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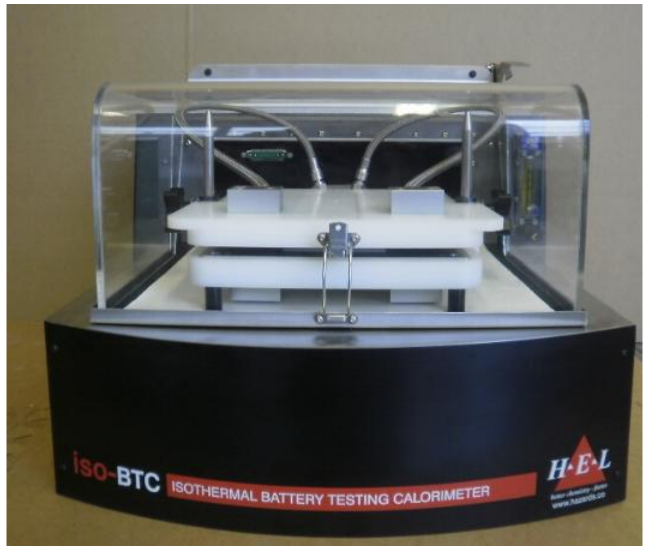

Iso-BTC

Operating Manual

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Iso-BTC – User guide.

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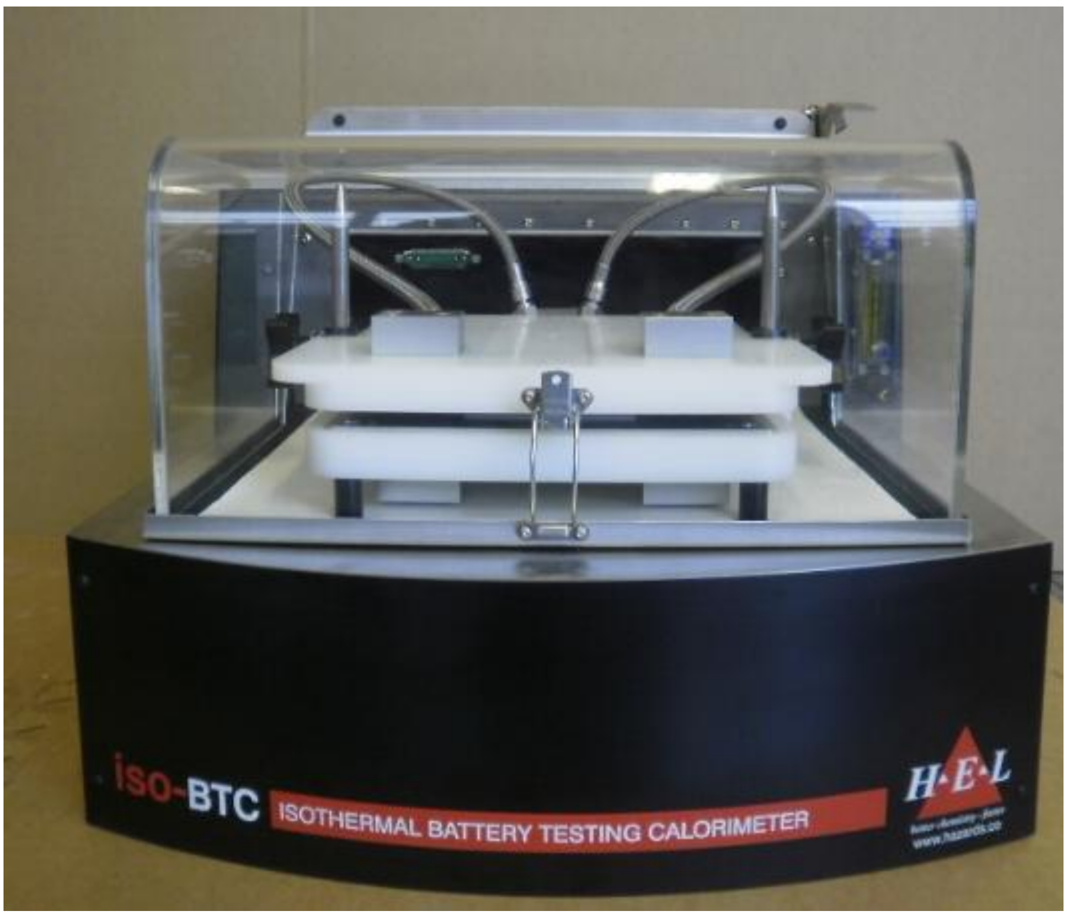
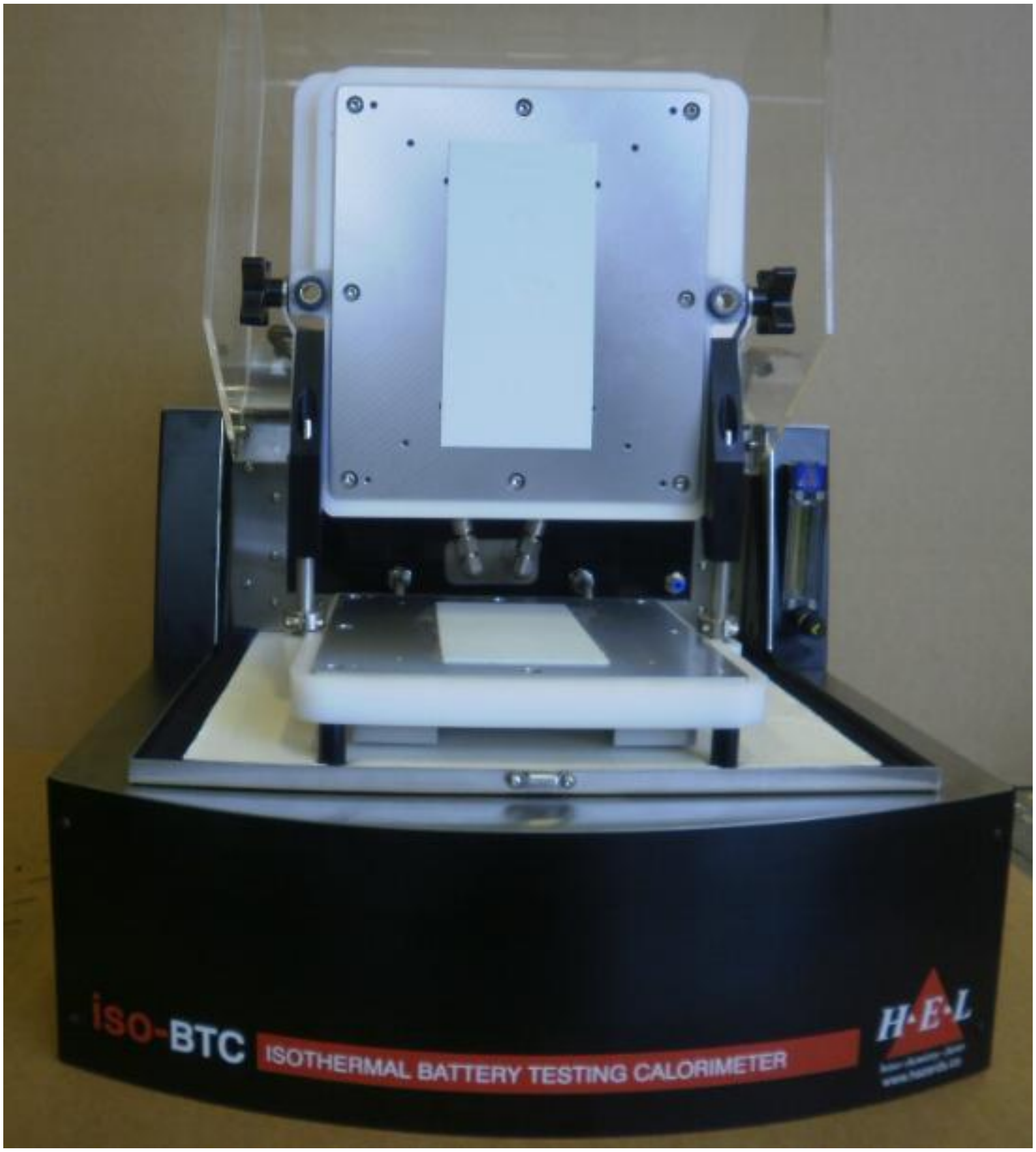
Introduction

The iso-BTC is an isothermal battery calorimeter and is designed to elucidate the thermal behaviour of batteries – typically during charging and discharging. The iso-BTC is primarily targeted at monitoring batteries during “normal use”; examination of the consequences of battery misuse is usually left to HELs other battery calorimeter – the BTC.

Iso-BTC comprises of a battery compartment (see below) which sits upon an electronics enclosure. The connection between the battery enclosure and electronics is via a single cable which is fixed to a rear corner of the battery enclosure.





The electronic systems of the iso-BTC are responsible for measuring the battery temperature(s), controlling the heaters which are used to control this battery temperature, monitoring the voltages of individual cells in the battery and measuring battery voltage and current during charge and discharge.

The battery enclosure is connected via two oil pipes to a chiller unit – this provides background cooling for the instrument (a pre-requisite for the *power compensation* calorimetry method – please see below).

Method of operation.

Iso-BTC employs a calorimetry method called **Power Compensation**. In power compensation a background heating/ cooling system is configured to control the *background temperature* of the battery some degrees below the required battery set point. One or more low power heaters are connected to the battery itself[1] and are used to bring the battery to its required set point. The power required to do this in the absence of any heat output from the battery is referred to as the **baseline power**. The power output to these fine control heaters is measured continuously within the iso-BTC electronics. If during a battery test the battery itself generates any heat, this will tend to increase the battery temperature and this in turn will result in the battery temperature control system decreasing the power output to the control heater(s). This decrease in control heater power is proportional[2] to the heat generated by the battery and the constant of proportionality (referred to as the **efficiency**) is readily determined during the course of the battery test. A number of different strategies can be applied to the evaluation of this parameter and these are described in detail, later in this document.

In operation the battery is sandwiched between two cold-plates[3] and it is these that apply the background cooling to the battery. The cold-plates will typically be run some degrees below the required battery temperature. This difference between the cold-plate set point and the battery set point is referred to as the **compensation drop** and will depend on the expected power output from the battery under test. The compensation drop should be selected so that the baseline power is greater than the largest exotherm expected from the battery under test. Further the compensation drop must be selected so that the control heaters have additional capacity (beyond the baseline power) to compensate for any endotherm that might occur[4].

