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(54) Titre : MODULE DE BATTERIE LITHIUM-ION A SYSTEME DE REFROIDISSEMENT
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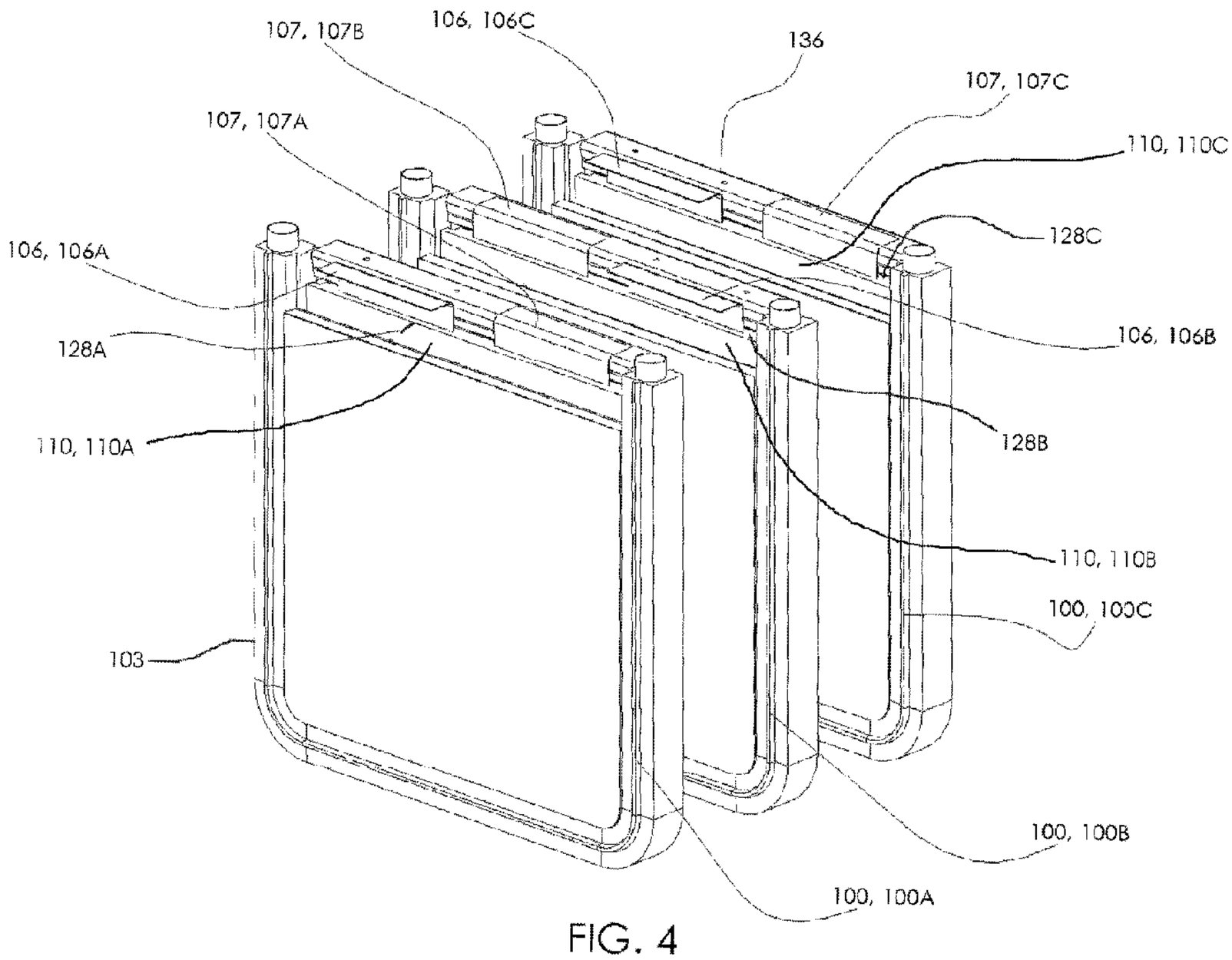

FIG. 4

(57) Abrégé/Abstract:
Apparatus, methods and systems are provided for cooling high power batteries. A plurality of carrier assemblies is stacked to form a cell stack. Each carrier assembly has a thermally conductive backing plate and a frame integrally formed therewith. A lithium-ion pouch cell (having a pair of cell tabs) is adhered to a front surface of the backing plate. Each cell tab is paired with a tab of opposite polarity of an adjacent battery cell. Thermally conductive compression bars are placed over the paired tabs to maintain electrical contact between the tabs. The compression bars also transfer heat to a cooling plate on top of the cell stack. Each carrier assembly incorporates a heat spreader sheet on a surface of the battery cell, a compressible foam sheet in front of the heat spreader sheet, and a thermally isolating sheet in front of the foam sheet.

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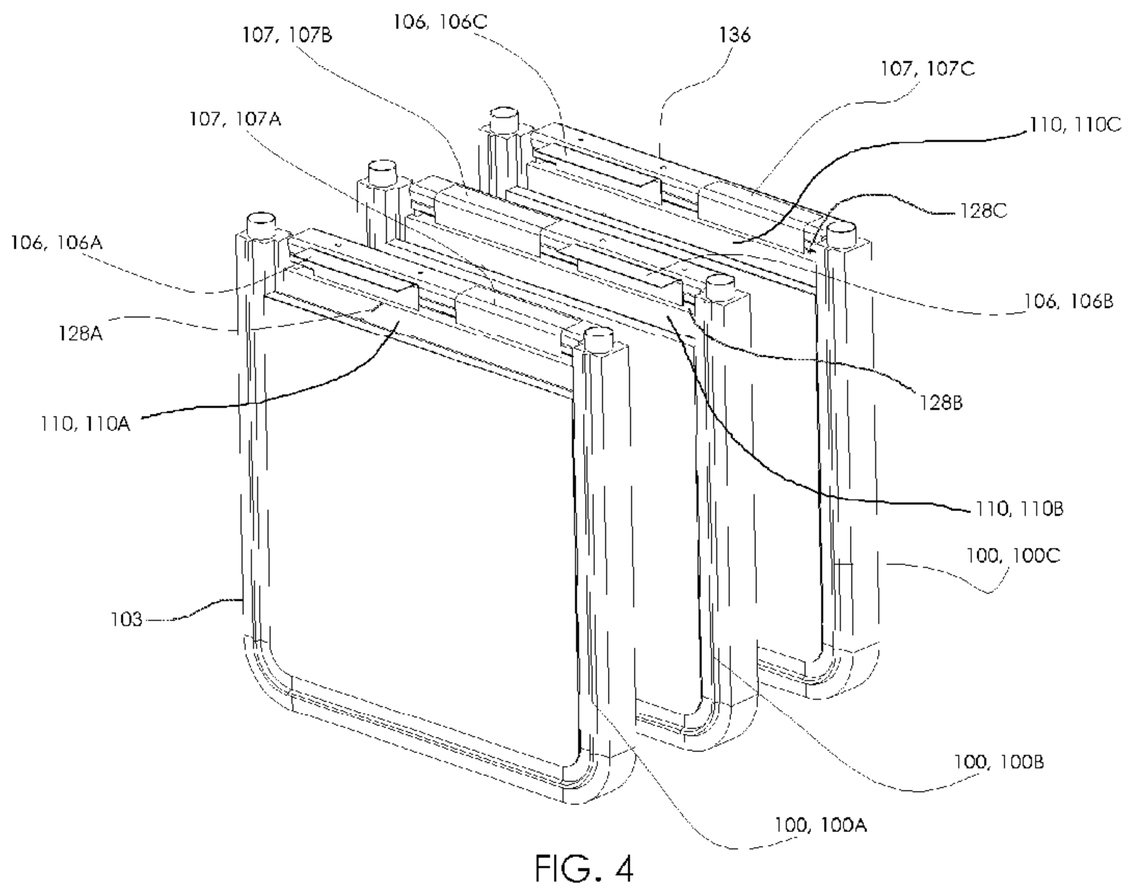

FIG. 4

(57) Abstract: Apparatus, methods and systems are provided for cooling high power batteries. A plurality of carrier assemblies is stacked to form a cell stack. Each carrier assembly has a thermally conductive backing plate and a frame integrally formed therewith. A lithium-ion pouch cell (having a pair of cell tabs) is adhered to a front surface of the backing plate. Each cell tab is paired with a tab of opposite polarity of an adjacent battery cell. Thermally conductive compression bars are placed over the paired tabs to maintain electrical contact between the tabs. The compression bars also transfer heat to a cooling plate on top of the cell stack. Each carrier assembly incorporates a heat spreader sheet on a surface of the battery cell, a compressible foam sheet in front of the heat spreader sheet, and a thermally isolating sheet in front of the foam sheet.

