Thermogalvanic Waste Heat Harvesting

Colin Wilburn

Advisor: Dr. David McCloskey

Trinity College Dublin

Laidlaw Scholars

Introduction

Waste heat is low grade heat (at $\sim 100°C$) that cannot be used in a conventional heat engine. In Ireland, up to 50% of input energy (~ 1800 ktoe) is lost as waste heat during conventional electricity production using fossil fuels [1]. Harnessing even 1% of this would prevent ~ 1 $MtCO_2e$ of emissions per annum. Thermally regenerative electrochemical cycles (TRECs) have shown high efficiencies (above 5%) with a clear path forward for new materials [2]. However, conventional TREC cells can be difficult to construct and test [3]. In this project, a thermal testing rig was constructed that can quickly identify cells suitable for TRECs. As well, button cells (which are compact and easy to manufacture), were tested in the rig with promising results.

Main Objectives

1. Build a thermal testing rig that can control the temperature of a sample.
2. Use the apparatus to test the suitability of a button cell for use in TRECs.

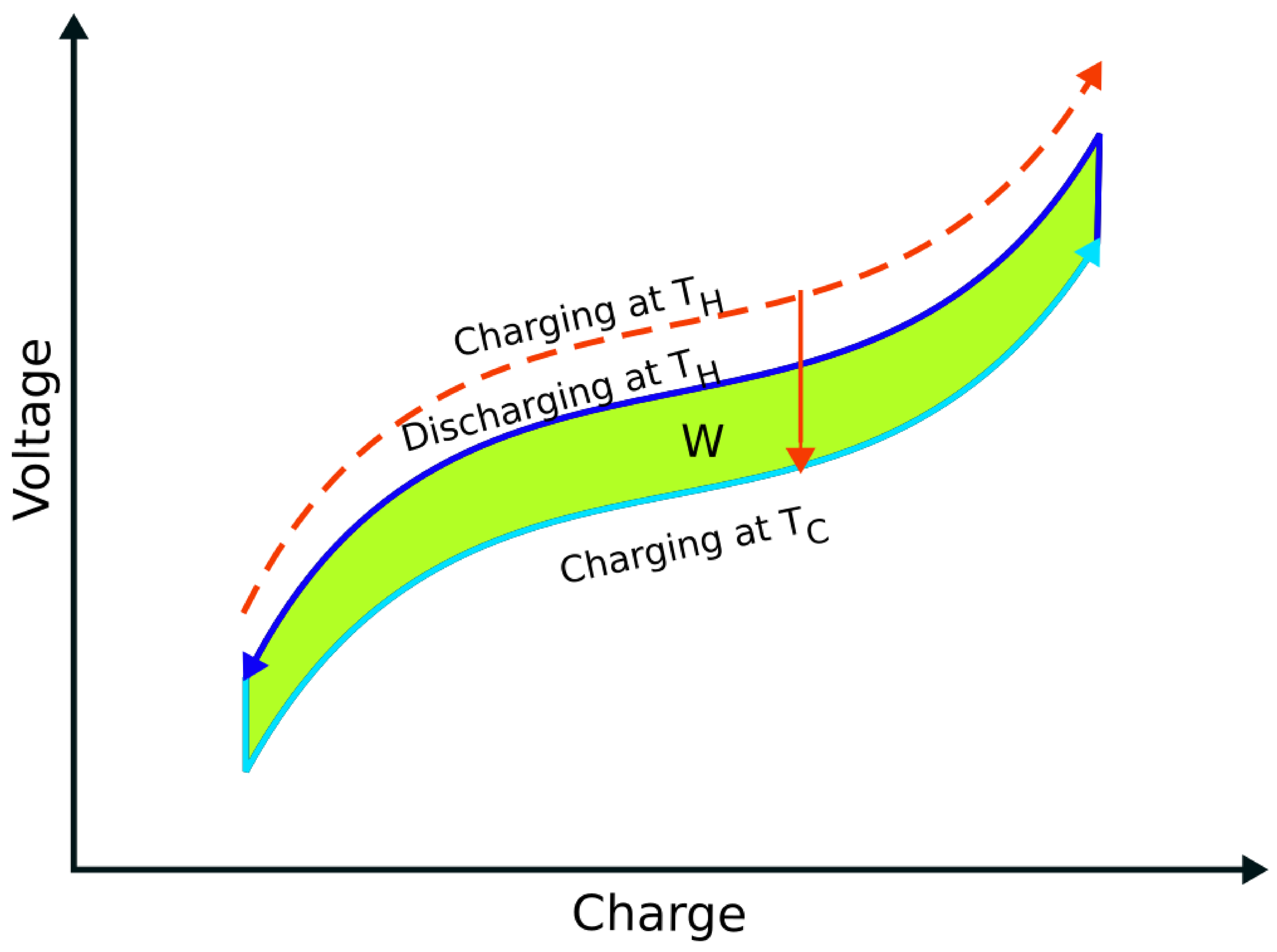

Figure 1: The basic thermodynamic cycle of a TREC. If the system were held at T_H for charging *and* discharging, energy would be lost due to internal resistance, etc. Figure adapted from [3].