The Heat Spreader

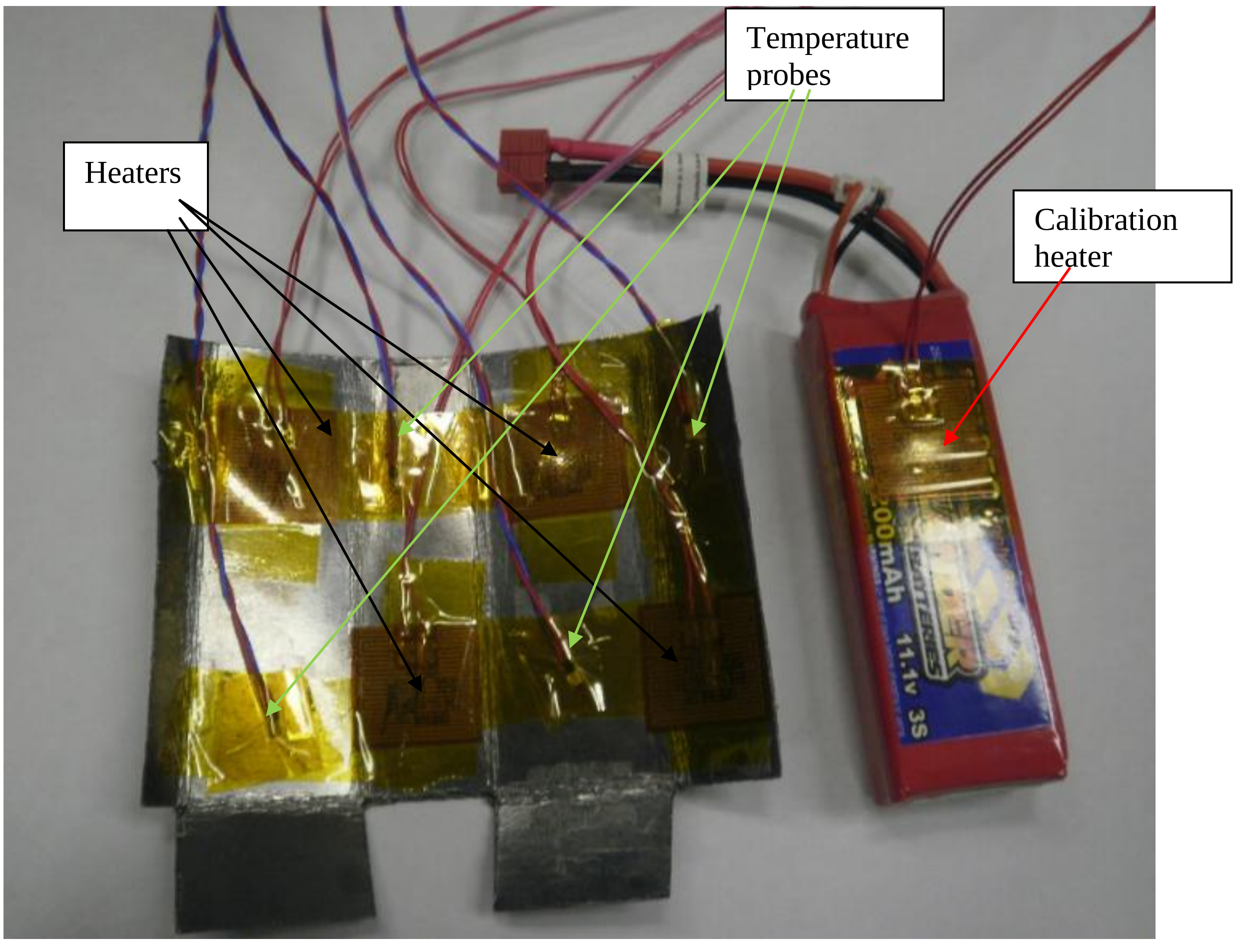
Since a battery is typically a solid object manufactured from a number of different materials of varying thermal conductivity, maintaining all parts of a battery at the same temperature during a test can be a challenging if not an insurmountable problem. It is complicated by the facts that

a) the heaters used to heat the battery will almost certainly not be able to uniformly heat the entire battery surface (unless heaters are designed specifically for each type of battery)
b) during testing the battery itself may be generating heat, again non-uniformly

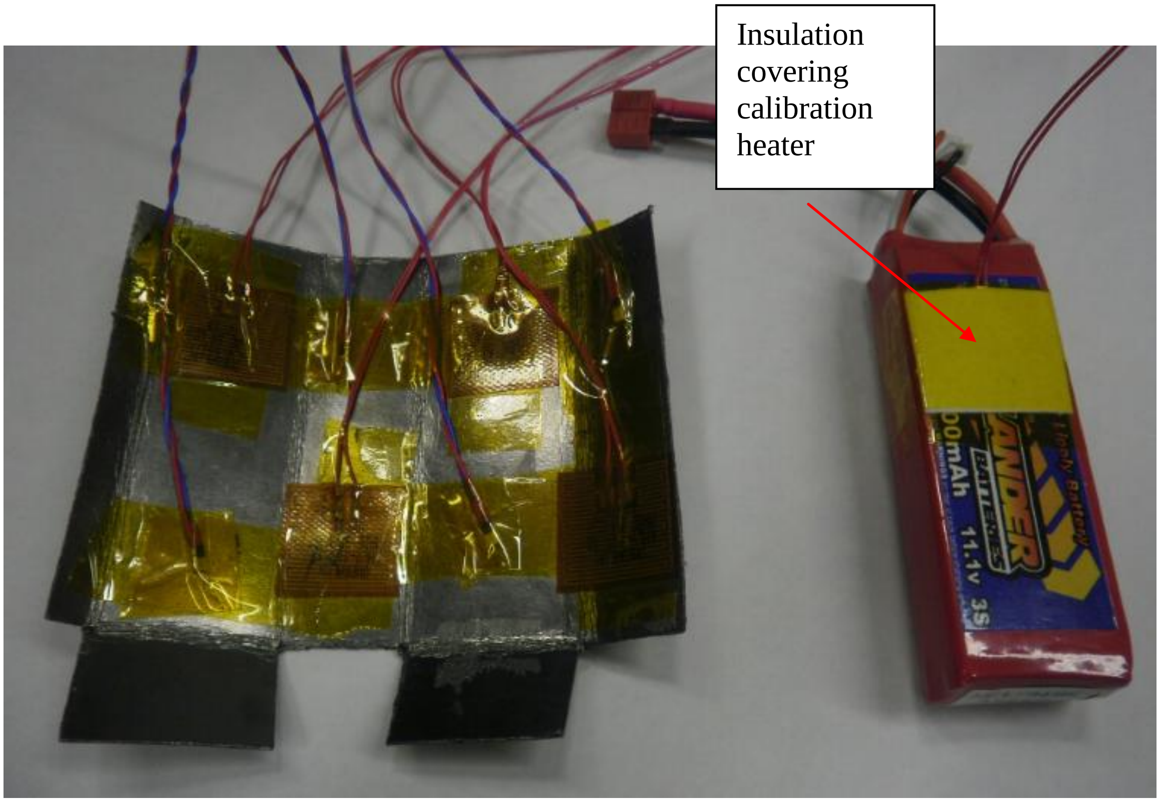
[1] Or to a “heat spreader” which is wrapped around the battery
[2] “Proportional to” but not typically “identical to” because of direct interactions between the heating and cooling systems which bypass the device under test
[3] Referred to as cold-plates because they are colder than the battery – but NOT necessarily colder than ambient
[4] This occurs commonly during the charging cycles of lithium batteries

When temperature differences across the battery during testing are allowed to become too large, associating any battery behaviour with a specific temperature can be somewhat arbitrary.

To reduce the impact of this problem batteries are typically wrapped in a **heat spreader**. IsoBTC heat spreaders are typically manufactured from a highly conductive graphite material whose in-plane thermal conductivity is typically higher than that of aluminium. Control heaters and temperature probes are attached to the surface of this spreader which is then wrapped very tightly around the battery to test. A heat spreader for a typical prismatic battery is shown in the image below.

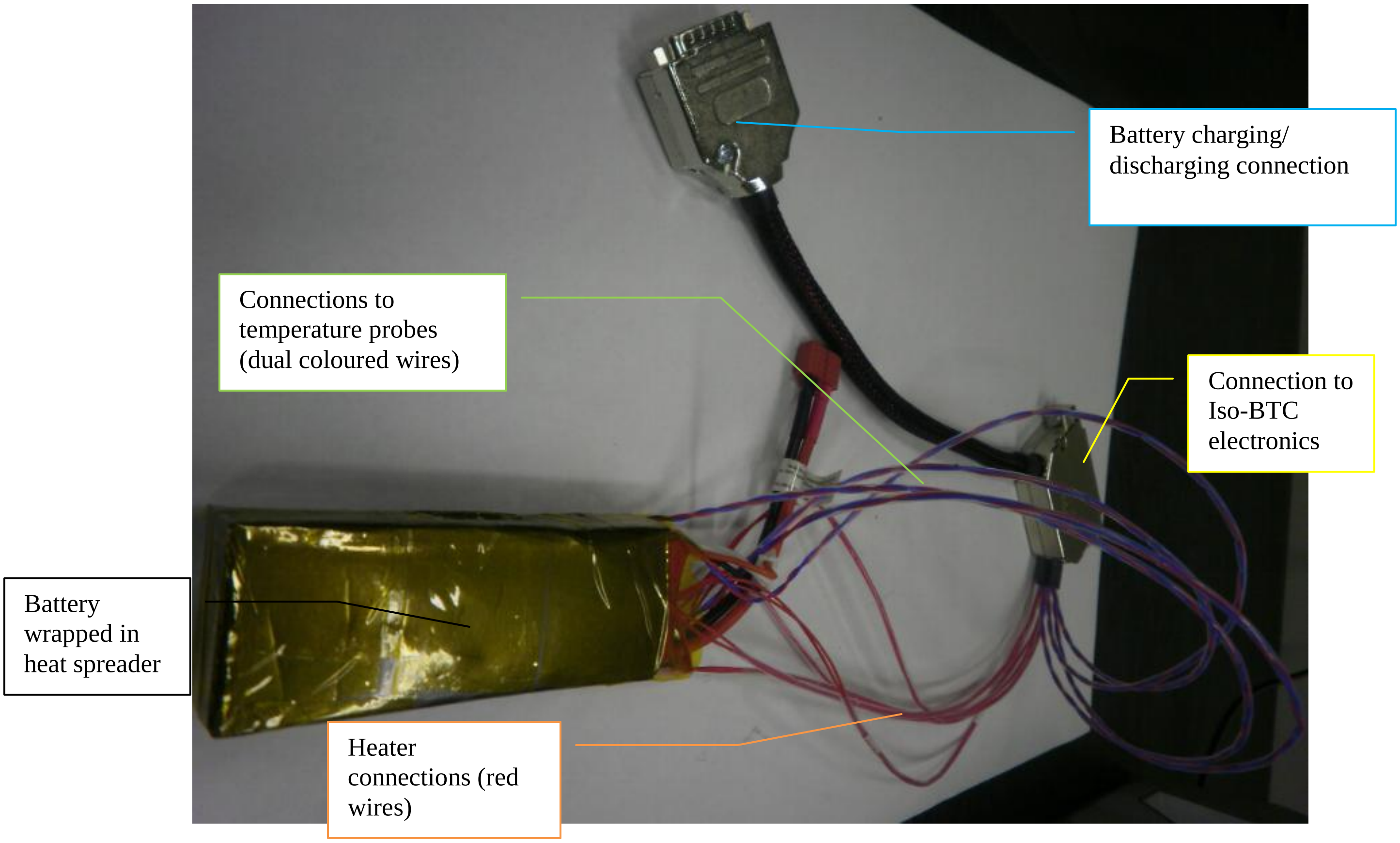


The calibration heater pictured in the image above (and the following image) is used for the online evaluation of efficiency. This, and alternate strategies for efficiency determination, are described later in this document.



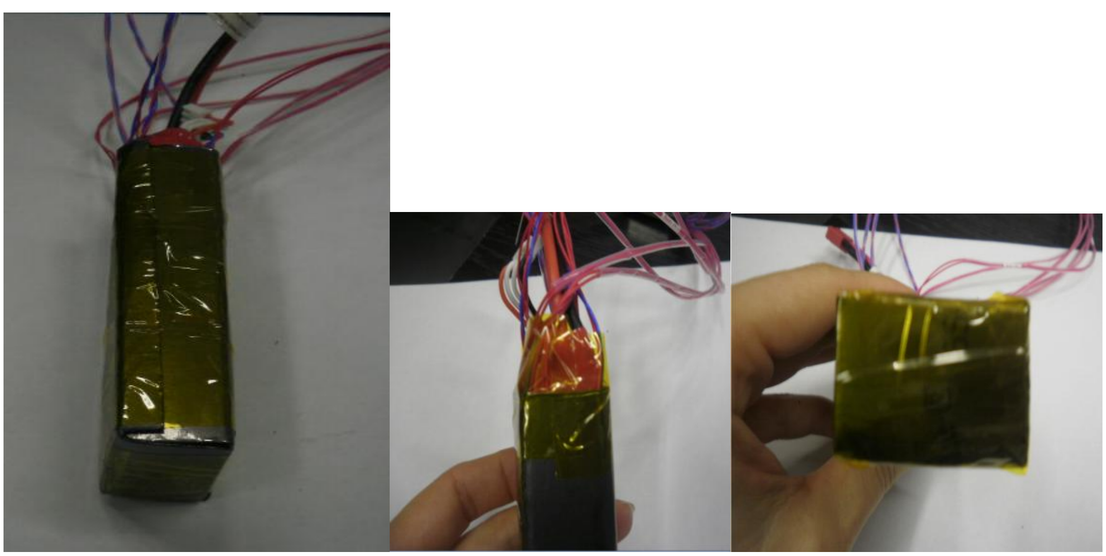
When wrapped around the battery and fixed using a suitable temperature resistant but thermally conductive tape[5] the battery and its spreader constitute a simple assembly which can be plugged into the BTC control system via a single connector. This assembly for the prismatic battery shown above can be seen in the image below.

