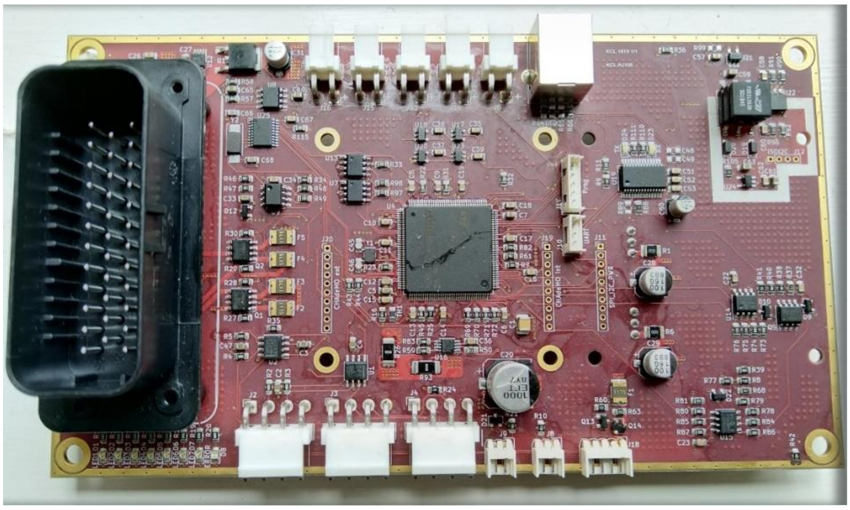
INTERCAL

BATTERY MANAGEMENT SYSTEMS

Introducing the Intercal BMS

A Breakthrough in Early Detection of Thermal Runaway Risk



October 2023

FOREWORD

The ongoing problem of serious and apparently spontaneous lithium-ion battery fires continues to trouble the transport sector and the battery energy storage industry. Current generation battery management systems (BMS) have proven incapable of giving adequate advance warning of these types of fire. The number of incidents is small but they can be catastrophic.

Lithium-ion fires propagate rapidly, giving off intense heat in a self- sustaining chain-reaction known as thermal runaway. Once started they are notoriously difficult to extinguish, giving rise to the risk of injury or loss of life as well as extensive damage to assets and infrastructure. Developing more effective techniques for predicting thermal runaway remains a key priority for industry, insurers and regulators.

Thermal runaway can be provoked by overcharging, traumatic damage or externally-applied heating. These problems can all be managed and largely controlled by good engineering. The more insidious issue is thermal runaway linked to the occurrence of internal short circuits (ISC) in a faulty or slightly damaged cell which can trigger what appears to be a completely spontaneous incident. Since an ISC can develop gradually over time before reaching a critical stage, it can in theory be predicted if the early symptoms can be detected. The industry has been trying for many years without success to develop an effective method of detecting early-stage faults in cells. Intercal (UK) and their partners have now developed, tested, and documented a BMS capable of providing very early warning of nascent cell faults long before they become critical.

The inability of current BMS technology to detect the early symptoms of a developing ISC directly results from the universal use of automated routine cell voltage balancing. Routine balancing has to date been considered essential in order to maintain the usable capacity of series-connected batteries over time. However, this constant process of selective cell voltage adjustment serves to mask the initially tiny voltage anomalies that arise in the early stage of a developing ISC. If routine balancing could be avoided, these voltage anomalies would be simple to detect.

By exploiting the exceptionally stable behaviour of healthy lithium-ion cells and using novel circuitry and a unique charging algorithm, the Intercal BMS enables the elimination of cell voltage balancing hardware and software throughout the usable lifetime of the battery. Tests described in this White Paper demonstrate that this gives the Intercal BMS the sensitivity to detect cell voltage anomalies potentially tens or hundreds of hours before the conditions for thermal runaway arise. This has been achieved while delivering fully equivalent performance to a voltage balancing BMS in terms of energy capacity, battery life and charging rates.

Developed and patented by Intercal (UK) during a 10-year research programme concluding in 2022, the Intercal BMS is a game-changer for all medium and higher voltage applications where safety and the avoidance of thermal runaway events are paramount.

The Intercal BMS offers other benefits. Eliminating balancing hardware and software leads to reduced battery cost and simplified battery assembly. The absence of high voltage balancing wires enables straightforward and safe maintenance and repair of installed battery packs. It also avoids any fire risk from external short circuits arising from chafing of balancing wires.