Theory

TRECs rely on the thermogalvanic effect, or the temperature dependence of the electric potential produced by an electrochemical reaction:

$$\alpha = \frac{\partial V}{\partial T} \tag{1}$$

A battery with positive α can be discharged at a higher temperature T_H and charged at a lower temperature T_C to extract energy. To calculate the efficiency, we consider the work output W_{out} of the battery and the heat Q_{ext} extracted from the environment. To calculate the work output

$$\begin{aligned} W_{out} &= Q_H - Q_C - E_{loss} \\ &= m\alpha q_c \Delta T - E_{loss} \end{aligned} \tag{2}$$

where q_c is the charge capacity. There are two input heats, Q_{dis} during discharging and $mc_p\Delta T$ during the heating. Thus the total input heat is

$$Q_{in} = m\alpha T_H q_c + mc_p\Delta T \tag{3}$$

Finally, the efficiency is found to be [2]:

$$\eta = \frac{W_{out}}{Q_{in}} = \frac{m\alpha q_c \Delta T - E_{loss}}{m\alpha T_H q_c + mc_p\Delta T} \tag{4}$$

To maximize efficiency, then, desirable batteries should exhibit:

– High charge and discharge capacity q_c

– Large isothermal coefficient α

In particular, knowledge of α would allow researchers to select promising candidates for use in TRECs.

Methods

Two thermoelectric units were used to heat and cool the battery as required. Copper disks on top and bottom of the sample served as heat spreaders and electrodes connecting the battery to electrical testing equipment. The open circuit voltage (OCV) of the battery was measured for varying temperatures.