[5] Kapton is typically used



Key considerations when making a heat spreader for a given battery are considered in detail later in this document.

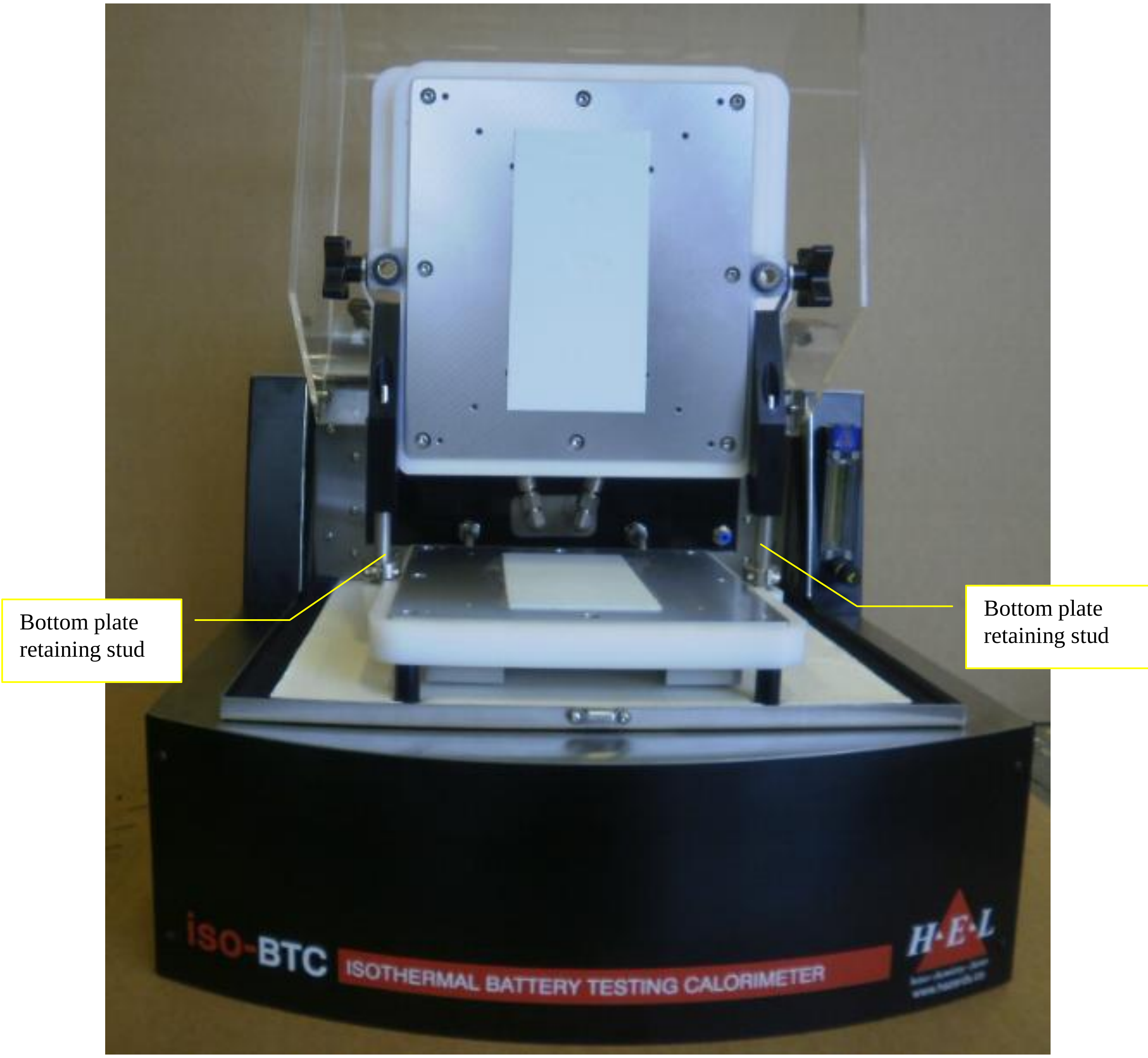
It is also considered wise to seal the gap between the battery and the heat spreader at the cable end (top end of spreader in above photo) – this will help to prevent heat loss from the inside of the battery assembly during calibration (see below).



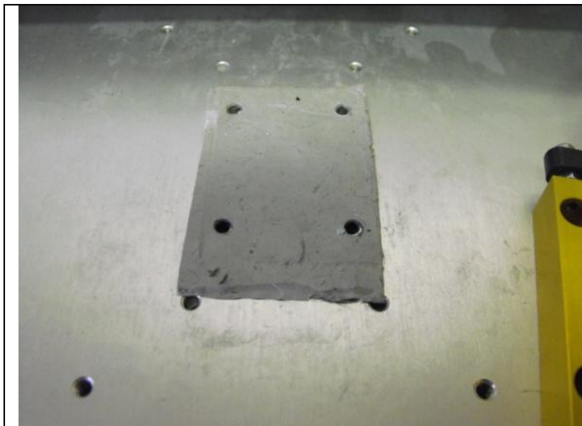
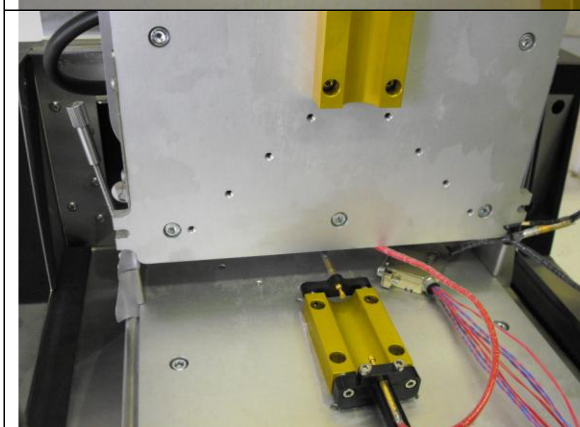
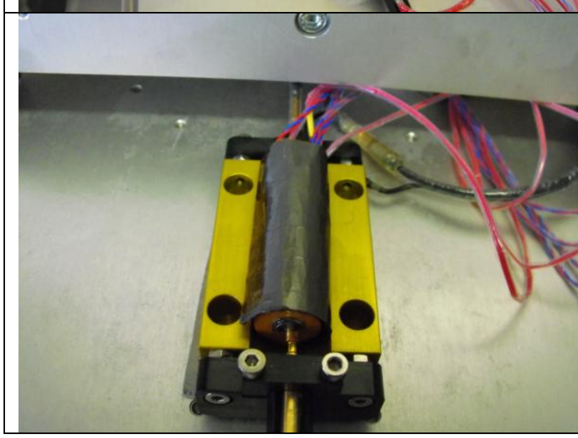
Installing the "Battery Under Test" in the iso-BTC.

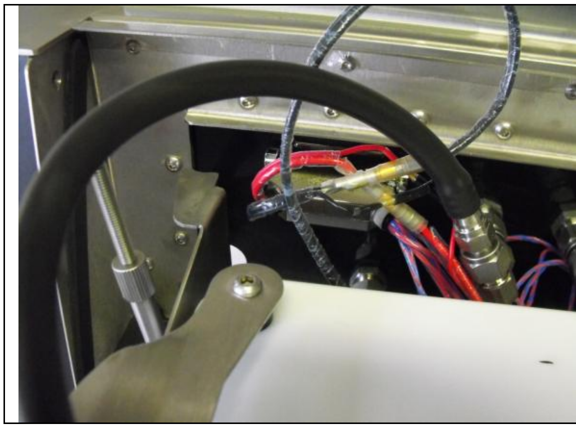
To access the inside of the battery enclosure the transparent lid should be lifted as in the figure below.

To install or remove a battery from the Iso-BTC the top plate can be lifted and supported on the *bottom plate retaining studs* (as shown in the photograph below).



This gives access to the cooling surfaces of both the top and bottom plates. Examination of these shows a pattern of threaded holes by which the adapters for different battery geometries can be attached. Pouch and prismatic batteries are typically laid directly onto the bottom plate – a layer of thermal interface material is normally placed between the battery and the cooling plates to give reproducible heat transfer characteristics between the battery assembly and the plates (see frame 1 in sequence below). Battery adapters are typically made up of two separate halves, one of which is attached to the top plate and the other – in the corresponding position – to the bottom plate (see frame 2). Note that again a layer of thermal interface material is normally positioned between the adapters and cooling plates. Batteries/ battery adapters should be positioned as close as possible to the centre of the cooling plates to make it as easy as possible to keep the plates parallel. The cabling from the battery assembly can be threaded through the gap between the plates (frame 3) and plugged into the mating connector mounted on the back-panel of the battery chamber (frame 4). The top plate should then be replaced (with the top half of the adapter – if fitted – positioned on top of the battery).

	1) a sheet of thermal interface material is placed on the cooling plates where the battery (or adapter) is to be mounted
	2) the two halves of the battery adapter are attached to top and bottom cooling plates (on top of the thermal interface material). NOTE the central positioning of the adapter halves
	3) the battery in its heat spreader is inserted into the battery adapter. Note the battery terminal connections are telescopic although it may prove simpler to release the two hex-bolts shown at the bottom of this photograph when inserting the battery assembly into the adapter. The telescopic connections can then be compressed and the bolts re-tightened.

	4) the connector from the battery assembly can then be connected to the mating connector mounted in the top left hand corner of the battery enclosure back plate.

NOTE: the lid of the battery enclosure should be lowered before and experiment is started to minimise the impact of environmental temperature changes during the experiment.

Summary

To remove battery from the Iso-BTC

1) open battery compartment
2) release battery assembly connector from mating connector on the back of the battery compartment
3) lift top plate and slide the top plate on the bottom plate retaining studs

The battery (and adapter) can then be removed from the calorimeter

To install battery in Iso-BTC

1) If not already so positioned lift top plate and slide the top plate on the bottom plate retaining studs
2) Position battery on lower plate being careful to ensure that the entire contacting face of the battery is positioned on the thermal interface layer clearly visible on the bottom plate. Ensure battery is as central as possible
3) Feed battery assembly connector through gap under the vertically supported cooling plate and plug into socket in corner of battery compartment
4) Return top plate to a horizontal orientation and slide the top plate onto the bottom plate retaining studs.
5) Close battery compartment to prevent fluctuations in baseline caused by ambient changes
6) When working at sub-ambient temperatures use Nitrogen purge.

The installed battery can then be tested.