With Intercal's comprehensive experimental findings recently peer reviewed and published in the Journal of Energy Storage (JES), we are now inviting participation by one or more partners to trial the technology in real-world applications with a view to commercial production. A complete specification for the hardware and software is available.

This White Paper introduces the reader in outline to both the theory of the Intercal BMS and the results of Intercal's testing and development programme.

Full technical detail and references can be found in the JES research paper "*Rethinking lithium-ion battery management: Eliminating routine cell balancing enhances hazardous fault detection*" published in the Journal of Energy Storage Vol. 63 (2023) or at https://www.sciencedirect.com/science/article/pii/S2352152X23003286.

A supporting technical paper explains more of the technical background to the laboratory trials. "*Development of Bespoke Hardware and Software to Enable Testing of a Novel Method of Managing the Charge and Discharge of Series-Connected Battery Packs*" can be found at https://authors.elsevier.com/sd/article/S2215-0161(23)00291-1

The Intercal BMS is protected by Patents in the US, China and the UK. A European patent application is pending. Details are in the Appendix.

This technology was developed with financial support from Innovate UK, the UK's innovation agency and from the Worcestershire Proof of Concept Programme, part funded from the European Regional Development Fund.

THE CHALLENGE

The development of lithium-ion battery systems in transportation, energy storage and auxiliary power applications is attracting considerable effort into improving battery performance, enhancing fire safety and reducing costs. The BMS, which controls and monitors the performance of the battery pack, is a key focus for research.

For power applications, including electric vehicles (EV) and battery energy storage systems (BESS), battery packs are formed of cells, or modules comprising blocks of cells, connected in series (Figure 1). There may be up to 100 or more cells or modules in a battery to provide the required energy capacity and output voltage for the particular application.

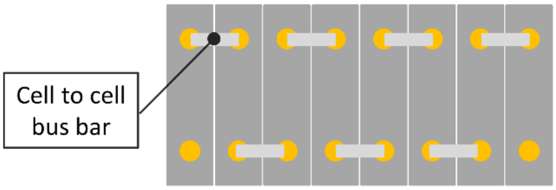


Figure 1: Series connected cells forming a battery

For any such configuration to function effectively, the constituent cells must be maintained in a balanced or equalised state of charge. If this balance is lost, the usable capacity of the battery is constrained by the difference in state of charge of the highest and lowest cells. Lithium-ion batteries present significant challenges in maintaining this balance owing to their intolerance of overcharging or over discharging. Charging has to terminate as soon as any cell reaches full charge, and discharge has to terminate when any cell becomes fully discharged (Figure 2). Failure to control the pack in this way will lead to rapid deterioration of the affected cells and a risk of thermal runaway and fire.

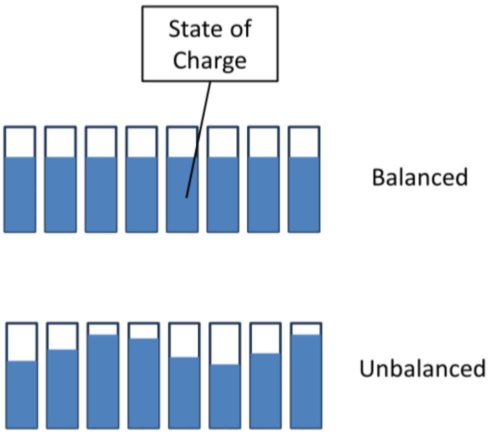


Figure 2: Illustration of balanced and unbalanced batteries

As explained in the next section, all current BMS technology is based on the assumption that, even if the state of charge of all the cells is carefully equalised at the outset, over time this balance will inevitably be lost and as a consequence the usable capacity of the pack will diminish. To address this problem, current BMS designs incorporate wiring, hardware and software to monitor and constantly adjust the charge balance of each cell or cell block in the series string.

Although this is a long-established orthodoxy, there remains a surprising lack of clarity or consistency among researchers and the industry about precisely why lithium-ion batteries are expected to lose balance over time. The reasons most commonly given include intrinsic variations between batches of cells in capacity, internal resistance, self-discharge and response to ageing. But capacity and internal resistance variations do not of themselves inevitably cause imbalance, while it is widely known that true self-discharge of healthy lithium-ion cells is absolutely minimal. As regards the effect of ageing on loss of balance, Intercal could find no direct research on the matter. The lack of critical examination of this subject may in part be due to legacy thinking based on the fact that imbalance does occur in lead acid and other long-established battery chemistries.