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LITHIUM ION BATTERY MODULE WITH COOLING SYSTEM

Reference to Related Applications

[0001] This application claims priority from United States Application No. 62/117,686 filed on 18 February 2015 and entitled LITHIUM ION BATTERY MODULE WITH COOLING SYSTEM. For purposes of the United States, this application claims the benefit under 35 U.S.C. §119 of United States Application No. 62/117,686 filed on 18 February 2015 and entitled LITHIUM ION BATTERY MODULE WITH COOLING SYSTEM which is hereby incorporated herein by reference for all purposes.

Technical Field

[0002] The technology described herein relates to high power batteries and apparatus, methods and systems for cooling such batteries.

Background

[0003] There are generally two categories of battery applications: energy storage applications and power applications. For energy storage applications, the battery tends to be discharged quickly and charged back slowly, or vice versa. For such applications the battery capacity is such that the battery's RMS C-rate is typically less than 0.5 C. In many cases, the battery's RMS C-rate is less than 0.1 C. Example energy storage applications include uninterruptible power supply (UPS), and load leveling of solar power to accommodate for gaps between power demand and supply at different times of the day (e.g. day versus night).

[0004] In power applications, the battery needs to supply energy within a short time frame, and be quickly recharged to be ready for the next event. Power applications require less energy storage but more power to be delivered. For such applications the battery's RMS C-rate is generally above 0.5 C, and in some cases, approach 10 C. Example power applications include grid frequency regulation and grid stabilization.

[0005] As current flows through a battery cell, the cell's internal resistance produces heat. The flow of current I through a cell having a resistance R over a specified time t generates heat Q in accordance with Joule's first law:

$$Q = I^2 \cdot R \cdot t \qquad \text{Equation (1)}$$

wherein the heat Q produced is equal to the square of the current I multiplied by the resistance R of the cell and the time t. As can be seen from Equation (1), increasing the current I from 1 C to 4 C (as may be required for power applications, for example) will increase heat generation by a factor of 16 (i.e. $(4\ C)^2/(1\ C)^2$). Therefore, even for a moderate increase in current, it can become a challenge to remove the heat generated by a battery cell. If the cell overheats, thermal runaway can occur. If the cell is stacked in close proximity to other battery cells, then the thermal runaway in the cell can propagate to these other cells, which may result in a fire or explosion.

[0006] Because of the challenges in cooling a cell when increasing the current, manufacturers of large format batteries typically focus their efforts on the design of batteries for energy storage applications where the battery's RMS C-rate is relatively low as discussed above. However, when such batteries are used for power applications, large capacity battery modules are required to meet the power application demands. This leaves extra battery capacity that is not being used much of the time.

[0007] Battery cells come in different sizes and shapes, including cylindrical or flat. Due to its geometry, it is generally difficult to remove heat from a cylindrical cell, such as, for example, an 18650 cell (or the like) which is typically about 65 mm long and about 18 mm in diameter and has a capacity of 2 Ah. Instead of cylindrical cells, flat cells are often preferred for high power battery applications, since flat surfaces can be cooled more efficiently. Flat cells include, for example, prismatic cells, layered cells, pouch cells and the like.

[0008] Some efforts have been made to address the cooling of multi-cell battery power systems. Methods of cooling battery cells include, for example, passive radiation, air cooling and liquid cooling. For battery power systems incorporating flat cells, methods of cooling include:

- Placing the pouch cells in a cell carrier which holds the pouch cells by their edges, and providing cooling passages to cool the edges, as described for example in US Patent Application Publication No. 2013/0266838. This design relies on the thermal conductivity of the battery cell itself to distribute heat to the edges. This may not be effective in cooling the battery cell in high power battery applications since the thermal conductivity of the battery cell is low.

- Placing the pouch cells in a plastic cell carrier and placing a heat conductive sheet over each pouch cell to move heat to an outside edge of the plastic cell carrier, as described for example in US Patent No. 8,835,037. The heat conductive sheet is thin (typically less than 1 mm thick) and thermal conductivity of the heat conductive sheet is typically anisotropic or directionally dependent (for example, a graphite sheet has very high in-plane conductivity but very low through-plane conductivity). Due to these limitations, the battery cell may not be sufficiently cooled in high power applications, and thermal runaway may occur, damaging the plastic cell carrier and the cell.
- Placing the pouch cells in an aluminum casted structure that has small liquid-containing channels close to the flat surface of the cells, as described for example in US Patent No. 8,404,375. This design is subject to various drawbacks: the small liquid channels may not provide for reliable flow; the channels are prone to leaks of the liquid coolant due to the thinness of the channel walls; and the apparatus is complex and therefore difficult and costly to manufacture.

[0009] There is a general desire for apparatus, systems and methods that address and/or ameliorate at least some of the aforementioned problems and otherwise assist with cooling a high power battery cell, module and/or system.

[0010] The foregoing examples of the related art and limitations related thereto are intended to be illustrative and not exclusive. Other limitations of the related art will become apparent to those of skill in the art upon a reading of the specification and a study of the drawings.

Summary

[0011] Aspects of the technology provide a battery module having a plurality of battery cell carrier assemblies stacked on top of one another to form a cell stack. Each carrier assembly includes a thermally conductive backing plate and a frame integrally formed therewith. The frame extends along at least a portion of a perimeter of the backing plate. The frame comprises a channel extending through the frame for receiving a liquid coolant. The liquid coolant-receiving channel may be provided by way of a pipe extending through the frame. The pipe may be made of stainless steel, copper, aluminum and/or the like. The frame and backing plate may be made of aluminum or other

suitable thermally conductive material. The frame may extend adjacent to the first side edge, the bottom edge and the second side edge of the backing plate.

[0012] Each carrier assembly includes a battery cell (e.g. such as a lithium-ion pouch cell) disposed on a front surface of the backing plate. The battery cell has a positive current collector tab and a negative current collector tab extending from the battery cell. In particular embodiments the collector tabs extend from an upper edge of the battery cell. The carrier assemblies in a cell stack may be stacked with alternating polarities so that positive and negative current collector tabs are reversed with respect to those of an adjacent carrier assembly. Apart from the current collector tabs having the most positive and most negative terminals in the cell stack, each one of the current collector tabs is paired with and connected to a current collector tab of opposite polarity in a battery cell of an adjacent carrier assembly. The battery module incorporates a plurality of compression bars. A compression bar is placed over a corresponding pair of connected current collector tabs. The compression bar helps to maintain electrical contact between the paired tabs and remove heat from the current collectors.

[0013] In certain embodiments, each carrier assembly has a compressible foam sheet disposed in front of the battery cell. In some embodiments, each carrier assembly also has a heat spreader sheet disposed between the battery cell and the foam sheet. The heat spreader sheet may be a flexible graphite sheet. The heat spreader sheet extends to and contacts the frame.

[0014] In particular embodiments, each carrier assembly incorporates a thermally isolating sheet disposed in front of the foam sheet. The thermally isolating sheet may be a ceramic sheet. The ceramic sheet acts as a heat barrier between adjacent carrier assemblies, and can help to contain a thermal runaway event to one battery cell carrier assembly.

[0015] The battery module may have a plurality of electrically isolating bars. Each electrically isolating bar is adapted to support a pair of connected current collector tabs, wherein the connected current collector tabs are folded over the electrically isolating bar. In particular embodiments, the compression bars are placed over the folded current collector tabs. The compression bars may be made of a thermally conductive material, such as copper. The battery module may include an upper cooling plate placed over the compression bars. The cooling plate is disposed perpendicularly to the

cell stack and extends between front and rear ends of the cell stack. At least one thermal gap pad is disposed underneath the cooling plate for compressing the compression bars and transferring heat from the compression bars to the cooling plate.