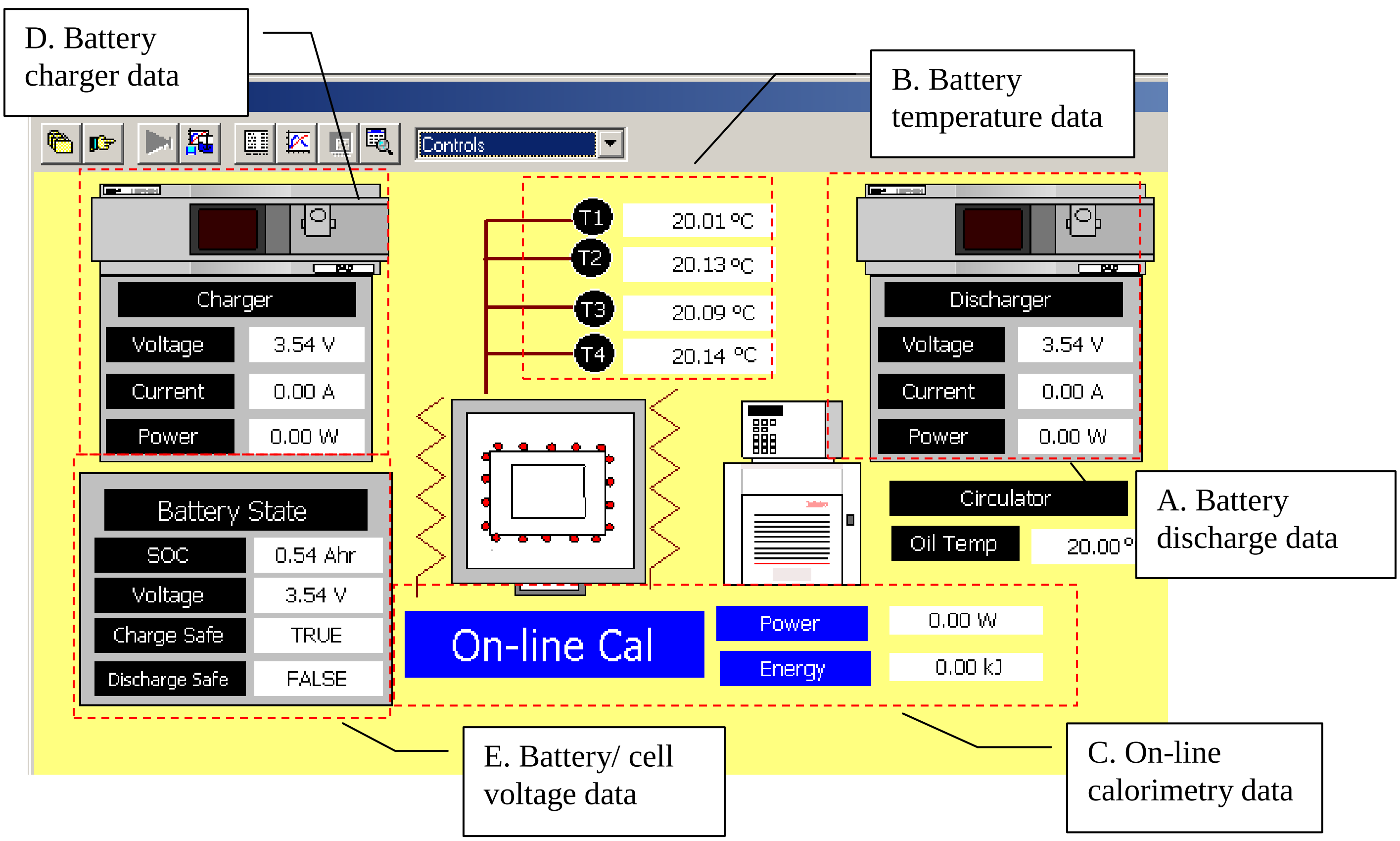
The iso-BTC software.

Introduction

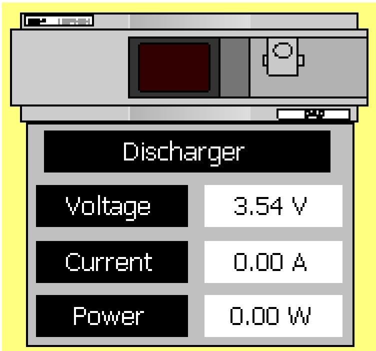
The Iso-BTC control system is based around HELs WinISO software. While control of individual components of the system can be accomplished from the *mimic window* Iso-BTC experiments are normally controlled via the in-built recipe system. This is described later in this section.

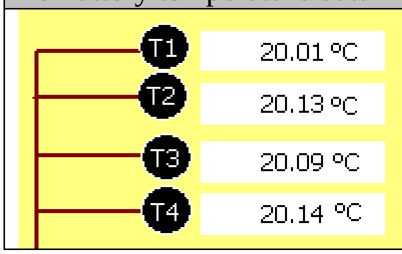
The mimic window.

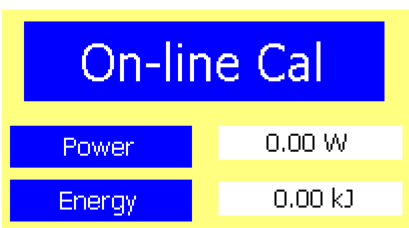
The mimic window contains a schematic view of the Iso-BTC. It presents key real-time data as well as presenting a means of accessing individual components of the system. A typical example is shown below.

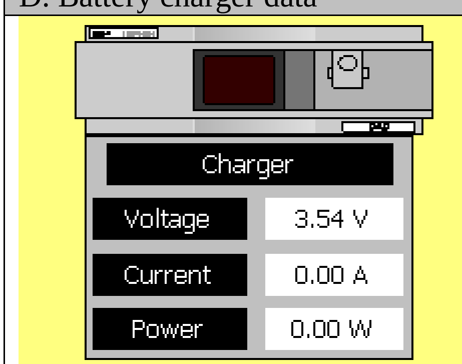


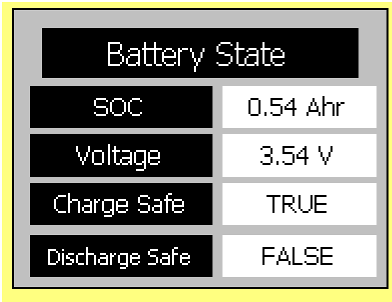
The separate sections of the mimic are described individually below.

A. Battery discharge data	
	While labelled as presenting battery discharge data the voltage field (read by sense lines attached directly to the battery terminals) gives a reliable indication of the battery terminal voltage at all times. On double clicking in any of the dischargers numeric display panels a dialog box is displayed which allows the discharge to be activated and its discharge level set. NOTE: by manually activating the discharger in this way it is very easy to over-discharge and consequently damage a battery

B. Battery temperature data	
	Shows the various measurements of battery temperature – returned from a number of sensors distributed around the battery. Four sensors are typically available (T1-T4) and these are averaged to give the “Battery temperature” which is used as feedback in all temperature control.

C. Online calorimetry data	
	These fields show the real-time calorimetry data “Power release” and “Energy release” determined by the WinISO on-line calorimetry system. NOTE: these values are estimates while the calculation is actually running in that they do not incorporate baseline interpolation i.e. there will be no adjustment for baseline shift during the “heat release”. Such adjustments are applied as the data is written at the end of the experiment.

D. Battery charger data	
	These data are typically read directly from the battery charging unit (either a separate PSU or a component of the incorporated battery cycling unit). Exact behaviour will depend on the cycler being used but typically the voltage and current fields will only display the current battery condition when the charger is active – at other times typically showing the last used charging parameters.

E. Battery/ cell voltage data	
	These data are returned by the cell monitor system built into the Iso-BTC and allow both a conservative charge/ discharge strategy to be employed AND easy change over between batteries containing different numbers of cells and different technologies. “Charge safe” and “Discharge safe” are determined by comparing the current cell voltages (there can be more than one) against maximum and minimum calibrations stored within the software. These flags are typically used as terminating conditions in the WinISO recipe system avoiding the need to encode individual battery characteristics into every recipe. Configuration of these facilities are described in the next section of this manual

Configuration/ Calibration before battery test.

While an increasing majority of modern batteries are based around lithium ion chemistry there are many variants of this technology which operate at slightly different voltages (with maximum, minimum and nominal voltages varying by over a volt between the various options). Additionally Iso-BTC might be required to test single cells or batteries containing multiple cells and there may be a need to switch between different formats/ chemistries frequently. Further a conservative charge and discharge strategy should be employed where each cell is monitored and charging/ discharging should be terminated when any single cell reaches its safe limit.

With these requirements in mind the cell monitor system (CMS) was implemented and incorporated on the Iso-BTC. The salient features of this system are described below.

1) CMS is configured to monitor a certain maximum number of cells – typically 3. However not all these cells need to be present – CMS can be configured to monitor a sub-set of these during any given experiment by simply entering the number of cells currently installed
2) Maximum and minimum allowed cell voltage levels are stored as system calibrations – when moving from one cell chemistry to another it is only necessary to change the relevant voltage limits in a single place.
3) The potential of each installed cell is monitored using a sense wire approach. This eliminates any voltage drops between battery and measurement circuit caused by the large currents typically involved. For uninstalled cells CMS returns a cell voltage of 0V.
4) CMS also estimates a current “State of Charge” (SOC) by integrating and balancing charging and discharge currents (this is typically done on a whole

battery basis – not cell by cell). Initial charge is arbitrarily set as 0Ahr and all subsequently reported SOC values are relative to this.

NOTE: since cell management is intimately entwined with the behaviour of the battery cycling system, the elements of the CMS system that are actually relevant to a given Iso-BTC installation will depend critically on the battery cycler in use. For battery cyclers which support only a single cell, only a single cell voltage will be monitored/processed.

WinISO plans (see below) can use the “ChargeSafe” and “DischargeSafe” terminating conditions which are updated whenever new battery potential data becomes available. This avoids the need of referencing cell voltages explicitly within any plan.

WinISO Plans

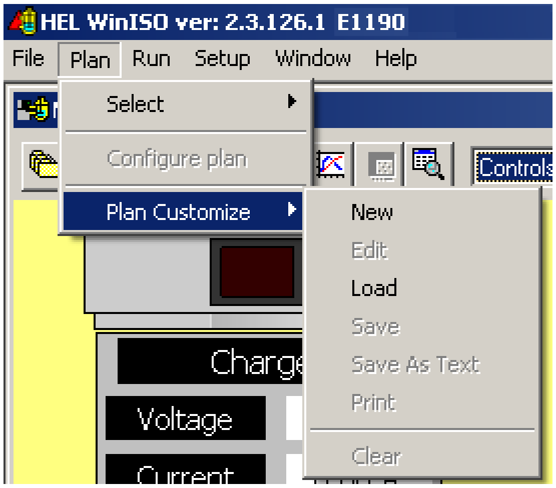
A **plan** is the term used to describe an experimental recipe of arbitrary complexity which, after creation, can be saved to disk allowing it to be reused at a later date. A plan consists of a number of **steps** – each step contains

1) a set of controller settings which implements the required control strategy for the step
2) a number of terminating conditions which control when the step will stop running and which step (if any) will start to run afterwards.

In addition to the steps which contain the experimental details for the plan, a plan additionally contains

1) an elaborate set of safety conditions to ensure the safe operation of the experiment. These allow an arbitrarily complex set of fault conditions to be explicitly identified and for each, a set of remedial actions that can be specified for dealing with the fault condition
2) a specification of the data that should be displayed while the experiment is running
3) a specification of the data that should be saved to disk when the experiment is completed.

When these facilities are enabled, new plans can be created, edited and saved and then reloaded by using the options in the Plan Customise menu (see below).



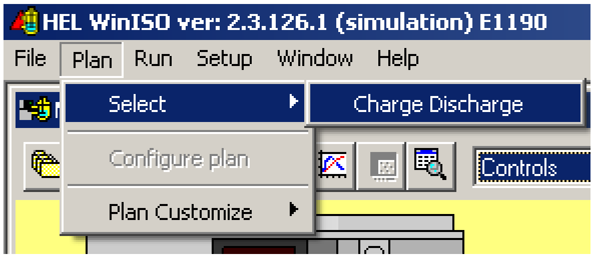
Due to the complexity of the required plans however the ability to create plans is not always provided – instead a set of **standard plans** is provided which automate the normally required tests. Use of these Standard tests is described in the following section.

For further information on the WinISO plan system precise details can be found in the WinISO Software manual.