Set alongside this uncertainty over the precise causes of imbalance, there has been persistent anecdotal but informed evidence, notably from the amateur EV community, that series connected battery packs do not lose balance other than where a cell develops a fault or loses the capacity to hold charge.

Unless routine cell balancing is indeed essential, there are powerful arguments to avoid using it. As described below, charge balancing wiring apparatus and control systems are complex and cumbersome. For safety reasons this inhibits battery maintenance in the field and it introduces additional points of failure into the system. Most significantly, it is evident that routine intervention to restore charge balance will serve to mask the small but cumulative voltage deviations caused by an emerging ISC which can develop very slowly over time before suddenly reaching criticality.

CURRENT PRACTICE

In-service charge balancing as currently practised requires the BMS to measure or calculate the charge of every cell and adjust them routinely.

This is most commonly achieved by providing a separate high voltage balancing circuit for each cell or cell module, all managed by a master unit which dissipates charge from the highest voltage cells (Figure 3). Recently some manufacturers have moved towards achieving the same result through the use of wireless communication to cell boards. This eliminates the balancing wires but adds complexity in other ways. Another approach, also requiring balancing wires to each cell, incorporates circuitry and software to redistribute charge between cells in the pack to achieve balance, with consequent cost implications which to date have limited the use of this approach.

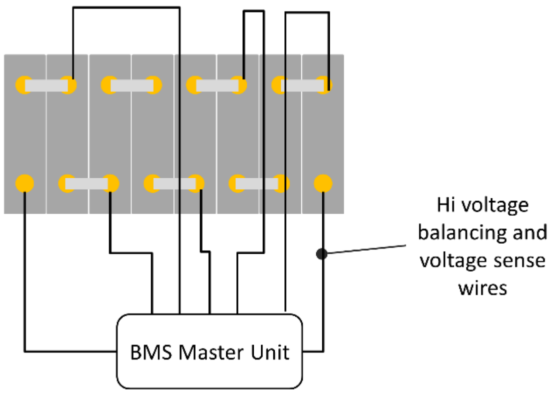


Figure 3: Schematic of conventional balancing BMS

A challenge with all of the above balancing methods is that voltage measurement, the only readily available direct means of assessing the state of charge of each cell, is not always a reliable indication of state of charge owing to the varying dynamic voltage response of individual cells during or soon after charge or discharge. To overcome this, prior art adopts a number of proxy techniques. These may involve coulomb counting and/or modelling using the impedance and capacity characteristics of each cell. Trying to improve the accuracy and reliability of these techniques while avoiding excessive cost is a key area of current industry and academic research and development.

THE INTERCAL ALTERNATIVE

Intercal developed and patented its BMS several years ago and have recently completed a set of trials which together demonstrate effective long-term performance under a wide range of conditions with differing battery chemistries.

Critical to the effectiveness of the Intercal BMS is the uniquely stable processes in healthy lithium-ion batteries that distinguish them from traditional batteries. The key measures are Coulombic efficiency and self-discharge.

Coulombic efficiency is the measure of the proportion of amp-hours of charge input that is stored by the battery and available for use. For lithium-ion cells this is exceptionally high, being very close to 100.00%. Self-discharge, a serious issue for many battery chemistries, has been shown to be absolutely minimal for lithium-ion cells. Indeed, recent research has indicated that it is only the process of physical degradation through sustained cycling and calendar aging that accounts for the coulombic efficiency to fall short of 100% or for irreversible self-discharge to occur.

Over time and constant cycling, the component cells in a battery may age and lose capacity at different rates. As indicated earlier, the capacity of the whole battery will be constrained by the weakest cell, so to maximise usable capacity through the lifetime of a battery, a BMS must ensure that the weakest cell is fully charged.

On the basis of the above, Intercal concluded that for it to be practicable to eliminate routine cell balancing while still ensuring long term battery performance, three requirements must be fulfilled:

1. Cells must be very accurately balanced before assembly or commissioning.
2. There must be no variation in charge currents or load on individual cells, down to a low microamp level.
3. The charge algorithm needs to accommodate the small variances in cell capacity and impedance that are known to occur within batches of cells, together with any effects of ageing, ensuring that the weakest cell is always fully charged.

