.g. looms in weaving) rather than a few (e.g. blast furnaces in steelmaking);
(b) currently a dearth of instrumentation/automation (the blowing of glass bottles rather than the making of cars);
(c) the opportunity for parasitic powering of the devices by energy scavenging from the unit (electrolytic processes, hot processes such as casting or extrusion and processes involving vibration such as machining);
(d) reasons, such as safety or cost, that inhibit transmission of process data by wire or optical fibre.

8 CONCLUSION

The lack of instrumentation of Hall–Héroult potlines and their poor energy efficiency induced the implementation of sensor networks to monitor process parameters. Wireless sensing technology appears to be promising in that it offers a minimally interfering, low-cost platform without compromising safety at the plant. Preliminary tests have successfully shown that mesh networks containing eleven mica2 motes, some of which are powered thermoelectrically, can operate reliably and continuously in the plant's harsh environment, while accurately measuring duct temperatures. Moreover, some initial trials demonstrated that other sites are possible for further energy-scavenging mote locations, facilitating a complete sensing solution.

Although further research is needed to create a completely automated, 'plug-and-play' compatible sensing system, our initial investigation promises an answer for improving Hall–Héroult cell instrumentation, which in turn should improve the Hall–Héroult process. Furthermore, this work provides a valuable test bed that can be applied to other manufacturing operations which lack vital instrumentation of various parameters and where wired solutions prove infeasible.

ACKNOWLEDGEMENT

This project was carried out in collaboration with Alcoa and was partially supported by the University of California's Energy Institute. Special thanks are due to Russell Painter of the Alcoa Technical Centre for his assistance with the field tests at Eastalco.

REFERENCES

1 **Evans, J. W.** Application of wireless technology to energy consuming industries, *UCEI Grant Proposal*, May 2004.
2 **Akyildiz, I. F., Su, W. Sankarasubramaniam, Y.,** and **Cayirci, E.** Wireless sensor networks: a survey. *Comput. Netw.*, 2002, **38**(4), 393–422.
3 **Akyildiz, I. F., Wang, X. D.,** and **Wang, X. L.** Wireless mesh networks: a survey. *Comput. Netw.* 2005, **47**(4), 445–487.
4 **Stankovic, J. A., Abdelzaher, T. F., Lu, C. Y.,** *et al.* Real-time communication and coordination in embedded sensor networks. *Proc. IEEE*, 2003, **91**(7), 1002–1022.
5 **Sinopoli, B., Sharp, C., Schenato, L.,** *et al.* Distributed control applications within sensor networks. *Proc. IEEE*, 2003, **91**(8), 1235–1246.
6 **Evans, J. W.** and **DeJonghe, L. C.** *The production of inorganic material*, 1992, pp. 314–316 (Macmillan Publishing Co., New York, NY).
7 Available from http://www.aluminum.org/template.cfm?Section=The_Industry.
8 **Cynthia Carol.** Alcan Primary Metal Group, TMS Annual Meeting, San Francisco, February, 2005.
9 *MPR – mote processor radio board, MIB – mote interface/programming board. user's manual* Rev. A, December 2003, Document 7430-0021-05.
10 *MTS/MDA sensor and data acquisition boards user's manual* Rev. A, April 2004, Document 7430-0020-03.
11 Available from http://tinyos.net/special/mission.
12 **Madden, S. Hellerstein, J.,** and **Hong, W.** *TinyDB: In-network query processing in TinyOS*, Version 0.4 September, 2003.
13 Available from http://www.world-aluminium.org/environment/lifecycle/lifecycle1.html.
14 Available from http://www.tellurex.com/12most2.html.
15 **Schneider, M. H.** *Designing and implementing a thermoelectrically-powered wireless sensor network to monitor the process parameters of aluminium extraction.* MS Thesis, UC Berkeley, 2004.
16 **Dando, N.** *Light metals 2004* (Ed. A. T. Taberaux), 2004, pp. 245–248 (TMS, Warrendale, PA).
17 Available from http://www.betatherm.com/zero_ower.htm.
18 **Madden, S.** *The design and evaluation of a query processing architecture for sensor networks.* Doctoral Dissertation, UC Berkeley, 1999, TinyDB Thesis.
19 **Barclay, J.** and **Reig, J.** *Light metals 2001* (Ed. J. L. Anjier), 2001, pp. 1219–1224 (TMS, Warrendale, PA).
20 **Chapman, C. L.** and **Lee, S.** Thermal performance of an elliptical pin fin heat sink. Proceedings of the 10th IEEE Semi-Therm Symposium, 1994, pp. 24–31.
21 **Leland, E., Lai, E.,** and **Wright, P. K.** A self-powered wireless sensor for indoor environmental monitoring. 2004 Wireless Networking Symposium, 20–22 October 2004.
22 **Steingart, D., Ho, C., Evans, J. W.,** and **Wright, P. K.** Design of an on-chip secondary lithium ion polymer microbattery for millimeter-scale wireless nodes. Advanced Materials for Energy Conversion II, TMS 2004, pp. 339–343.
23 **Roundy, S., Wright, P. K.,** and **Rabaey, J.** 2003. A study of low level vibrations as a power source for wireless sensor nodes. *Comput. Commun.*, 2003, **26**(11), 1131–1144.
24 **Levis, P.** and **Culler, D.** Mate: A tiny virtual machine for sensor networks. *ACM Sigplan Notices*, 2002, **37**(10), 85–95.