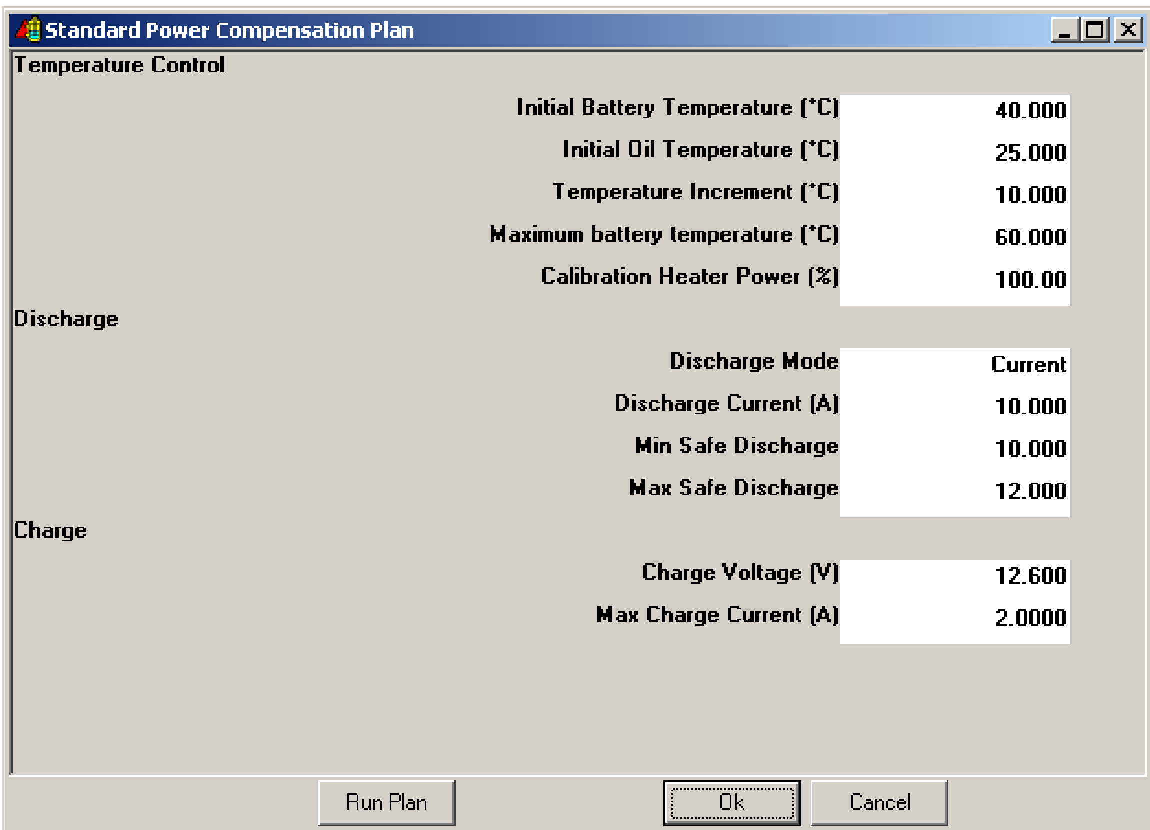
Standard Plans.

Where a standard testing protocol is to be used to test a battery, the flexibility of the WinISO plan system is not required – it would be virtually the same plans that would be run each time the Iso-BTC is used. Since the precise conditions used for each test may differ slightly, it would be ideal to provide a simplified mechanism for manipulating the key experimental parameters used within a plan while preserving the structure of the plan (i.e. the arrangement of steps). This is exactly the approach provided in the WinISO Standard Plan system. Standard plans contain the normal sequence of steps and terminating conditions as described above but in addition contain a **custom editor** which allows the key parameters of the test to be edited in a simple and more importantly a consistent way. These important parameters are presented on a form (potentially with multiple pages, should the complexity of the test warrants this); the parameters can be edited and are saved back to the plan if the user selects the Ok button. Any changes can be discarded by typing the Cancel button.

The Standard Plans are accessed by opening the Select sub-menu which appears in the main WinISO Plan menu (see below).



In this example a single Standard Plan is shown entitled “Charge Discharge”. This plan (which is invariably shipped with Iso-BTC systems) examines the temperature dependence of charge/ discharge profiles. It consists of 14 steps but some of these are contained within a loop causing them to execute many times at different temperatures. Rather than having to edit these 14 steps separately this test can be customised by using the plans Custom Editor shown below – containing only 11 fields many of which will stay the same between runs.



When the test parameters have been selected the plan can be run using the Run Plan button at the bottom of the form – alternatively the menu options in the WinISO Run menu can be used.

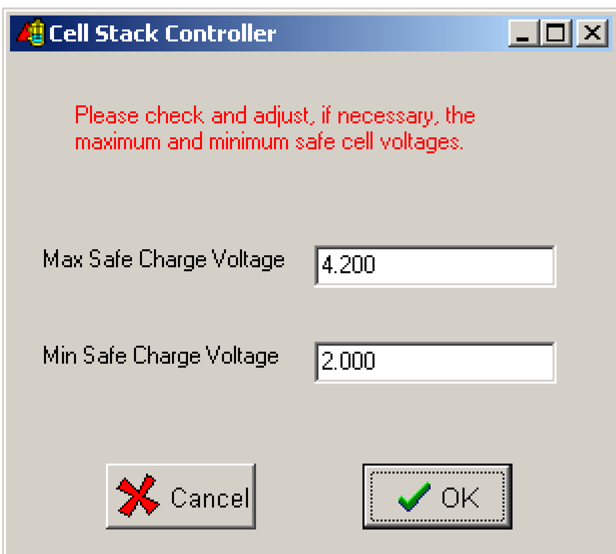
This custom editor is displayed when a new plan is selected or when the “Plan | Configure Plan” menu option is selected.

Additional Standard Plans may be available – as standard test protocols emerge these will be supported by new Standard Plans and these will be distributed with Iso-BTC systems.

The user should refer to the WinISO software manual for detailed information about WinISO facilities such as plan control, calibration etc.

Reviewing battery parameters before executing a plan.

Because modern batteries employ many different chemistries, the voltages that might be used within an Iso-BTC test may vary frequently. As previously explained, the maximum and minimum voltages for a battery are stored as calibrations of the Cell Stack Controller – it is this device which provides the "Safe to charge" and "Safe to discharge" terminating conditions that are typically used as step terminating conditions within plans. Because of the potential danger of cycling a battery outside this range, it has be deemed necessary to the review these voltage limits before each test is started. Thus, on selecting the "Run" menu option, the following form is displayed.



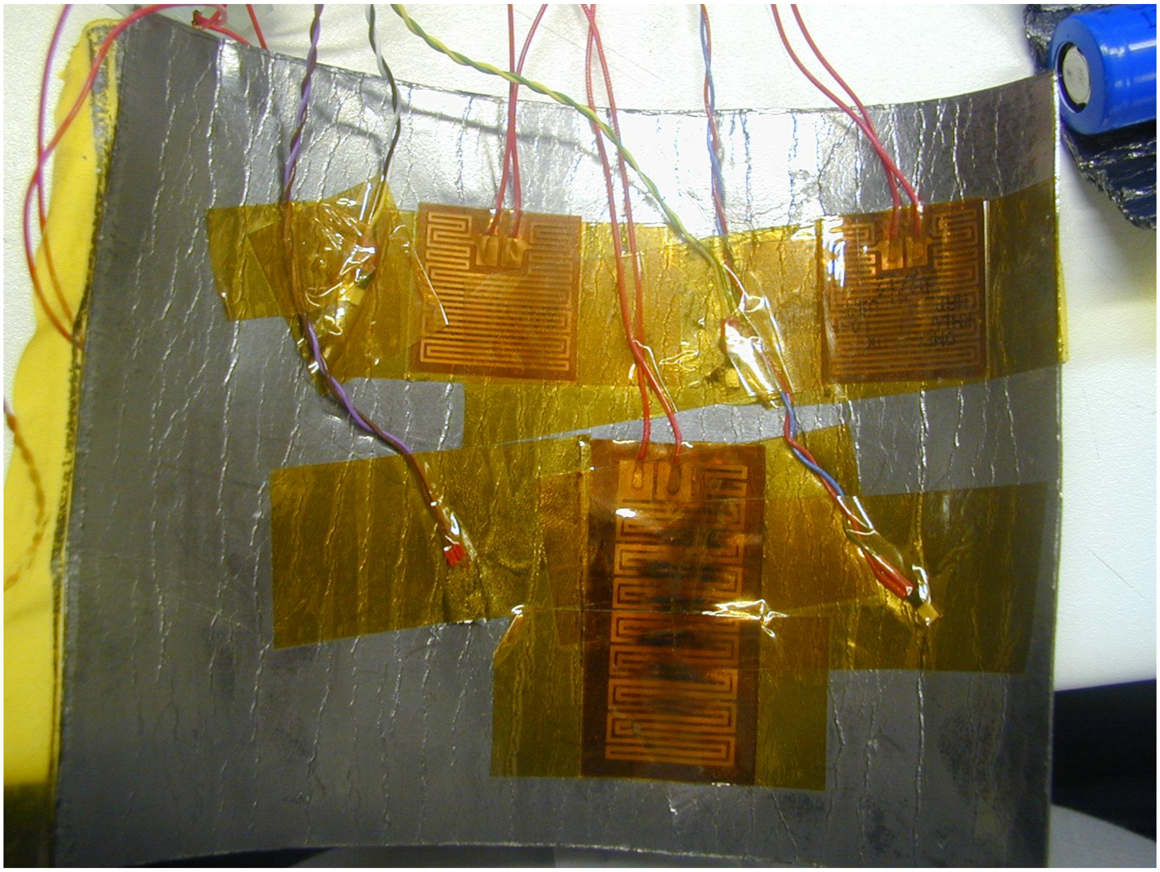
Clearly the values shown as the max and min safe voltages may vary for different Iso-BTC configurations but these should be edited so as to be consistent with the batteries currently under test.

On changing the max and min safe voltages in this form, these new settings are saved so they will be used not only in the current test but in all subsequent tests, until again changed.

Heat spreader construction

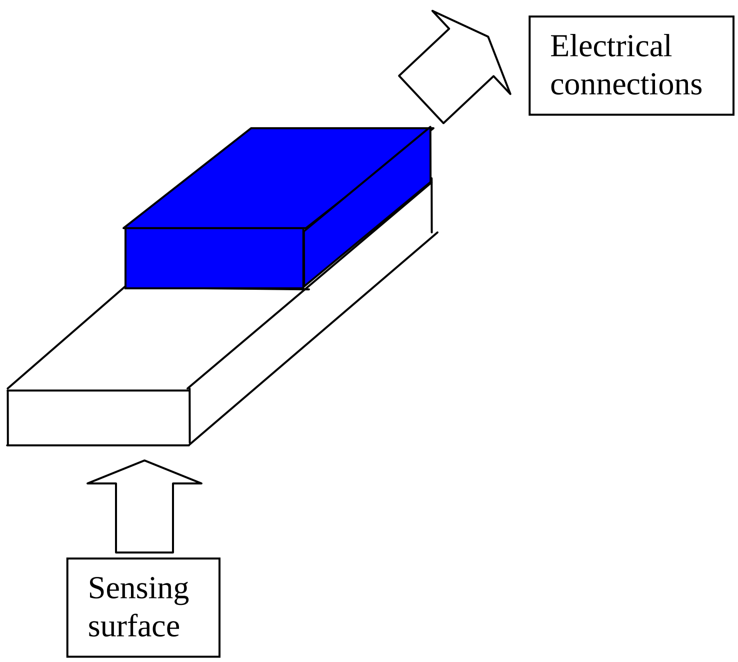
The purpose of the heat spreader is to maximise the contact area between the heaters and the battery – to emulate the situation where the heaters uniformly cover the surface of the battery. However as has been previously noted the battery will itself generate heat and there is no guarantee that it will do this uniformly. Consequently it is also necessary to make a number of measurements of the battery temperature so that an average can be used for control purposes. This requirement for multiple battery temperature measurements is also conveniently incorporated into the heat spreader.

Below is a typical heat spreader (actually for an Overlander battery). A number of heaters and temperature probes are evenly distributed across the surface of the spreader taking care not to position any of the temperature probes too close to a heater. The power rating of the heaters that are required will reflect the maximum power that a battery can generate (see Method of operation above) and it is desirable to supply this power through as large a heater area as possible to maximise uniformity. Consequently most HEL heat spreader assemblies incorporate 1 square inch/ 10W control heaters.



When supplied thermal control assemblies will have heaters and temperature probes already connected to an appropriately sized and shaped template of heat-spreader material (as shown above). This material does however become worn after extended use and can eventually need replacing. When replacing the heat spreader the following criteria should be observed.