[0016] In some embodiments, each carrier assembly has a tongue extending from one side of the carrier assembly and a groove defined in the opposite side of the carrier assembly. To form the cell stack, the tongue of one carrier assembly is inserted into the corresponding groove of an adjacent carrier assembly.

[0017] Other aspects of the technology provide for a method of manufacturing a battery cell carrier assembly. The method includes: integrally forming a base structure having a thermally conductive backing plate and a frame comprising a liquid coolant-receiving channel, the frame extending along at least a portion of a perimeter of the backing plate; placing a battery cell (such as a lithium-ion pouch cell) on a front surface of the backing plate; adhering a heat spreader sheet to a front surface of the battery cell; and adhering a compressible foam sheet to a front surface of the heat spreader. The heat spreader sheet may comprise a flexible graphite sheet. The method may further include placing a thermally isolating sheet in front of the compressible foam sheet. In particular embodiments, the method may include insert-casting a pipe into the frame. The pipe may be made of stainless steel and/or copper, and the frame and backing plate may be made of aluminum.

[0018] Further aspects of the technology provide for a method of manufacturing a battery module. The method includes: stacking, on top of one another so as to form a cell stack, a plurality of battery cell carrier assemblies manufactured according to the methods described herein or having the features described herein; and, placing a cooling plate on top of the cell stack, the cooling plate extending between front and rear ends of the cell stack. The carrier assemblies may be stacked with alternating polarities so that positive and negative current collector tabs are reversed with respect to those of an adjacent battery cell carrier assembly. For the carrier assemblies that do not contain the most positive terminal in the cell stack, a negative current collector tab of the carrier assembly is folded with a positive current collector tab of an adjacent carrier assembly over an electrically isolating bar to form a folded tab pair. A compression bar is placed over each of the folded tab pairs for compressing and maintaining electrical contact between the positive and negative current collector tabs in each of the folded tab pairs. The compression bars are made of thermally

conductive material. At least one thermal gap pad is placed underneath the cooling plate and against the compression bars so as to transfer heat from the compression bars to the cooling plate.

[0019] In addition to the exemplary aspects and embodiments described above, further aspects and embodiments will become apparent by reference to the drawings and by study of the following detailed descriptions.

Brief Description of Drawings

[0020] Exemplary embodiments are illustrated in referenced figures of the drawings. It is intended that the embodiments and figures disclosed herein are to be considered illustrative rather than restrictive.

[0021] FIG. 1 illustrates an assembled battery cell carrier assembly according to one embodiment. FIG. 1A illustrates a partial cross-sectional view of this battery cell carrier assembly, taken along line A-A in FIG. 1.

[0022] FIG. 2 is an exploded view of the FIG. 1 battery cell carrier assembly.

[0023] FIG. 3 illustrates a base structure of the FIG. 1 battery cell carrier assembly. FIG. 3A is an enlarged top plan view of a terminal end of the base structure showing the frame and pipe.

[0024] FIG. 4 illustrates three of the battery cell carrier assemblies of FIG. 1 arranged to be stacked together, and shown spaced apart from each other to more clearly show the alignment of the cell tabs.

[0025] FIG. 5 illustrates a plurality of battery cell carrier assemblies stacked together to form a battery module. FIG. 5A is a detail view showing a compression bar to be placed over a folded cell tab pair.

[0026] FIG. 6 illustrates a battery module according to one embodiment incorporating an upper cooling plate and thermal gap pad. FIG. 6A is a top plan view of the battery module of FIG. 6. FIG. 6B is a partial cross-sectional view taken along line B-B in FIG. 6A.

[0027] FIG. 7 illustrates a battery module according to one embodiment incorporating an upper cooling plate and end plates.

[0028] FIG. 8 illustrates a battery module according to one embodiment. FIG. 8A is a detail view of the connections between pipes of adjacent battery cell carrier assemblies in the battery module of FIG. 8.

[0029] FIG. 9 is a graph of the voltage profile of a sacrificial cell and other cells in a battery module according to an embodiment of the invention during an internal cell failure test.

[0030] FIG. 10 is a graph of the voltage and temperature profiles of a sacrificial cell in a battery module according to an embodiment of the invention during an internal cell failure test. The profile for the average temperature of the non-sacrificial cells is also shown in the graph.

[0031] FIG. 11 is a graph of the temperature profile of a sacrificial cell, adjacent cells and other cells in a battery module according to an embodiment of the invention during an internal cell failure test.

[0032] FIG. 12 is a graph of the voltage and temperature profile of a free-standing battery cell during an internal cell failure test.

Description

[0033] Throughout the following description, specific details are set forth to provide a more thorough understanding to persons skilled in the art. However, well known elements may not have been shown or described in detail to avoid unnecessarily obscuring the disclosure. Accordingly, the description and drawings are to be regarded in an illustrative, rather than a restrictive, sense.

[0034] FIG. 1 shows one fully assembled battery cell carrier assembly **100** in accordance with a particular embodiment. A partial cross-sectional view of assembly **100** is shown in FIG. 1A. An exploded view of assembly **100**, showing more clearly all of its various components, is illustrated in FIG. 2. Assembly **100** comprises a flat battery cell **110** and a cell carrier for holding the battery cell

110 (shown in FIG. 2). A plurality of assemblies **100** can be stacked on top of one another (arranged parallel to one another) to make up a cell stack for a battery module.

[0035] As best seen in the exploded view of FIG. 2, battery cell carrier assembly **100** comprises a plurality of layered components. The plurality of components making up battery cell carrier assembly **100**, excluding the battery cell **110**, is also collectively referred to herein as a "cell carrier" for the battery cell **110**. In the illustrated embodiment the cell carrier's first layer is a base structure **105** at the rear or back of assembly **100** and the cell carrier's last layer is a thermally insulating outer layer **125** at the front of assembly **100**. A plurality of other layers is disposed between the base structure **105** and thermally insulating outer layer **125**.

[0036] Base structure **105** comprises a thermally conductive, rigid or semi-rigid backing plate **102** and a frame **103** extending around at least a portion of the periphery **104** of backing plate **102**. Base structure **105** provides support and rigidity for battery cell **110**. Base structure **105** also functions as a heat conductor to assist in cooling cell **110**. In particular embodiments backing plate **102** and frame **103** are integrally formed. As explained in more detail below, the integral formation of base structure **105** may provide for more effective heat transfer away from (or toward) battery cell **110**. Base structure **105** may be made of aluminum, copper and/or another suitable metal or other material with good thermal conductivity. In the illustrated embodiment, each base structure **105** supports a single battery cell **110** (i.e. there is one cell **110** disposed on each backing plate **102**).

[0037] For safety reasons, a thin electrically isolating layer (not shown in FIG. 2) may be disposed on front surface **109** of backing plate **102**. The electrically isolating layer may be, for example, a polymide film, such as a Kapton® tape which is in the order of 25 μm in thickness, however, other suitable electrically isolating materials may be used as a thin film or coating on backing plate **102**. A battery cell **110** is placed over the front surface **109** of backing plate **102**, on top of the electrically isolating layer, so that the battery cell is electrically isolated from the backing plate. In particular embodiments, cell **110** is secured to backing plate **102** by way of compression provided by a compressible foam sheet **120** placed over heat spreader **115** and cell **110** (as described in further detail below). Alternately, or in addition to the compressible foam sheet, a thermally conductive adhesive may be used to adhere cell **110** to backing plate **102**.

[0038] In certain embodiments, cell **110** does not extend all the way out to frame **103** of base structure **105**. Keeping the edges of cell **110** away from frame **103** protects the cell **110** against mechanical shocks that would damage the edges of cell **110**. Edge impact may result in short circuits in internal layers of cell **110** that may lead to thermal runaway.

[0039] In the illustrated embodiment, cell **110** has a first tab **106** serving as a positive current collector and a second tab **107** serving as a negative current collector. Cell **110** may be a lithium ion (Li-Ion) pouch cell. Cell **110** may comprise, for example, a XALT® 75 Ah High Power (HP) lithium ion cell. However, other suitable lithium-ion cells, pouch cells and/or flat cells may be used. Apart from tabs **106**, **107** which extend from an upper edge **108** of cell **110**, pouch cells are typically enclosed in a flexible aluminum bag. Pouch cells are typically flat, and are therefore generally space efficient. In alternate embodiments, other types of flat battery cells **110** may be contained in battery cell carrier assembly **100**, such as, for example, flat cells enclosed in metal cases. Flat battery cells can be generally cooled more efficiently than cylindrical battery cells due to the flat cell's larger surface area.