As explained in the research paper and the technical paper cited above, Steps 1 and 2 are readily achieved. Cell voltages were equalised at full discharge ("bottom balancing"), while a method of voltage recording was employed that ensured that the drain on each cell was extremely low.

The critical innovation is the charge algorithm. Devised by Intercal and dubbed "CC/CCeV", this approach requires just a simple low-voltage daisy-chain connection to cell boards providing voltage and (preferably) terminal temperature data to a BMS master (Figure 4 and Figure 5). The master modulates charging currents so as to prevent the weakest cell from exceeding its maximum allowable voltage. Cell boards are powered externally, typically from a low voltage source such as the 12-volt system in a car, and not by the cell itself. This ensures requirement 2 above can be met.

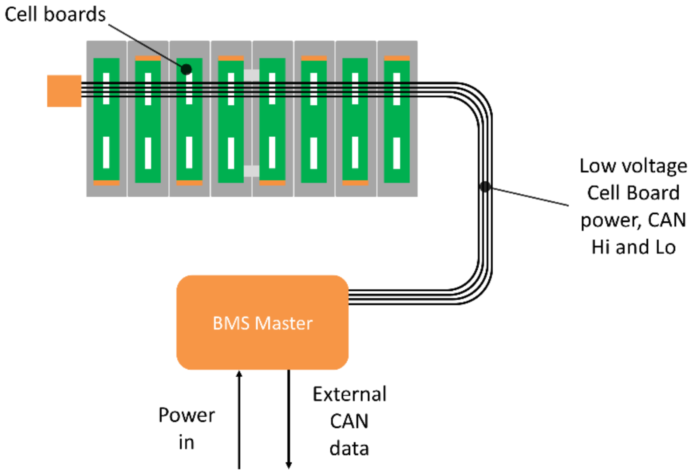


Figure 4: Schematic of Intercal BMS without high voltage wires

The results of Intercal's test programme are set out in the research paper, and are not replicated here. Four highlights, however, illustrate how effective the method has proven to be:

- Test 2 comprised 2000 deep cycles of a Lithium Iron Phosphate battery pack. No measurable loss of balance occurred, even though the cells all showed significant signs of ageing.
- Test 7 explored the effect of putting a steep temperature gradient across a Nickel Manganese Cobalt battery pack. This caused marked changes in the dynamic response and degradation rates in the colder cells. The results showed however that the cycling capacity of the pack remained maximised, with negligible loss of voltage balance until the eventual onset of rapid end-of-life cell degradation.
- Test 8 ran the Intercal BMS in parallel with a conventional balancing BMS, each managing a pack of Nissan Gen 4 modules. The test ran through 1000 deep cycles over 300 days, during which time cell ageing led to a loss of pack capacity of around 8-9%. On measures of both charge time and usable capacity, the pack managed by the Intercal BMS was found to marginally outperform the pack controlled by the conventional BMS. At Cycle 900, the energy capacity of the Intercal pack was 2% higher, while charge time was 1% quicker.
- No material loss of balance occurred in any of the other tests described in the JES paper other than after very rapid end-of-life degradation set in or, crucially, where life-limiting cell faults emerged.

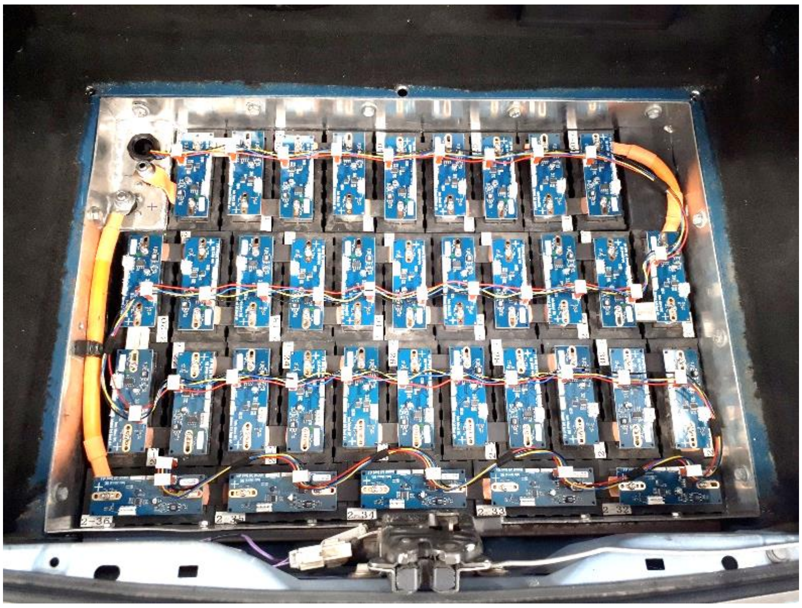


Figure 5: A prototype installation of the Intercal BMS showing simple daisy chain wiring for cell board power and data communications

This latter finding regarding imbalance caused by cell faults is the key to early ISC detection.