1. Heaters should be distributed evenly across the heat spreader with the heating surface pointed INWARDS towards the battery (i.e. writing facing the spreader). Heaters should be positioned so as to contact the battery (i.e. avoiding overlapping regions of the heat-spreader)
2. temperature sensors (all 4 MUST be attached to heat spreader) should also be distributed across the heat spreader and should not be positioned too close to any heater so as not to be overly influenced by it
3. the temperature sensors are PT100 devices and consist of a ceramic plate upon which a “blue bead” is attached and through which wire connections exit the device (see below). The primary sensing surface of the device is the underside of the white ceramic plate. The temperature sensor should be orientated so that this sensing surface will be in contact with the battery (i.e. the blue bead should be in contact with the heat spreader). The temperature probes should be fixed in this appropriate orientation using Kapton tape.



4. electrical connections from the heat spreader should all be routed to exit from one end of the heat spreader and should be routed AROUND heating elements rather than be allowed to lie over the top of them. If allowed to lie over the heaters, direct heating of the temperature sensors will become possible and the cables could prevent good contact between the heaters and the enclosed battery.

Efficiency Evaluation.

Evaluation of the efficiency is the only complication in what is otherwise an extremely simple calorimetric approach. The efficiency represents the factor by which the control heater power must be reduced to compensate for a given heat release from the battery under test. It is always greater than 1 because a fraction of all heat generated by the control heaters is lost directly to the cooling system. It is a complex function of the geometry of the battery, heaters and cooling system and no accurate method of predicting its value is currently available. However, the efficiency is readily measured – a calibration heater is used to inject a known amount of heat into the battery, the response of the control heaters can be directly measured and the efficiency calculated as the ratio of these two power values. However, injecting the heat into the battery is frequently NOT a simple process. Once evaluated, all energy measurements made by IsoBTC are automatically adjusted accordingly. A number of separate strategies for efficiency determination are employed.

Use of a battery emulator to evaluate efficiency

This is now generally the preferred method of efficiency determination because it is largely immune to error and can be highly reproducible. As commented above, the efficiency is a function of the geometries of the battery, heat-spreader and cooling plates, so by replacing the battery by an identically shaped object, which contains an embedded calibration heater, equivalent efficiency values can readily be measured. Emulators are frequently constructed as metallic boxes, containing some suitable filling and, of course, the calibration heater(s). Emulators are typically provided with the IsoBTC calorimeter, corresponding to a customer's geometry of interest. When this approach to efficiency evaluation is adopted, efficiency evaluation is carried out as a separate test which is run on the emulator BEFORE the battery is tested. When the emulator is replaced by the battery for the actual test, care should be taken to ensure that the wrapping of the battery (by the thermal control assembly) is identical to that of the emulator during the calibration.

On-line evaluation of efficiency

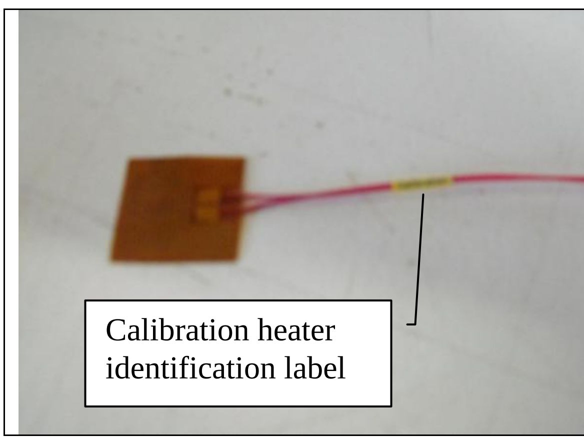
When the calibration heater can be embedded within the battery to test, the efficiency can be accurately evaluated during the actual battery test. This embedding of the calibration heater is readily possible when the battery to test consists of a number of separate cells – the calibration heater must be inserted between the cells so as to be totally enclosed. This approach to embedding the calibration heater is also generally employed during MCp determinations, where the object being tested frequently consists of a "stack" of cells or batteries – both to achieve a suitable geometry AND to allow embedding of the calibration heater. MCp determination is described in detail, later in this document.

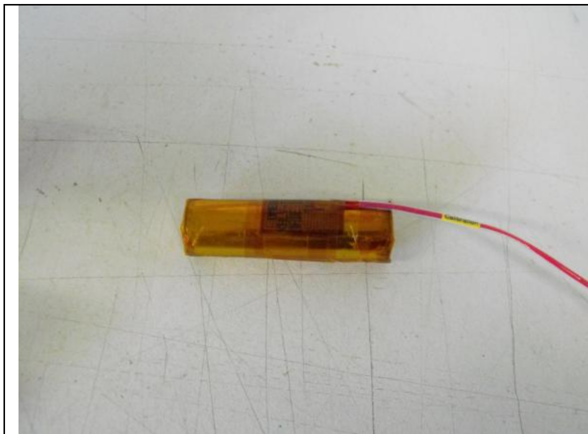
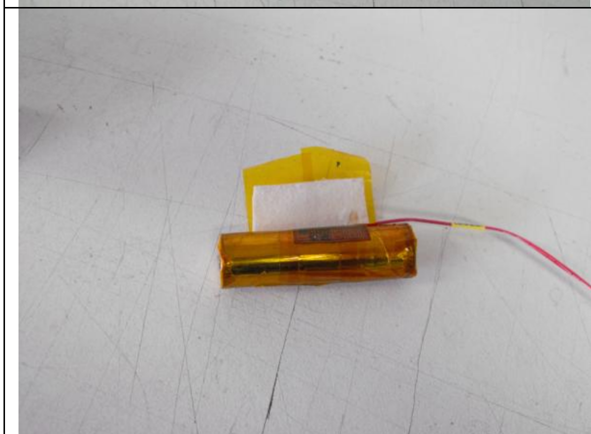
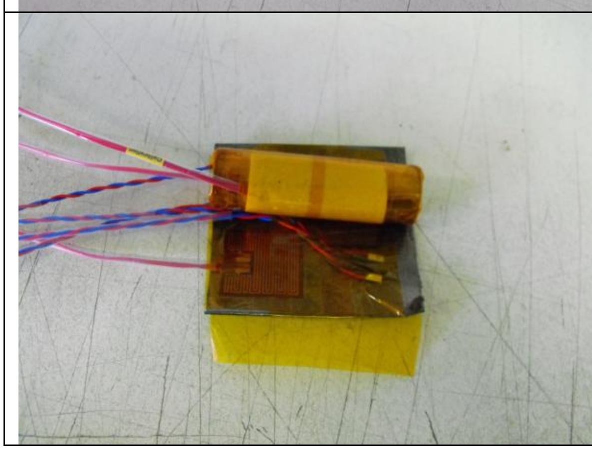
Where an emulator is not available, the efficiency can still be evaluated during the battery test, using a calibration heater attached to the outside of the battery. Where such a heater is incorporated into a thermal control assembly, it is marked clearly (typically using yellow rings on its electrical connections) to distinguish it from the other heaters used solely for thermal control. Positioning and use of this calibration heater is critically important if accurate results are to be obtained. The calibration heater must be isolated from the heat spreader to prevent the kind of interactions with the cooling system which have necessitated this calibration in the first place. This isolation is achieved in two ways

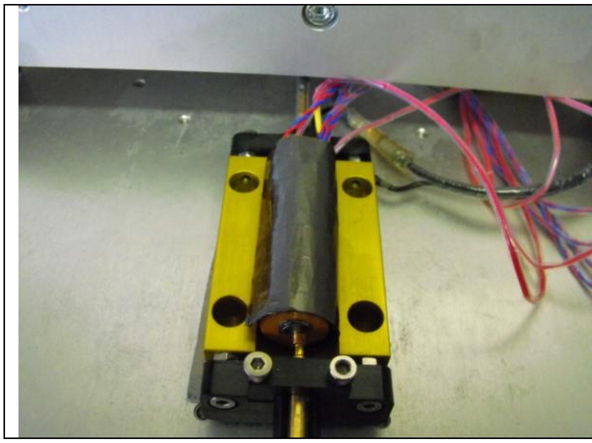
1) the calibration heater is attached directly onto the battery and covered with a layer of insulation – this *thermally bonds* it to the battery rather than the heat spreader
2) when the heat spreader is wrapped around the battery it is positioned so that the calibration heater is directly underneath one of the thermal control heaters. Power levels used for calibration are typically a fraction of a watt – thermal control heaters however typically run at many watts and so are invariably hotter than the calibration heater. In this way there is a temperature gradient which prevents heat flow from the calibration heater away from the battery.

Use of an emulator is preferred over this method because, after even all precautions have been taken, it is still possible to experience heat losses from the calibration heater during calibration. Further these heat losses might be different each time the thermal control assembly is wrapped around the battery. This can introduce errors into the output of the calorimeter which are impossible to quantify. These errors could be of the order of 10-20%; should this level of error not be considered problematic, on-line determination of efficiency does represent a convenient method of operation.

A typical set of operations for correct positioning of the calibration heater are shown (for the case of an 18650 battery) in the following set of frames.

	The calibration heater is clearly marked with a yellow label showing the text “calibration”. When a new thermal control assembly is purchased the calibration heater will be the only heater not bonded directly to the heat spreader. It is critical, however, when renewing the heat spreader in such an assembly that it is this heater that remains free – it is driven entirely differently from the other thermal control heaters.

	The heater should be taped (with kapton) directly to the battery.
	A layer of insulation (typically *kaowool paper*) should then be firmly fixed over the top of this heater
	When wrapping the battery in its heat spreader an effort should be made to ensure that one of the heart spreader heaters is positioned directly above the calibration heater

	The battery/ thermal control assembly positioned in its adapter in the Iso-BTC.

The calibration heater is supplied with its own software control that can be activated within a WinISO plan. Activation of this control is detected by the WinISO control system which can measure both the power input to the calibration heater AND the response of the thermal control heaters to this power. This allows the **efficiency** to be automatically determined and this can then be incorporated in all measurements made by the on-line calorimetry system.

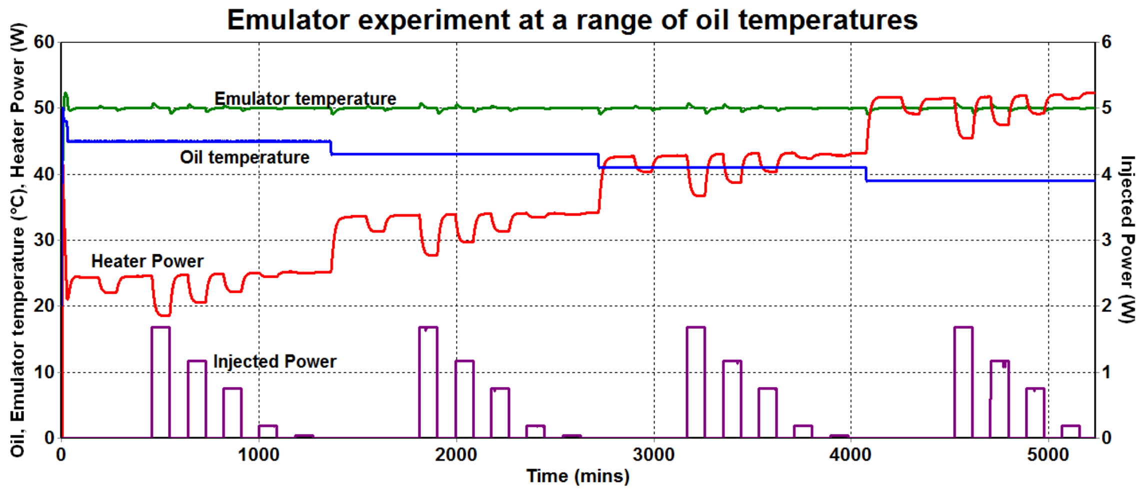
The wider impact of the efficiency factor.

The impact of the efficiency factor is somewhat wider than just necessitating the incorporation of a correction factor in calorimeter measurements. The maximum power that the calorimeter can measure is also reduced by the factor of the efficiency (although this can readily be extended electronically again where necessary). Further, and more positively, the resolution of the power measurement is also improved by factor of the efficiency.