[0040] As the next layer, a heat spreader **115** is disposed on a front surface **111** of cell **110** (see FIGS. 1A, 2). Heat spreader **115** is formed of a suitable material to help distribute heat from cell **110** to cooler surfaces. For example, in some embodiments, heat spreader **115** is a graphite sheet. The graphite sheet may be flexible. In other embodiments, heat spreader **115** is aluminum or copper foil, or the like, or it can be made of any other suitable material for distributing heat. Using a flexible heat spreader **115** allows for some expansion and contraction due to temperature changes in cell **110**, and accommodates for changes in the thickness of cell **110** over time (typically, cell **110** will thicken as it ages). Heat spreader **115** assists in distributing heat from cell **110** outward toward the edges of assembly **100** (as the battery is generally cooler away from the cell or toward its outer edges, due to the coolant-containing pipe **121** extending through frame **103**). In some embodiments, heat spreader **115** extends all the way to frame **103** of base structure **105**. This allows heat spreader **115** to help carry heat out toward pipe **121** in frame **103** so that the heat can be removed by liquid coolant flowing in pipe **121**. Heat spreader **115** may be adhered to cell **110** using a suitable contact adhesive. Heat spreader **115** may also be adhered to portions of frame **103** using the contact adhesive.

[0041] Next, as seen in FIGS. 1A and 2, a compressible foam sheet **120** is placed over front surface **116** of heat spreader **115**. Contact adhesive may be used to adhere compressible foam sheet **120** to heat spreader **115**. Once a plurality of cell carrier assemblies **100** has been assembled and stacked to form a battery module **150**, the foam sheet **120** in each cell carrier assembly **100** helps to compress other cell carrier assembly layers (e.g. such as heat spreader **115** and cell **110**) together and/or to backing plate **102**. Foam sheet **120** helps to ensure that the layers of assembly **100** are held together even as cell **110** expands and contracts during operation of the battery. The compression provided by foam sheet **120** assists in adhering battery cell **110** to backing plate **102**. Such foam sheet **120** may replace the need to use thermally conductive adhesive to bond battery cell **110** to backing plate **102**, although in some embodiments, strips of adhesive tape (placed, for example, at the corners of cell **110**) may be used to temporarily adhere the cell **110** to backing plate **102** during assembly. In other embodiments, other suitable compressible materials may be used in place of the compressible foam sheet **120** to compress the other layers while still allowing for some expansion of cell **110**.

[0042] Finally, a thermally insulating outer layer **125** is placed over front surface **121** of foam sheet **120**. In particular embodiments, outer layer **125** is a ceramic sheet. In alternate embodiments, other suitable heat insulation materials may be used for outer layer **125**. Outer layer **125** acts as a thermal barrier and limits heat transmission between adjacent battery cells **110** or battery cell carrier assemblies **100**. Outer layer **125** helps to prevent thermal runaway in one cell from propagating to the adjacent battery cells **110**. Outer layer **125** therefore protects against thermal runaway propagation, reducing incidents of fire or explosion which could be caused by such an event. Outer layer **125** may be adhered to foam sheet **120** using a suitable contact adhesive.

[0043] The cooling aspects of base structure **105** are described in more detail below with reference to FIG. 3. Base structure **105** comprises a backing plate **102** and a frame **103**. Backing plate **102** has a rectangular shape, defined by a periphery **104** comprising opposed upper and lower edges **128**, **129** and opposed first and second side edges **130**, **131** (extending between upper and lower edges **128**, **129**). In the illustrated embodiment, frame **103** has three contiguous portions extending along three respective sides of backing plate **102** to form a general U-shaped or C-shaped bar. Specifically, frame **103** comprises a first side portion **117** extending along first side edge **130** of backing plate **102**; a middle portion **118** continuing perpendicularly to first side portion **117** and extending

between side edges **130**, **131** and along lower edge **129** of backing plate **102**; and a second side portion **119** parallel to first side portion **117** and extending along second side edge **131** of backing plate **102**. Frame **103** extends between a first terminal end **126** located at the upper end of first side portion **117** and a second terminal end **127** located at the upper end of second side portion **119**.

[0044] A liquid coolant-receiving channel extends continuously through all three portions **117**, **118**, **119** of frame **103**. In the illustrated embodiments the liquid-coolant receiving channel is provided by way of a pipe **121**. Pipe **121** extends through frame **103**, between an inlet **122** and an outlet **123** located at terminal ends **126**, **127**, respectively of frame **103**. Pipe **121** has a channel or bore **124** therethrough (see FIG. 3A) for carrying liquid coolant through frame **103** alongside backing plate **102**'s edges **129**, **130** and **131**. As the cell **110** produces heat, the liquid coolant in pipe **121** assists in carrying heat away from backing plate **102** (from the three sides) and also away from frame **103**. However, if the battery is placed in a cold environment, then the liquid coolant in pipe **121** can be heated, if necessary, to deliver heat to backing plate **102** and frame **103** in order to maintain the battery within a desired operating temperature range. The liquid coolant may be water, a water-based coolant or any other liquid suitable for travelling through pipe **121** and removing heat from (or bringing heat to) backing plate **102** and frame **103**.

[0045] The temperature of the liquid coolant may be controlled to maintain the battery at a constant temperature that is beneficial for the particular battery chemistry used. In particular embodiments, for example, the liquid coolant temperature and/or the liquid coolant flow rate is regulated so that the temperature of the battery is maintained within an acceptable range. In some embodiments the acceptable range for the battery temperature is 10°C to 15°C. In other embodiments the acceptable range is 10°C to 20°C. Other temperature ranges may be preferable for still other embodiments (e.g. other temperature ranges may be preferable for other types of battery cells or battery chemistry used). Depending on the ambient temperature, it may be necessary to adjust the temperature of the liquid coolant upward or downward to bring the battery temperature to within the acceptable range. In particular embodiments the temperature of the liquid coolant is not regulated. For example, cold or unheated tap water may be circulated through the pipes **121** in a battery module **150**. The water may be circulated through the pipes **121** at a configurable flow rate (such as 1 GPM or 0.003785 m^3/min).

[0046] In particular embodiments, inlets, outlets **122**, **123** of adjacent battery cell carrier assemblies **100** are connected in series. Outlet **123** of a first battery cell carrier assembly **100** is connected to the inlet **122** of a second, adjacent battery cell carrier assembly **100**, and so on, so that the same liquid coolant circulates through the frame **103** of each battery cell carrier assembly **100** in turn. In other embodiments, outlets **122**, **123** connect to inlet and outlet manifolds, respectively. FIGS. 8, 8A show an exemplary battery module **150** in which series connections between pipes **121** of adjacent battery cell carrier assemblies **100** are formed by way of caps **170** placed over the adjacent inlets and outlets. As shown in FIG. 8A, one cap **170** is placed to cap outlet **123A** of one pipe **121A** and an inlet **122B** of an adjacent pipe **121B**. Cap **170** facilities liquid connection between pipes **121A**, **121B**. In particular, liquid coolant leaving outlet **123A** of the first pipe **121A** flows through a passageway in cap **170** and into inlet **122B** of the second pipe **121B**.

[0047] In particular embodiments, frame **103** is integrally formed with backing plate **102**. The integral formation of the base structure **105** decreases heat resistance to cold surfaces (as there is no gap between backing plate **102** and frame **103**), and allows for the efficient removal of heat (i.e. heat is moved out toward the three sides of backing plate **102** where it is then removed through liquid cooling provided by frame **103**). Frame **103** may be made of one or more thermally conductive materials such as aluminum, copper or the like or any other suitable material that can be cast, molded and/or otherwise formed to provide for a frame containing a pipe **121** or other liquid coolant-receiving channel. Backing plate **102**, which is integrally formed with frame **103**, may be made of the same material as frame **103**. In some embodiments, pipe **121** is made of stainless steel, copper and/or other suitable material for forming a pipe. While it is not necessary that pipe **121** be constructed of stainless steel or copper, one advantage of using such material is that it is less prone to galvanic corrosion than other materials such as aluminum. However, since such material is generally costlier and heavier than aluminum, in particular embodiments, the frame **103** and the backing plate **102** may be made of aluminum while pipe **121** is made of stainless steel or copper. In some embodiments, a stainless steel pipe having a diameter of 12 mm and a wall thickness of 0.6 mm is used for pipe **121**. A pipe diameter in the range of 8 mm to 15 mm (or 10 mm to 20 mm in other embodiments) provides robustness to the frame structure and reduces the chance of clogged pipes and provides more effective cooling, as compared to smaller pipe diameters. Using a pipe with a wall thickness of less than 1 mm (such as 0.6 mm in one example embodiment) facilitates heat transfer between the base structure material and the coolant flowing through the pipe.