Isolated from the interference of charge balancing currents, very subtle early changes to the normally very stable thermal and voltage response of cells during charge and discharge can be discerned. In Test 8, this was trialled by placing a 1500 ohm simulated ISC across one of the test cells in each pack. This was calculated to cause an imbalance of the 115Ah battery of just 1% over a 20-day period. Figure 6 shows the cell voltages after a rest period at the end of full charge in the pack controlled by the conventional BMS. It can be seen that the BMS constantly corrects the very small voltage anomaly that occurs in each cycle, allowing no detectable trend to emerge. By contrast, Figure 7 shows how the voltage anomaly cumulates and rapidly becomes detectable in the pack controlled by the Intercal BMS.

Based on these important findings, the current focus of Intercal's research is refining detection algorithms to distinguish fault-related voltage drift from other causes of voltage variation such as changes in impedance. The principles behind this are straightforward and simple detection criteria can be applied to eliminate false alarms.

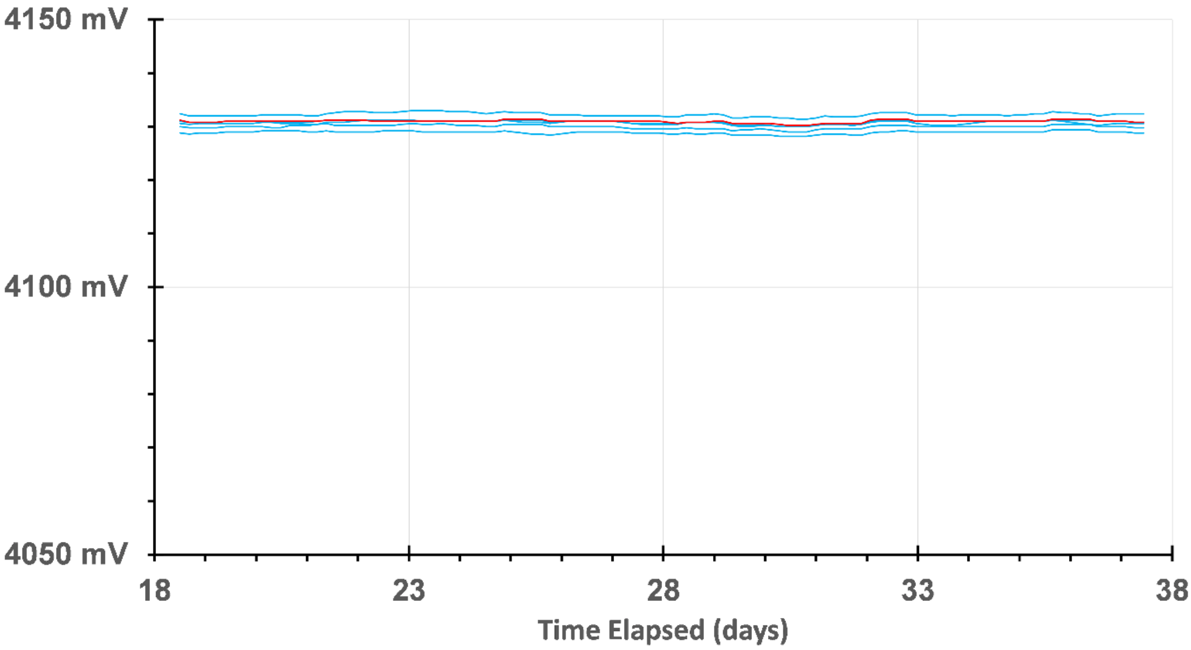


Figure 6: Test 8 simulated ISC - Conventional BMS. The cell voltage traces begin 18 days after the 1500 ohm simulated ISC (red trace) was introduced. No trend is detectable