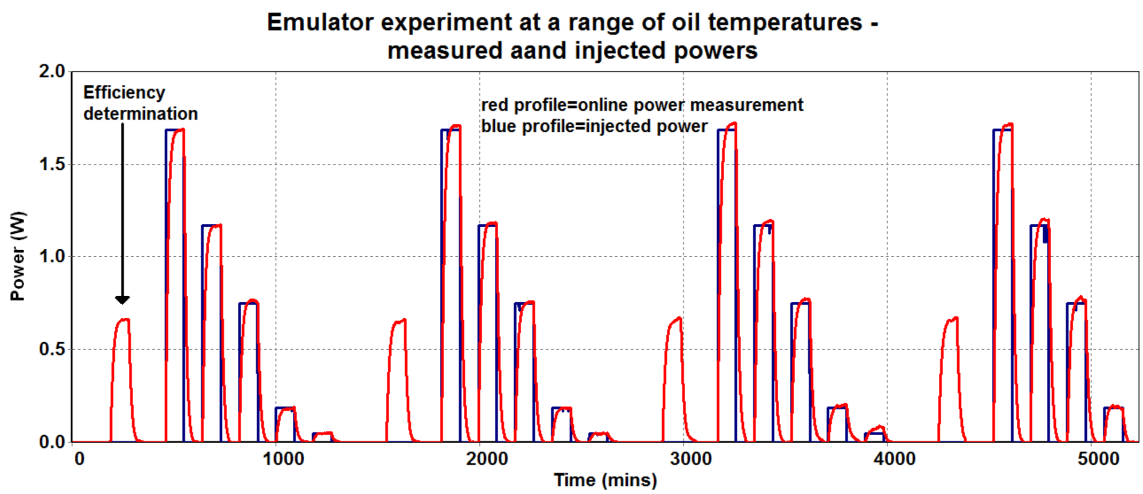
Validating calorimeter response using an emulator

Battery emulators are not only used for efficiency determination, their ability to release variable amounts of heat can be used to fully validate a calorimeters performance. Further, this variable power can frequently be generated by battery cycling hardware which is already incorporated into the calorimeter. In this case, emulators are typically supplied with the IsoBTC, along with plans to exercise them. These emulators generally incorporate two separate heaters, allowing the calibration and validation processes to be carried out independently.

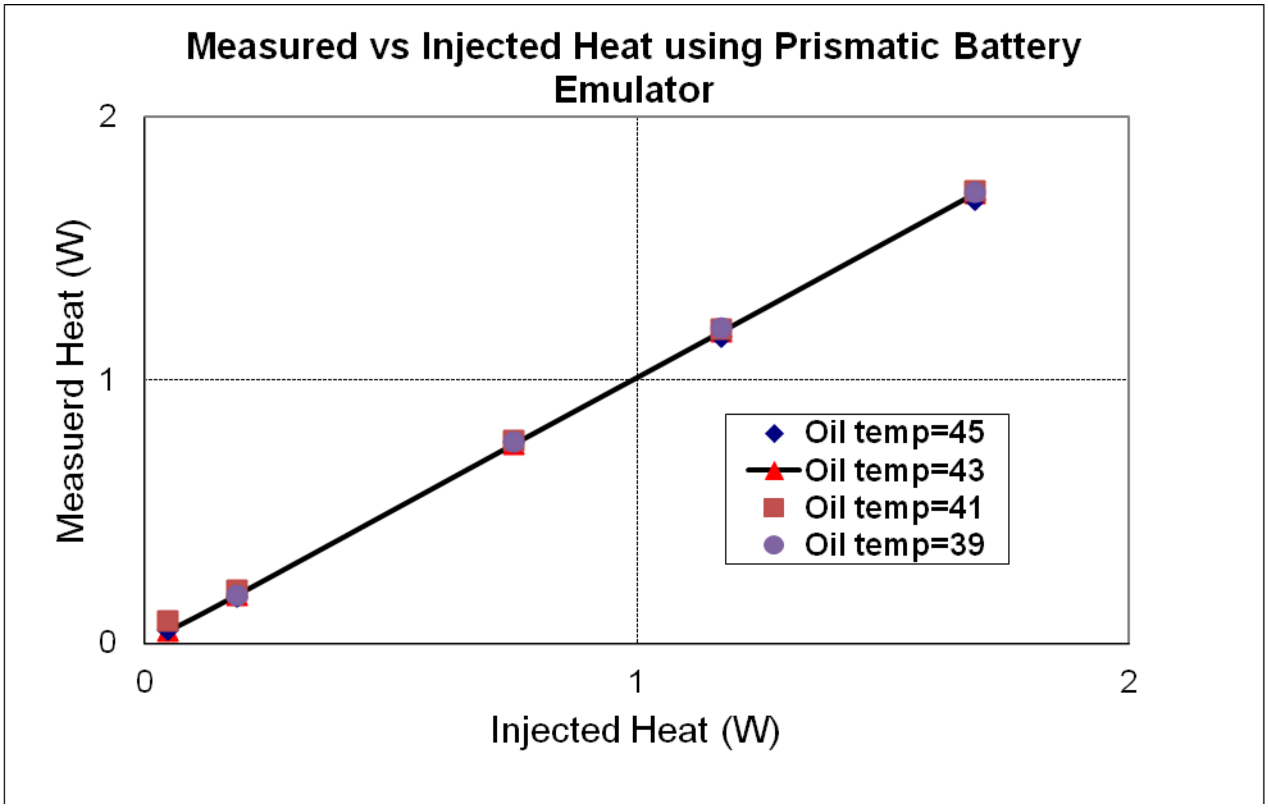
This is well demonstrated by the following large data-set, representing an experiment on a prismatic emulator.



In this experiment the IsoBTC has been programmed to hold the emulator at 50°C. During this test, the oil temperature is progressively, stepwise reduced – each time the oil temperature (blue profile) is reduced, the baseline heater power (red profile) rises to compensate for this. At each oil temperature, a number of different power levels are injected into the emulator and the power output to the control heaters is seen to change correspondingly, changing so as to compensate for the injected heat. The calorimeter automatically measures this power reduction (also compensating for any changes in the baseline power during the experiment), reporting this as its on-line power measurement. The injected power and corresponding online power measurement for the above experiment are shown in the figure below.



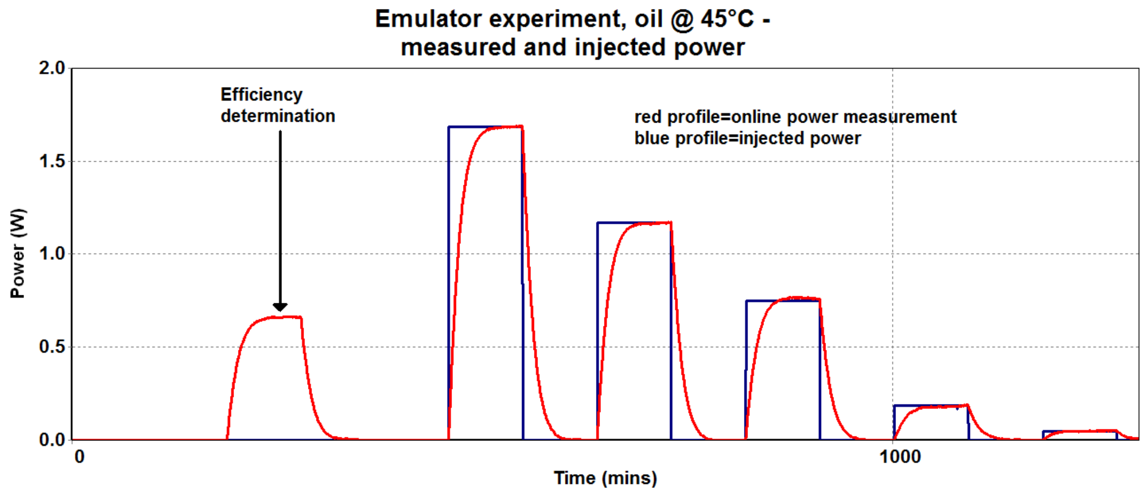
It is clear that the agreement in this case is very good – it is also apparent that the power measurement is unaffected by the changes in oil temperature. The relationship between the injected and measured power for the four values of oil temperature are summarised in the figure below – the multiple datasets are coincident.



The errors associated with the power measurement are summarised, for the four oil temperatures employed, in the table below.

Oil temperature	Advance (Emulator-oil)	Baseline power (W)	Gradient (Measured heat vs injected heat)	Error/%
45	5	35.6	1.00	0
43	7	41.1	1.01	1
41	9	46.6	1.00	0
39	11	52.3	1.02	2

The section of data from the first oil temperature employed (45^{o}C) is reviewed below.



This section of the previous data has been represented to allow several important observations to be made that reinforce points already made:

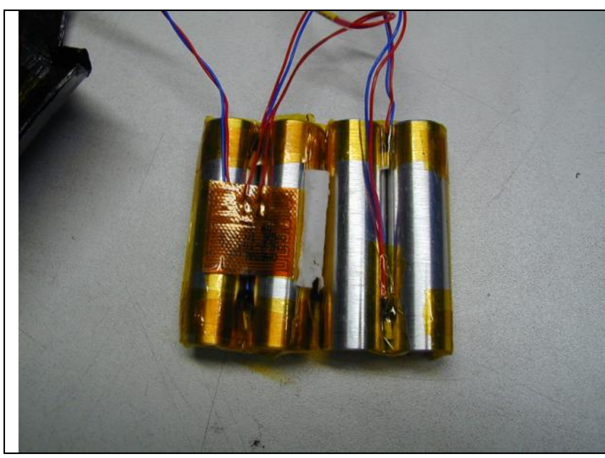
1) the injected power profile has sharp edges, whereas the measured power profiles have much more curved edges, reflecting the time constant of heat transfer through the emulator. Clearly the calorimeter is capturing this **residual heat.**
2) The first calorimeter response in the figure above (@~200mins), labelled **efficiency determination** does not correspond to an emulator heat injection (no corresponding blue profile), rather this is a response to a second **calibration heater**. With their close proximity to the cooling plates, heat is invariably lost directly from the control heaters to the cooling system, effectively by-passing the battery. The consequence of this is that, since only a fraction of the control heater power flows to the sample (i.e. emulator or battery), the control heater power has to back off **more** than the heat release from the sample to compensate for it. If not compensated for, this heat loss would result in an error in the calorimeter measurement. The factor by which the control heater power needs to be reduced to compensate for a given heat release from the sample is, referred to as the **efficiency** and has been already been fully explained within this document. This is an entirely linear effect so the same value of the efficiency applies at all power levels. The magnitude of this parameter is entirely dictated by the geometry of the sample and the placement of the control heaters within the thermal control assembly. Accurately predicting its value would be very difficult. Fortunately measuring it is extremely easy – by measuring the calorimeter response to a known heat input and then calculating the ratio of these two power values. This process is entirely automated on IsoBTC with the last efficiency value determined automatically being applied to the calorimeter's on-line power measurement. This also explains the importance of having reasonable emulators for batteries that are to be tested, since it is generally not possible to embed a calibration heater inside a battery. Since the emulator's geometry is the same as the battery's and can use the same thermal control assembly, then the efficiency will be the same.