[0048] According to some embodiments, a method of manufacturing base structure **105** includes using high pressure dye casting techniques to force molten metal (such as aluminum) into a mold having the shape of base structure **105**, with the result that backing plate **102** and frame **103** are provided in one integrally formed piece. Pipe **121** can be made by bending a pipe (e.g. such as a stainless steel pipe or a copper pipe as described above) to the desired C-shape or U-shape, and insert-casting pipe **121** into the base structure **105**. This can be done, for example, by placing the bent pipe **121** into the mold, clamping the pipe down to hold it in position, and using high pressure dye casting to force the molten metal into the mold. Once the material is cooled, the formed base structure **105** is taken out of the mold. This technique of manufacturing the base structure **105** embeds and intimately bonds pipe **121** to the base structure **105**, and results in an integrally formed base structure **105** with no gap between the backing plate **102** and the frame **103**. In one example embodiment, the mold is configured so that the formed base structure **105** has a backing plate **102** with dimensions of 270 mm x 280 mm and a frame **103** which has a width of 19 mm. In the frame **103** is embedded the pipe **121**, for example, a stainless steel pipe having a 12 mm diameter and a wall thickness of 0.6 mm. The backing plate **102**, frame **103** and pipe **121** may have different dimensions in other embodiments.

[0049] A battery cell carrier assembly **100** having the components as described herein assists in drawing the heat produced in battery cell **110** out toward backing plate **102** as well as toward the outer edges of the battery cell carrier assembly (i.e. toward frame **103**), where it can be further drawn away by the liquid coolant travelling through a coolant-receiving channel in frame **103** (such as a pipe **121** as seen in FIG. 2, for example). In the illustrated embodiment, pipe **121** extends around the three edges **129**, **130** and **131** of backing plate **102** and therefore provides cooling from three sides of the cell carrier. Once the battery cell carrier assembly **100** is assembled with other carrier assemblies **100** into a battery module **150**, mechanisms are also provided to draw heat away from the upper edge **128** of each backing plate **102**. These mechanisms may include, for example, a cooling plate placed over the cell stack for drawing heat away from the current collectors on the upper edge of the battery cell, as described below.

[0050] Once the battery cell carrier assemblies **100** (each holding a battery cell **110**) have been assembled as shown and described above, they can be stacked one on top of the other (arranged parallel to one another) to form a cell stack for a battery module **150** (shown in FIGS. 5 and 6). Each

battery cell carrier assembly **100** may include interlocking features in order to facilitate the stacking of the carrier assemblies. Such interlocking features may enable the carrier assemblies **100** to be stacked together without requiring any external enclosures to hold together the cell stack. For example, features for providing a tongue and groove connection between adjacent battery cell carrier assemblies **100** may be incorporated into the frame **103** of each base structure **105**. In the illustrated embodiment, as best seen in FIGS. 3 and 3A, frame **103** has a protrusion or tongue **135** extending from one side of the frame (e.g. the front side of the frame **103** as seen in the illustrated embodiment). On the other side of the frame (e.g. the back side of the frame **103** as seen in the illustrated embodiment), frame **103** has a complementary groove **137**. FIG. 3 shows the back side of a cell carrier assembly **100** in which the groove **137** is located at the interface between the backing plate **102** and the frame **103**. Tongue **135** and groove **137** may extend continuously along the full length of frame **103** between the frame's terminal ends **126**, **127**, as shown in the illustrated embodiment. However, this is not necessary, and in other embodiments tongue **135** and groove **137** may extend only along a partial length of frame **103**, or they may be provided in discrete segments at spaced apart locations on frame **103**. Battery cell carrier assemblies **100** are arranged into a stack by inserting the tongue **135** of a base structure **105** of one battery cell carrier assembly **100** into a complementary groove **137** of a base structure **105** of an adjacent battery cell carrier assembly **100**. In the illustrated embodiment, an O-ring or gasket **134** is seated in the groove **137** to help form a seal between the adjacent battery cell carrier assemblies **100** at the tongue and groove connection.

[0051] It is not necessary that the inter-carrier connection comprises a tongue and groove connection as shown in the illustrated embodiment. In other embodiments, frame **103** may incorporate other types of tongue and groove connections, or other complementary or interlocking features to enable assemblies **100** to be stacked together. These may include: pin and socket-type connections between adjacent assemblies **100**; protrusions on the side of one assembly **100** (e.g. on the frame **103**) and corresponding recesses on one side of an adjacent assembly **100** (e.g. on the frame **103**); or locating rods through adjacent frames **103** tying the cell stack together; and the like.

[0052] Once the desired number of battery cell carrier assemblies has been stacked together to form the cell stack, the cell stack may be secured by straps, ties, rods or other means. Such means can help to compress each tongue into a corresponding groove of an adjacent cell carrier assembly. For example, FIG. 7 shows a battery module **150** incorporating a pair of straps **145** extending between

the front end **148** and rear end **149** of the module. Straps **145** have tensioning means **146** for tightening the straps to produce the desired compression. In addition, strap tensioning means **146** may be adapted to accommodate for expansion and contraction of the cell stack, as a result of changes in heat and/or material creep over time. Electrically isolated end caps **151**, **152** are provided to cap the battery module's front end **148** and rear end **149** respectively. End caps **151**, **152** may also be secured to the cell stack using straps **145**. In other embodiments, rods may be used in place of straps **145**. The rods may extend through holes in the end caps **151**, **152** or other structure in the battery module **150** and may be bolted down to compress the cell stack.

[0053] For each of the assembled battery cell carrier assemblies **100**, frame **103** extends around three sides of backing plate **102** (side edges **130**, **131** and lower edge **129**). In particular embodiments, the fourth, upper edge **128** of backing plate **102** is made available for forming the required electrical connections between the battery cells. A method for stacking the battery cell carrier assemblies **100** and connecting the battery cells **110** is described below with reference to FIG. 4. In particular embodiments, cooling may also be provided at the fourth edge **128** of backing plate **102** and at the current collectors at tabs **106**, **107** (as described below).

[0054] By way of example, three adjacent battery cells **110A, 110B, 110C**, shown in FIG. 4, can be arranged and connected in series as follows. First, battery cell carrier assemblies **100A, 100B, 100C** respectively carrying battery cells **110A**, **110B**, **110C** are stacked in alternating fashion, with positive and negative terminals reversed with respect to an adjacent cell. For example, as seen in FIG. 4, negative terminal tab **107A** of first battery cell **110A** is aligned with positive terminal tab **106B** of second battery cell **110B**, and negative terminal tab **107B** of second battery cell **110B** is aligned with positive terminal tab **106C** of third battery cell **110C** (and so forth if there are more than three carrier assemblies in the cell stack). The tabs **106**, **107** (i.e. the current collectors) are metal foil tabs. Each tab is folded with another tab over an electrically isolating bar **136**. In particular, negative terminal tab **107A** of the first battery cell **110A** is folded, along with positive terminal tab **106B** of the second battery cell **110B**, over a first electrically isolating bar **136** placed on top of upper edges **128A**, **128B** of cells **110A**, **110B**. Similarly, negative terminal tab **107B** of second battery cell **110B** is folded, along with positive terminal tab **106C** of third battery cell **110C**, over a second electrically isolating bar **136** placed on top of upper edges **128B**, **128C** of cells **110B**, **110C**. This results in two pairs of folded connected tabs: (1) tab **107A** of cell **110A** with tab **106B** of

cell **110B**, and (2) tab **107B** of cell **110B** with tab **106C** of cell **110C**. For each pair of folded tabs, one tab is folded over the other tab, and both of the folded tabs are folded over a bar **136** (shown in FIGS. 1 and 1A). Assuming that electrical contact is made between the tabs in each of the folded tab pairs, battery cells **110A**, **110B**, **110C** are connected in series through this arrangement. To hold the tabs in their folded position, fasteners **139** (such as screws, bolts, rivets or the like) (see FIG. 1) may be inserted through the folded tab pairs and bar **136**. In other embodiments, clamps or other mechanisms may be used to secure the folded tab pairs. Electrically isolating bars **136** may be made of plastic or some other suitably electrically isolating material.