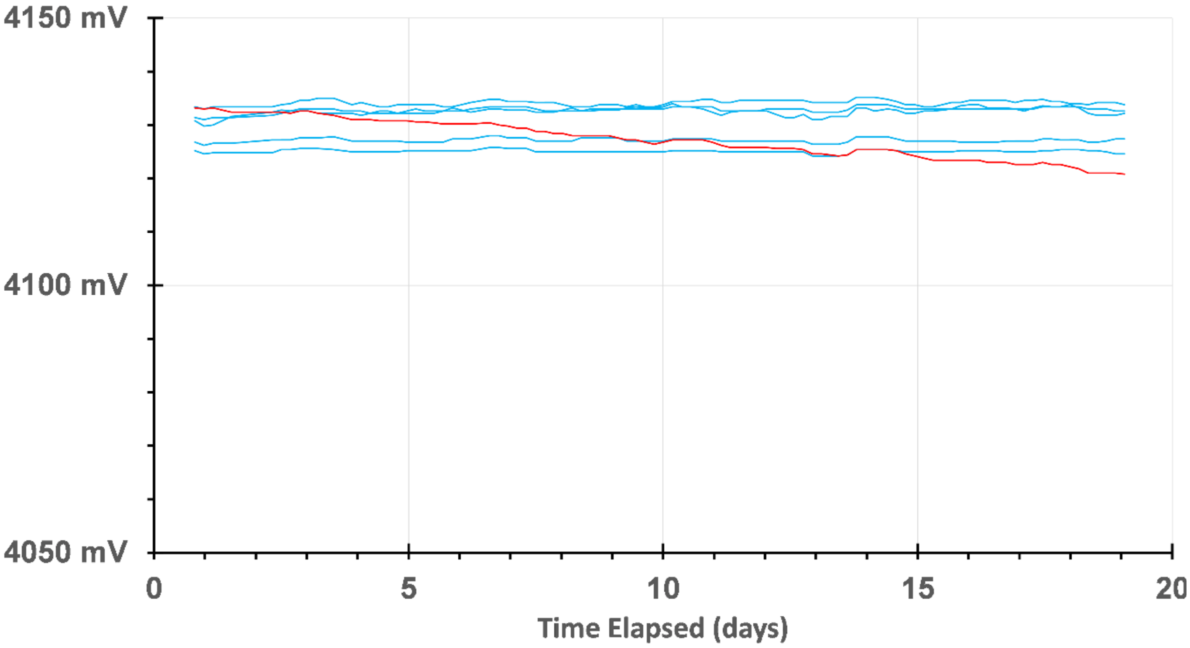


Figure 7: Test 8 simulated ISC – Intercal BMS. The cell voltage shown are from immediately after the simulated ISC (red trace) was introduced. The slightly wider initial voltage spread compared to Figure 6 reflects very small capacity variations between the cells in this bottom-balanced pack. The critical measure is the downward trend of the simulated cell voltage, not the absolute value

PARTNERSHIP AND LICENSING

As a pure research company, Intercal (UK) intend to commercialise its BMS technology through a licensing arrangement with one or more industry partners. While the laboratory results described in the research paper give a solid basis on which to move towards real-world applications, it is envisaged that the appropriate next step will be scaled-up testing by potential industry partners in real life applications.

Intercal are flexible about the precise route towards commercialisation but would highlight three promising areas, while recognising there will be others. These are:

- BESS, which would allow the functionality and fault detection capabilities of the Intercal BMS to be beta tested on a large scale while at the same time delivering a commercial return from the test installations.
- Motorsport, an established route for new vehicle technologies.
- Electric scooters, a sector where limited regulation and home charging have combined to cause increasingly frequent serious and life-threatening fire incidents and a consequent urgency to find solutions.

To facilitate rapid partner involvement, Intercal have prepared a detailed specification for the required hardware and software.

Intercal envisage that the necessary agreements may be in the form of an evaluation licence, with the option for the partner to obtain a commercial licence thereafter. Other approaches may be possible.

At this point Intercal are open to negotiations for arrangements which could include sectoral or geographic exclusivity subject only to the proviso that any exclusivity arrangements would be time limited.

APPENDIX

Intercal BMS Patent Status at August 2023

Case Ref.	Country	Publication No.	Current Number	Case Status
CNP7205	China	106537718	CN106537718B	Registered
EPP7205	European Patent Office	3170240	EP3170240A	Under examination
GBP7205X	United Kingdom	2528350	GB2528350B	Registered
USP7205	United States of America	2017/0214256	US10707686B	Registered