Heat capacity (MCp) determination

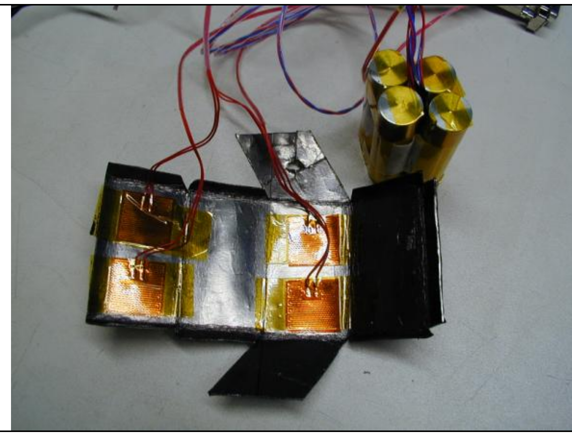
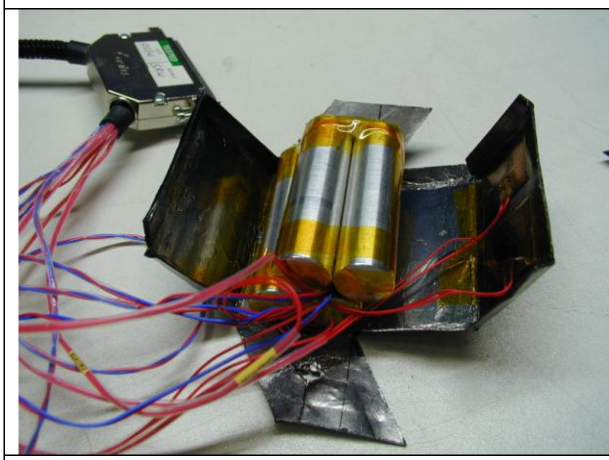
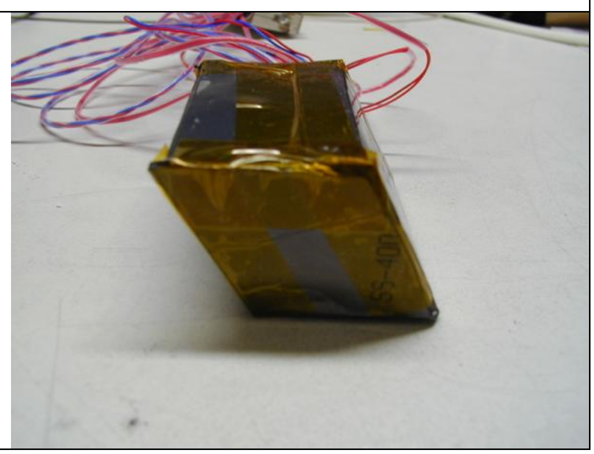
Heat capacity can be readily determined if a known amount of heat can be injected into a sample and the resulting temperature rise accurately measured. While simply explained, it can be problematic in practice to achieve. Care must be taken if accurately measuring heat input is to be achieved (because of un-measurable heat losses) and accurately assessing the sample temperature rise, where a sample is not heated evenly, is also not trivial.

However a readily applied, accurate method has been developed for heat capacity determination on the Iso-BTC, which can readily be applied at sub-ambient temperatures (this is virtually impossible on adiabatic calorimeters, where many heat capacity measurements originate). The principle is very similar to that employed for normal battery calorimetry although to achieve the most accurate results the heat capacity is determined for a **prismatic stack of batteries**, rather than for a single battery. The heat capacity of a single cell can then be determined by dividing the total heat capacity determined by the number of batteries in the stack. The methodology and sensitivities are described below. The photographs present the heat capacity determination applied to 4 aluminium 18650 emulators – allowing any error in the determination to be readily assessed.

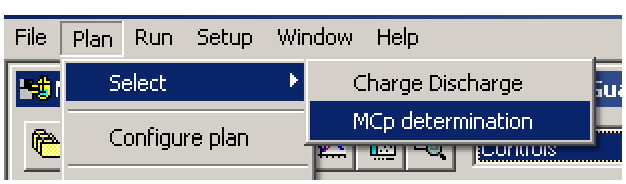
A number of target cells should be arranged in a prismatic pattern so that they can be seated within the IsoBTC **without the need for an adapter**. The calibration heater should be fixed to the surface of one of the batteries in the stack such that, as far as is possible, when assembled it is enclosed within the stack of batteries, with none of its surface visible from the outside. Additionally, the PT100 temperature probes should be removed from the thermal control assembly and these too should be fixed to the battery surfaces so that they too are entirely enclosed by batteries in the stack. These should not be positioned too closely to the heater.



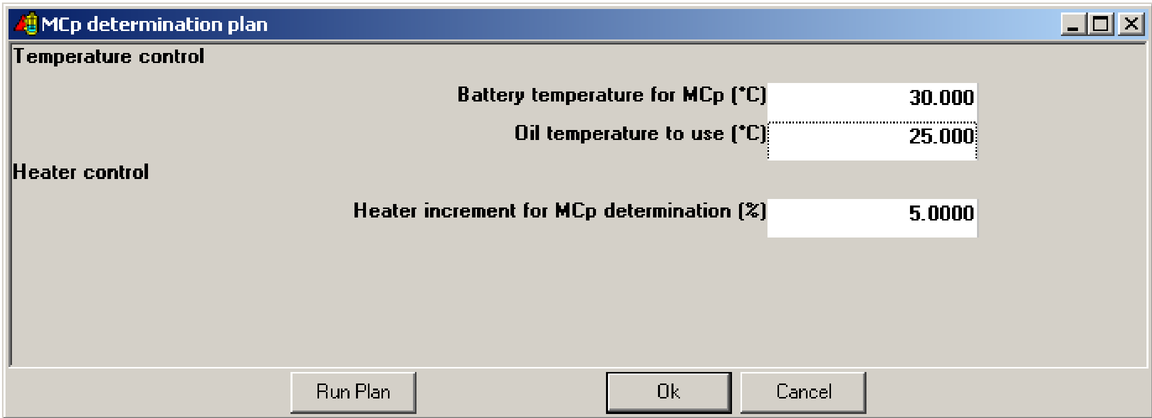
In the image to the left, four 18650 “batteries” will be used to assembly a prismatic stack. The batteries are grouped in pairs – the calibration heater is visible, fixed to the left hand pair of batteries. The four PT100 sensors with their connecting wires are visible, with two fixed to each pair of batteries

By placing the second pair of batteries on top of the first and securing with Kapton tape, the heater and temperature probes are entirely enclosed within the stack, as shown in the right had image, alongside the heat spreader in which the stack can be wrapped. If any of the calibration heater protrudes from the stack, this should be insulated with kaowool paper (which in turn should be fixed in place using kapton tape).	
	The heat spreader can be folded around the battery stack – a hole in one end allows the heater and temperature probe connections to be fed out for connection to the multi-way connector at the back of the Iso-BTC. This process is illustrated in the figure to the left.
After wrapping the heat spreader around stack it can be secured with kapton tape, as shown in the image to the right. This assembly is prismatic and can be placed in the Iso-BTC without the need for an adapter.	

A standard plan has been made available to carry out the evaluation, this should be selected from the Standard Plan menu as shown below.



On opening the plan a form requesting settings for the test will be displayed



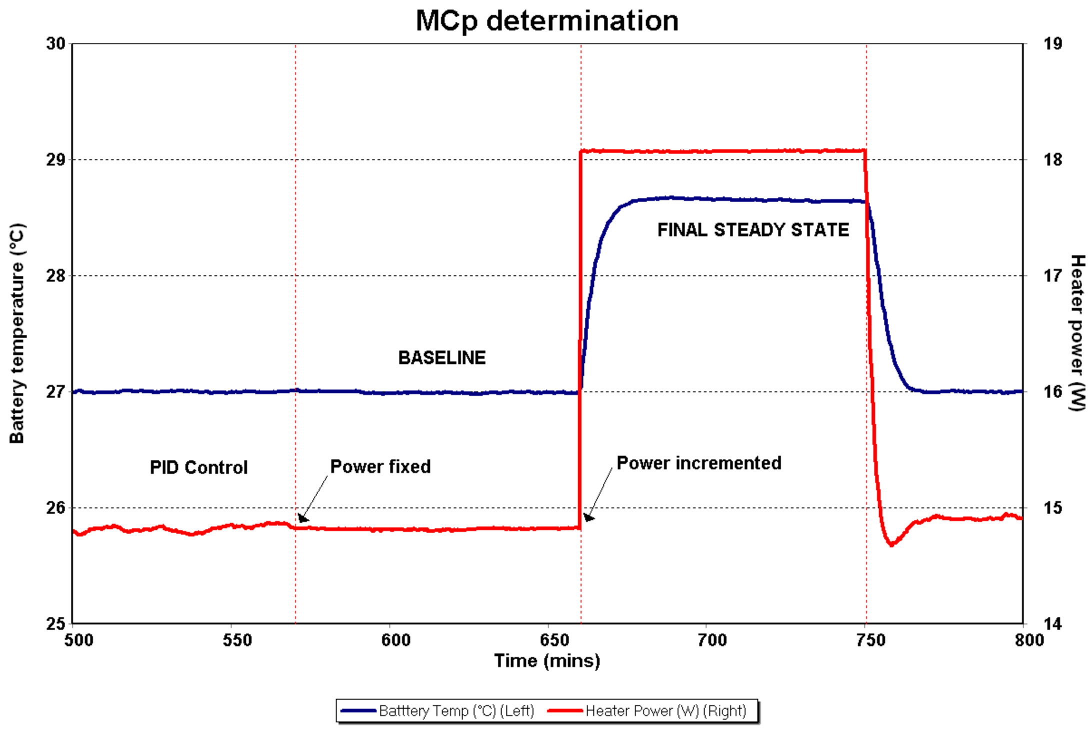
The required battery temperature should be entered in the relevant field. An oil temperature approximately 5^{o}C lower than the requested battery temperature should be entered. The heater increment can be left at 5%, although for very large battery stacks where this gives too low a temperature rise to measure accurately, this increment can be increased.

The plan can then be executed. The control strategy contained within the plan is as follows

操作

1) the battery temperature is stabilised at the required temperature by manipulating the power output to the control heaters via a PID control loop(with the oil stable at its set point). When stable, the power output from the control heaters perfectly balances the heat flow from the battery to the cooling system. This is referred to as the **baseline**.
2) An efficiency calculation is carried out (see page 4)
3) The battery is again stabilised at its required temperature using the control loop – when stable the output power to the control heaters is “fixed” i.e. held constant at the last value calculated by the control loop. As in (1) above, this power output exactly balances heat flow from the battery
4) Heater output is then increased by the user specified increment. Since heat loss from the battery was balanced by the power input during the baseline – the additional power associated with the increment will all contribute to an increase in battery temperature.
5) As the battery temperature rises, heat flow to the cooling system will also rise until the heat flow from the battery again balances the heat input from the control heaters and the temperature will again stabilise. From the difference in input power and temperature between the **baseline** and the **final steady state** the heat capacity of the sample can be determined. MCp is written to the output file along with the temperature and power data – its value will be seen to change at some point during the final steady state, once stabilisation of the battery temperature is detected. Data, from the 18650 stack experiment described above, is shown in the figure below[6].

[6] MCpCal-Guard 18650 Stack 20140408.dat



From the data above, considering **only the mass of aluminium in the sample**, the following results are obtained.

Temperature Rise	MCp Measured (J/K)	MCp Expected (J/K)	Error (%)
1.669	176.2	165.2	6.65

However the heat capacity of the heat spreader is significant (0.77J/g/K). The heat-spreader is designed to have a high in-plane thermal conductivity – to spread heat around the battery – but a much lower through plane conductivity – to prevent a thermal short-circuit between the heaters and cooling system. With the batteries wrapped in the heat spreader, the inside of the heat-spreader is in good thermal contact with the batteries and must be treated as part of the battery assembly. The outside of the heat spreader, in good thermal contact with the cooling system, must be considered as part of the cooling system. The dividing line between these is somewhere within the heat spreader material. This is another purpose of the heat spreader – to contain the thermal interface between Iso-BTC and the sample. A sensible approximation is to consider the interface to be half way between the inside and outside faces of the spreader. The consequence of this is that half the mass of the heat-spreader should be considered to be a part of the battery assembly – when this is taken into account, the error is significantly reduced – see below.

Temperature Rise	MCp Measured (J/K)	MCp Expected (J/K)	Error (%)
1.669	176.2	170.7	3.26

(total mass of heat-spreader was 14.1g)

This also explains the need to eliminate an adapter for accurate heat capacity measurements. When heating our sample, there is also the possibility that the temperature of any adapter that is used, would also increase slightly since this lies somewhere in between the Iso-BTC cooling system and the sample. In this case our measured heat capacity would then contain a contribution from the adapter. Even with many additional measurements, this contribution might be impossible to quantify.

Cylindrical samples represent one of the more complicated geometries – hence their selection as examples here. For pouch or prismatic samples, an appropriate stack can be formed by sandwiching just two batteries, with the calibration heater and temperature probes sandwiched between the two.