[0055] To maintain good electrical contact between the tabs within a pair of folded tabs, a compression bar **132** (see FIG. 5) may be placed over each pair of folded tabs to compress the tabs together. Compression bar **132** may have approximately the same dimensions as the upper surface of the pair of folded tabs. For example, compression bar may be 20 mm wide and 80 mm long in particular embodiments. One or more fasteners (such as screws, bolts, rivets or the like) may be inserted through corresponding holes **141** in each bar **132** to maintain compression on the folded tabs so that they remain in good electrical contact. In addition, compression bar **132** may be knurled on the underside **138** (i.e. on the side contacting the pair of folded tabs) so as to help to deform the material of the folded tabs and improve the electrical contact between the tabs.

[0056] Compression bar **132** may be made of any material suitable for applying compression to the pair of folded tabs. In particular embodiments copper is used for compression bar **132**. The high thermal conductivity of copper allows compression bar **132** to draw heat away from the pair of folded tabs. Thus, by providing thermally conductive compression bars, cooling can also be provided for the current collectors and at the fourth, upper edge **128A**, **128B**, **128C** of each battery cell **110**. Heat can be drawn away from the compression bars **132** by way of a cooling plate (described in more detail below with reference to FIG. 6).

[0057] While only three battery cells **110A**, **110B** ,**110C** are shown in FIG. 4, this is for illustrative purposes only, and it is to be understood that any number of battery cells may be arranged and connected together in series using the methods described above to form a cell stack. For example, using the techniques described herein, a total of 24 battery cell carrier assemblies **100** can be stacked and connected in series to provide a cell stack for a battery module **150** as seen in FIGS. 5 to 9. If

the lithium ion pouch cells **110** have a voltage of between 3.2 to 4.2 VDC, then a battery module **150**, containing 24 of such cells connected in series, has a voltage range of between 77 to 100 VDC.

[0058] To create a battery bank for high power applications, a plurality of battery modules **150** may be connected together in series to form a string. In particular embodiments, a string can have between 2 and 10 modules. Thus the voltage range of a string is between 154 to 200 VDC and 770 to 1000 VDC. In some embodiments up to 30 modules are connected in series to form a string. The strings can be connected in parallel to form the bank. The bank energy can vary from a few kWh to several MWh.

[0059] As seen in FIGS. 6, 6A and 6B, a cooling plate **155** is incorporated into battery module **150**. Cooling plate **155** is placed on top of the cell stack, so as to remove heat from the top of the battery cell carrier assemblies **100** (including at the cell tabs). Cooling plate **155** is placed over the compression bars **132** that are compressing the folded cell tab pairs (which are described above with reference to FIG. 4). Thus, cooling plate **155** draws heat away from compression bars **132** (and hence, away from the current collector tabs **106**, **107**). Cooling plate **155** may be made of aluminum, copper or any other suitable material with high thermal conductivity. Cooling plate **155** may be cooled by pipes containing liquid coolant (similarly to frame **103** of base structure **105**) or by other means such as Peltier heat pumps, heat pipes or the like. Also, cooling plate **155** may incorporate pipes, tubes, manifolds, nozzles and the like for handling the connections between the coolant-containing pipes **121** of the battery cell carrier assemblies **100**.

[0060] A pair of conformable, thermally conductive gap pads **157** (FIG. 6) is positioned between compression bars **132** and cooling plate **155** to help transfer heat between the compression bars **132** and the cooling plate **155**. Cooling plate **155** may be connected to the cell stack in a manner that allows for compression of the gap pads **157** (e.g. screws, bolts, or other fasteners may be used to secure cooling plate **155** to the cell stack and press down on the gap pad **157**). An electrically isolated cap (not shown) may be placed over the cooling plate **155** and power cables to protect against electrical exposure. A metal front plate **161** may be secured at the front end **148** of battery module **155** over the electrically isolated end cap **151** in order to protect the module's plastic parts.

[0061] As seen in FIG. 6, apertures or gaps **143A**, **143B** (collectively, apertures **143**) are defined in the cooling plate **155** over the most positive and negative terminals of the cell stack to allow for electrical power connections to outside of the module. The power connections can be connected to connectors at the front end **148** of the module by means of a power cable, flexible bus bar, or the like.

[0062] It can be appreciated that the apparatus, systems and methods in accordance with the embodiments described herein provide a number of advantages. For example:

- Cooling is provided both for the individual battery cell and the battery module as a whole. For example, at the battery cell level, cooling is provided through features of the cell carrier. Battery cell carrier assembly **100** includes a backing structure **105** (comprising backing plate **102** and frame **103**) and heat spreader **115**, all of which assist in drawing heat away from cell **110** to the outside edges and outer flat surfaces of the battery cell carrier assembly **100**. By using a liquid coolant in the pipe **121** that extends through frame **103**, cooling is provided around three sides of cell **110**. In addition, the current collectors or terminals at the upper edge of cell **110** are cooled by way of thermally conductive compression bars **132** placed over the folded tab pairs. Additional cooling for the battery module and cells is provided by way of the module's upper cooling plate **155**, which is placed over the cell stack (i.e. on top of the compression bars). One or more thermal gap pads **157** are positioned between the cooling plate **155** and the current collectors **106**, **107** to help transfer heat from the current collectors and the compression bars to cooling plate **155**. In this manner, cooling is provided around all sides of each cell **110**, including at the current collectors.
- The thermally insulating outer layer **125** of battery cell carrier assembly **100** acts as a thermal barrier to contain thermal runaway to one cell and prevent the heat from moving to adjacent cells. This feature, along with the cell cooling features that reduce the heat of a battery cell, help to protect against thermal runaway propagation within the module.
- Ease of assembly and reduction of parts are achieved by: incorporating cooling into the battery cell carrier itself (i.e. by way of the features of battery cell carrier assembly **100** described herein); using tongue and groove connections (or other similar connections) between adjacent battery cell carrier assemblies to eliminate the need for a separate enclosure to hold together a cell stack; and connecting adjacent battery cells in series by way of folded tab pairs, folded over an electrically isolating bar.

[0063] The cooling abilities of a battery module **150** incorporating battery cell carrier assemblies **100** as described herein have been evaluated by testing conducted by the applicant. Testing was conducted on a 6.5 kWh battery module **150** in accordance with the invention, comprising 24 battery cell carrier assemblies **100**, each assembly **100** holding one battery cell **110** comprising a XALT® 75 Ah High Power (HP) lithium-ion cell. The test comprised inducing an internal short circuit in a sacrificial battery cell within the battery module **150**, and further overcharging the sacrificial cell in order to attempt to cause a thermal runaway in the cell. The battery module **150** was prepared for the test by discharging the module to a lower voltage limit of approximately 3.4 V. A single cell **110** within the module **150**, referred to herein as the "sacrificial" or "overcharged" cell, was independently charged to its upper voltage limit of 4.2V. Thus, the voltage of the module **150** at the start of the test was approximately 82 V. The module **150** was instrumented with additional voltage and temperature sensors on the overcharged sacrificial cell and adjacent cells. The module **150** was placed in a system rack and connected to cooling supply and charging power supplies. The rack was also instrumented with temperature, pressure and flow sensors. Since the objective of the test was to evaluate the cooling abilities of the battery module **150** independent of special control systems, any additional safety functionality provided by way of such hardware and/or software was disabled for the test.