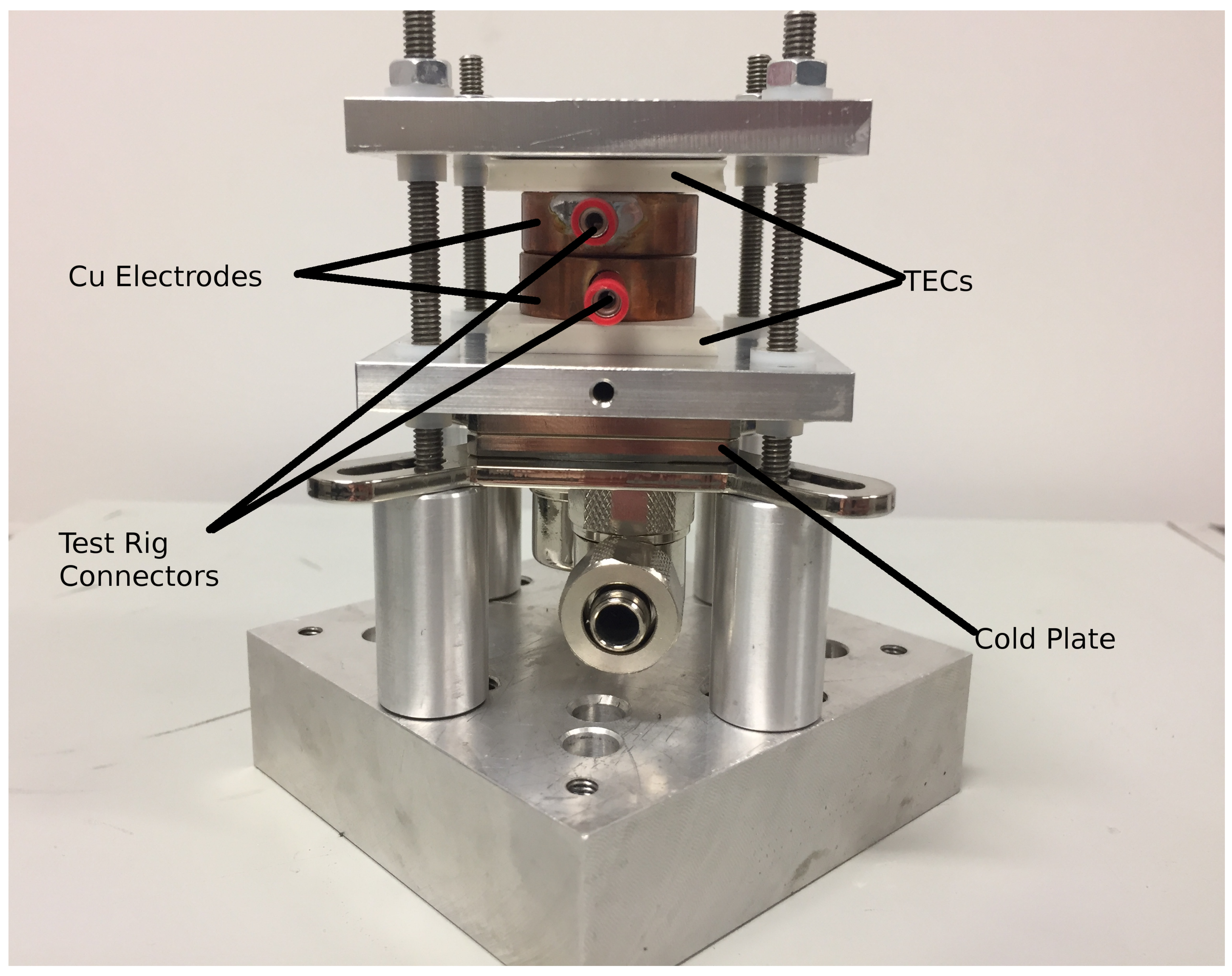

Figure 2: The thermal testing rig. In a later version, 3D printed parts were used for thermal insulation and structural stability.

Results

Figure 3 shows the change of the OCV of a graphite button cell battery. We calculate $\alpha \approx 0.57$mV/K, well within the range observed in the literature of 0.1 to 3 mV/K [2]. As well, the specific charge capacity of 350mAh/g compares well with more complex designs used in other experiments [3].

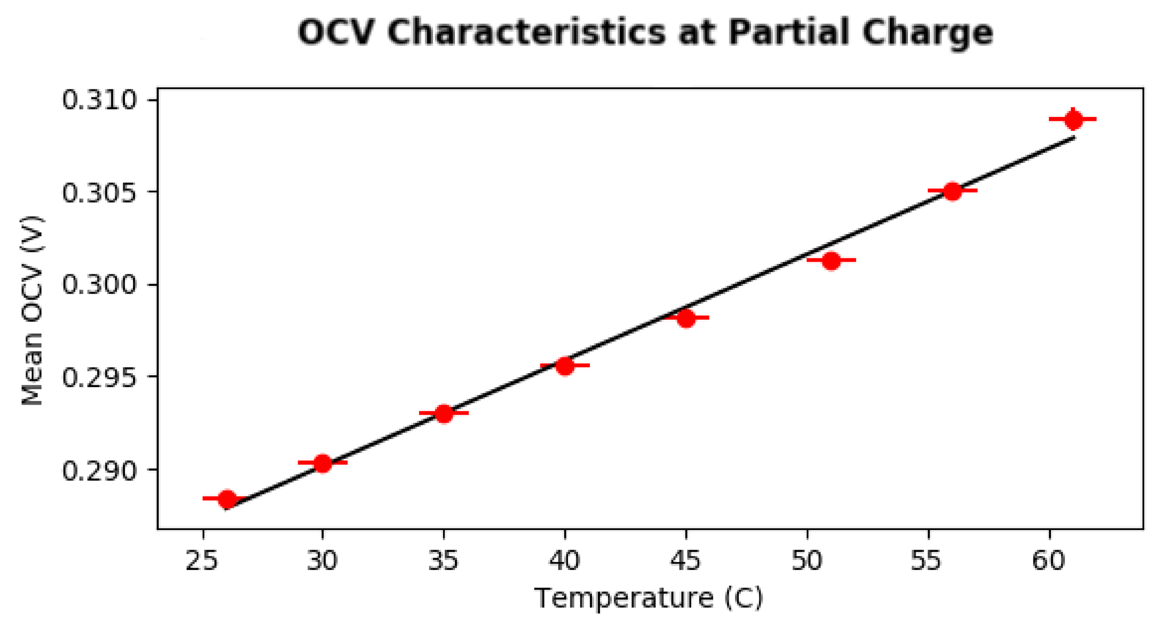

Figure 3: OCV of a graphite button cell for varying temperatures. α of the cell is given by the slope of the fitted curve.

Conclusions

- A thermal testing rig was designed and built to easily test batteries' suitability for use in TRECs.
- A button cell using novel electrode structures was tested, and it was shown to exhibit α comparable to the literature standard.

Forthcoming Research

With the proof of concept in this work, there remains a significant amount of testing to be done. In future research, button cells created from different materials should be tested in the thermal rig. With knowledge of their q_c and α, **Eqn. 4** can be used to predict their performance in a TREC. At this point, the thermal rig can be used to control the temperature during charge-discharge cycles, and more detailed measurements can be taken.

References

[1] Sustainable Energy Authority Ireland. "Energy in Ireland 1990 2015". In: *SEAI, Dublin, Ireland* (2016).

[2] Rui Long et al. "Performance analysis of a thermally regenerative electrochemical cycle for harvesting waste heat". In: *Energy* 87 (2015), pp. 463–469.

[3] Seok Woo Lee et al. "An electrochemical system for efficiently harvesting low-grade heat energy". In: *Nature communications* 5 (2014), p. 3942.

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