[0064] During the test, the module **150** was charged at a charging current of 1C and cooled with unheated tap water flowing at 1 GPM (0.003785 m^3/min) through the pipes **121** in the cooling frames **103** of the cell carrier assemblies **100**. Charging was continued until the non-sacrificial cells reached their upper voltage limit of 4.2V. At the conclusion of the charging phase, the module **150** was left idle to observe the voltage and temperature behaviour of the sacrificial cell. The module **150** was then discharged at the post-test discharge rate of 1C until all the cells were below the discharge end voltage of 3.6 V. The module **150** was then disconnected and removed from the rack, and disassembled to observe the state of the sacrificial cell and other cells of interest in the module **150**.

[0065] As a result of such testing, it was confirmed by the voltage and temperature profile of the sacrificial cell that such cell had experienced an internal cell failure resulting from the internal short circuit. In addition, the sacrificial cell bag had become compromised as evidenced by a visible tear in the pouch which was observed upon completion of the test. However, despite the failure of the

sacrificial cell, the temperature of the sacrificial cell was contained under 42°C for its entire charge period.

[0066] FIG. 9 illustrates the voltage profile of the sacrificial cell and the non-sacrificial cells over the entire test. As seen in FIG. 9, the sacrificial cell is overcharged during the entire test while the other cells are charged from near 0% SOC (State of Charge) to near 100% SOC.

[0067] FIG. 10 illustrates the voltage and temperature recorded for the sacrificial cell during the course of the 1C charge cycle. A sudden drop in cell voltage and corresponding temperature spikes are evidence of the cell's internal short circuit. It can be seen from FIG. 10 that even despite the internal short circuit the sacrificial cell temperature did not exceed approximately 42°C during the test, and does not have the same profile of a rapid, continuous rise as would have been the case had thermal runaway occurred. The sacrificial cell temperature also drops once the charging is finished. In addition, FIG. 10 shows that the profile of the average of the non-sacrificial cell temperatures is quite stable through the charge cycle.

[0068] FIG. 11 illustrates the temperature profile of the sacrificial cell, adjacent cells and other cells in the module during the charge cycle. As seen in FIG. 11, the temperatures of the other cells in the module appear to have been largely unaffected by the higher temperature of the sacrificial cell. The cells adjacent to the sacrificial cell became hotter than the remaining cells, but still remained significantly cooler than the sacrificial cell at all times. For example, during the test the temperatures were recorded and it was found that when the temperature of the sacrificial cell had risen by its maximum value of 37.7°C, one adjacent cell (on one side of the sacrificial cell) had a recorded temperature rise of 13.2°C while the other one of the adjacent cells (on the other side of the sacrificial cell) had a recorded temperature rise of 10.4°C. The average recorded temperature rise of all remaining cells (that were not adjacent to the sacrificial cell) was 3.7°C.

[0069] Reference tests were run on a single free-standing battery cell of the same make and model as those used in the aforementioned testing on battery module **150** (i.e. a XALT® 75 Ah High Power (HP) lithium-ion cell). This standalone cell was not contained in any cell carrier. The cell was placed on a metal plate for the duration of the test. To prepare for the test, the cell was charged to the same starting voltage of 4.2 V as the sacrificial cell in battery module **150**. Next, a 1C charge

was applied to the cell for up to one hour. FIG. 12 shows a graph of the voltage and temperature profiles of this cell. Also included in the graph for reference is the voltage and temperature profiles of the sacrificial cell within battery module **150** during the aforementioned tests conducted on battery module **150**. The data has been aligned in order to enable a comparison in the behaviour of each cell after the significant internal short circuit, in the free-standing cell (outside of battery module **150**) and sacrificial cell within the battery module **150**. As can be seen from FIG. 12, the temperature of the free-standing cell experiences thermal runaway after the internal short circuit. Its temperature continues to rise rapidly until the cell is destroyed by fire. By contrast, the sacrificial cell in the battery module **150** is contained (and even reduced) after experiencing the significant internal short circuit. Its temperature increases slowly over the course of the charge, but remains constrained and immediately begins to drop once the charging is stopped. As the sacrificial cell is discharged at 1 C from the overcharged state, the temperature of the sacrificial cell drops toward normal operating temperature.

[0070] Thus, these tests demonstrated that despite an internal cell failure of a sacrificial cell within the battery module **150** that was caused by overcharging of the sacrificial cell (resulting in a significant internal short circuit), thermal runway did not occur in the sacrificial cell or in any of the other cells. The temperature of the overcharged cell and adjacent cells were constrained and the average temperatures of the remaining cells was not substantially impacted by the overcharged cell. The failure of the overcharged cell did not result in failure or damage in the other cells of the battery module **150**.

[0071] Where a component (e.g. cell, pouch cell, battery module, current collector, tab, terminal, backing plate, carrier, pipe, frame, heat spreader, isolating bar, compression bar, etc.) is referred to above, unless otherwise indicated, reference to that component (including a reference to a "means") should be interpreted as including as equivalents of that component any component which performs the function of the described component (i.e., that is functionally equivalent), including components which are not structurally equivalent to the disclosed structure which perform the function in the illustrated exemplary embodiments.

[0072] While a number of exemplary aspects and embodiments have been discussed above, those of skill in the art will recognize certain modifications, permutations, additions and sub-combinations thereof. For example:

- It is not necessary that battery cells **110** are arranged and connected together in series in the manner described above with reference to FIG. 4. Battery cells **110** may be connected together using other techniques that would result in a series connection between the cells. In other embodiments, various subsets of the cells **110** within a battery module may be connected in parallel and/or in series.
- It is not necessary that the liquid connections between pipes **121** of adjacent battery cell carrier assemblies **100** be series connections as shown and described with reference to FIGS. 8, 8A. In other embodiments, liquid connections can be made between the battery cell carrier assemblies **100** in any combination of parallel and series connections.
- The gasket **134** providing a seal between adjacent battery cell carrier assemblies **100** can be placed in a separate groove outside the locating groove **137**.
- While it is described above that a liquid coolant in pipe **121** is used to carry heat away from frame **103** and backing plate **102**, it will be appreciated by one of skill in the art that other cooling means may be used to cool the battery cell. For example, in addition to or instead of the above-described liquid coolant-based cooling methods, other means may be used, including non-liquid coolant based cooling means, such as for example, Peltier coolers, heat pumps, fins for air cooling, or the like, and/or other means.
- In alternate embodiments, battery cells **110** can be stacked together in the same orientation as described above with reference to FIG. 4, but electrically connected via bus bars between the positive and negative tabs **106**, **107**.
- In alternate embodiments, positive and negative tabs **106**, **107** of adjacent battery cells **110** can be welded together instead of using compression bars **132** as described above.
- The battery module's top cooling plate **155** can be cooled with Peltier coolers, heat pumps, or fins for air cooling.
- The metal front plate **161** of a battery module can be used to secure the module to the rack carrying a string of battery modules.
- In certain embodiments, liquid coolant-receiving pipe **121** itself provides the frame structure (or at least a portion of the frame structure) for the cell carrier.

- Current collector tabs **106**, **107** do not need to extend from an upper edge **108** of battery cell **110** as shown in the illustrated embodiment. In alternate embodiments, the current collector tabs **106**, **107** may extend from a different edge of the battery cell **110** such as the lower and/or side edges. They may both extend from one edge of the battery cell **110**, or they may extend from different edges of the battery cell **110**. For example, one current collector tab **106** may extend from an upper edge of the battery cell **110** and the other current collector tab **107** may extend from the opposing, lower edge of battery cell **110**. Frame **103** (containing the liquid coolant-receiving channel) may be shaped to accommodate the current collector tabs **106**, **107**. For example the frame **103** may have one or more flat sections where the current collector tabs are located and/or the frame **103** may bend around the current collector tabs.
- In alternate embodiments the frame **103** may extend around all sides of the backing plate **102** so that the liquid coolant-receiving channel in the frame **103** circulates around a periphery of the backing plate **102** and the battery cell. In such embodiments the frame **103** may be shaped to accommodate the current collector tabs **106**, **107** extending from the cell, such as by having one or more flat sections where the current collector tabs are located and/or by bending around the current collector tabs. Alternately, the frame **103** may not wrap completely around the backing plate **102** and may have a gap where the current collector tabs are located. For example, the frame **103** may be generally C-shaped, and may have its opposing terminal ends located toward a centre of the upper edge of the backing plate. A space is therefore provided between the terminal ends of the frame **103** to accommodate the current collector tabs. The remainder of the frame **103** wraps around the side and bottom edges of the backing plate **102**.
- While a rectangular battery cell is shown in the illustrated embodiments, it is not necessary that the battery cell have this shape. A cell carrier according to the embodiments described herein may be used in connection with any size or shape of battery cell, which may be disposed on backing plate **102** of the cell carrier assembly **100**. Flat battery cells are typically preferable since they have the advantage that the cell carrier may be more effective in cooling such cells, given the cells' larger surface area.

It is therefore intended that the scope of the following appended claims and claims hereafter introduced should not be limited by the embodiments set forth in the examples, but should be given the broadest interpretation consistent with the description as a whole.

WHAT IS CLAIMED IS:

1. A battery module comprising:

a plurality of carrier assemblies stacked on top of one another to form a cell stack,

each carrier assembly comprising:

a thermally conductive backing plate and a frame integrally formed therewith, the frame comprising a liquid coolant-receiving channel extending around at least a portion of a perimeter of the backing plate; and

a battery cell disposed on a front surface of the backing plate, and comprising a compressible foam sheet disposed in front of the battery cell, the battery cell having a positive current collector tab and a negative current collector tab extending from the battery cell, wherein, apart from the current collector tabs having the most positive and most negative terminals in the cell stack, each one of the current collector tabs is paired with and connected to a current collector tab of opposite polarity in a battery cell of an adjacent carrier assembly; and

a plurality of compression bars, each compression bar placed over a corresponding pair of connected current collector tabs and adapted to maintain electrical contact between the paired tabs and remove heat therefrom.

2. The battery module according to claim 1 wherein in each carrier assembly, the battery cell is attached to a front surface of the backing plate by way of compression provided by the compressible foam sheet.

3. The battery module according to either one of claims 1 or 2 wherein each carrier assembly comprises a heat spreader sheet disposed between the battery cell and the foam sheet.

4. The battery module according to claim 3 wherein in each carrier assembly, the heat spreader sheet comprises a flexible graphite sheet.

5. The battery module according to either one of claims 3 or 4 wherein in each carrier assembly, the heat spreader sheet extends to and contacts the frame.

6. The battery module according to claim 1 wherein in each carrier assembly, the backing plate comprises opposing first and second side edges and opposing top and bottom edges, wherein the liquid coolant-receiving channel extends adjacent to the first side edge, the bottom edge and the second side edge of the backing plate.

7. The battery module according to any one of claims 1 to 6 wherein in each carrier assembly, the frame comprises a pipe and a bore of the pipe provides the liquid coolant-receiving channel.

8. The battery module according to claim 7 wherein in each carrier assembly, the pipe is formed of stainless steel and/or copper.

9. The battery module according to any one of claims 1 to 8 wherein in each carrier assembly, the backing plate comprises an aluminum plate.

10. The battery module according to any one of claims 1 to 9 wherein each carrier assembly comprises a thermally isolating sheet disposed in front of the foam sheet.

11. The battery module according to claim 10 wherein in each carrier assembly, the thermally isolating sheet comprises a ceramic sheet.

12. The battery module according to any one of claims 1 to 11 comprising a plurality of electrically isolating bars, each electrically isolating bar adapted to support a pair of connected current collector tabs, wherein the connected current collector tabs are folded over the electrically isolating bar.

13. The battery module according to any one of claims 1 to 12 wherein the compression bars are made of a thermally conductive material.

14. The battery module according to claim 13 wherein the compression bars are made of copper.

15. The battery module according to any one of claims 1 to 14 comprising an upper cooling plate placed over the compression bars, the cooling plate disposed perpendicularly to the cell stack and extending between front and rear ends of the cell stack.

16. The battery module according to claim 15 comprising at least one thermal gap pad disposed underneath the cooling plate for compressing the compression bars and transferring heat from the compression bars to the cooling plate.

17. The battery module according to any one of claims 1 to 16 wherein the carrier assemblies are stacked with alternating polarities so that positive and negative current collector tabs are reversed with respect to those of an adjacent carrier assembly.

18. The battery module according to any one of claims 1 to 17 wherein in each carrier assembly, the battery cell comprises a flat battery cell.

19. The battery module according to claim 18 wherein in each carrier assembly, the battery cell comprises a lithium-ion pouch cell.

20. The battery module according to any one of claim 1 to 19 wherein each carrier assembly comprises a tongue extending from one side of the carrier assembly and a groove defined in the opposite side of the carrier assembly, wherein to form the cell stack, the tongue of one carrier assembly is inserted into the corresponding groove of an adjacent carrier assembly.

21. The battery module according to any one of claims 1 to 20 wherein the cell stack comprises 24 carrier assemblies.

22. A battery bank comprising at least two battery modules according to any one of claims 1 to 21, wherein the battery modules are connected together in series.

23. The battery bank according to claim 22 comprising between two and 30 battery modules.

24. A method of manufacturing a battery cell carrier assembly, comprising:

integrally forming a base structure having a thermally conductive backing plate and a frame, the frame comprising a liquid coolant-receiving channel extending around at least a portion of a perimeter of the backing plate;

placing a battery cell on a front surface of the backing plate;

adhering a heat spreader sheet to a front surface of the battery cell; and

adhering a compressible foam sheet to a front surface of the heat spreader.

25. The method according to claim 24 wherein the backing plate comprises opposing first and second side edges and opposing top and bottom edges, the method comprising forming the liquid coolant-receiving channel such that the channel extends adjacent to the first side edge, the bottom edge and the second side edge of the backing plate.

26. The method according to either one of claims 24 or 25 wherein the heat spreader sheet comprises a flexible graphite sheet.

27. The method according to any one of claims 24 to 26 comprising insert casting a pipe into the frame, wherein a bore of the pipe provides the liquid coolant-receiving channel.

28. The method according to claim 27 wherein the pipe is stainless steel and/or copper, and the frame and backing plate are aluminum.

29. The method according to any one of claims 24 to 28 comprising adhering a thermally isolating sheet to a front surface of the compressible foam sheet.

30. The method according to any one of claims 24 to 29 wherein the battery cell is a lithium-ion pouch cell.

31. A method of manufacturing a battery module comprising:

stacking, on top of one another so as to form a cell stack, a plurality of battery cell carrier assemblies manufactured according to any one of claims 24 to 30; and

placing a cooling plate on top of the cell stack, the cooling plate extending between front and rear ends of the cell stack.

32. The method according to claim 31 wherein stacking the plurality of carrier assemblies comprises stacking the carrier assemblies with alternating polarities so that positive and negative current collector tabs are reversed with respect to those of an adjacent battery cell carrier assembly.

33. The method according to claim 32 comprising, for each carrier assembly apart from the one that contains the most positive terminal in the cell stack, folding a negative current collector tab of the carrier assembly with a positive current collector tab of an adjacent carrier assembly over an electrically isolating bar to form a folded tab pair.

34. The method according to claim 33 comprising placing a compression bar over each of the folded tab pairs for compressing and maintaining electrical contact between the positive and negative current collector tabs in each of the folded tab pairs.

35. The method according to claim 34 wherein the compression bars are made of thermally conductive material.

36. The method according to claim 35 comprising placing at least one thermal gap pad underneath the cooling plate and against the compression bars so as to transfer heat from the compression bars to the cooling plate.

37. The method according to any one of claims 32 to 36 comprising placing caps over adjacent terminal ends of the pipes of adjacent carrier assemblies so as to connect the pipes in series.

38. A cell carrier for a battery cell, the cell carrier comprising:

a thermally conductive backing plate for the battery cell and a frame integrally formed therewith, wherein the backing plate comprises opposing first and second side edges and opposing top and bottom edges, and wherein the frame comprises a liquid coolant-receiving channel extending adjacent to the first side edge, the bottom edge and the second side edge of the backing plate;

a heat spreader sheet positioned over the backing plate, wherein the battery cell is disposed between the heat spreader sheet and the backing plate; and

a compressible foam sheet adhered to the heat spreader sheet.

39. The cell carrier according to claim 38 wherein the compressible foam sheet is adapted to provide compression to attach the battery cell to the backing plate.

40. The cell carrier according to either one of claims 38 or 39 comprising a thermally isolating sheet disposed in front of the foam sheet.

41. The cell carrier according to claim 40 wherein the thermally isolating sheet comprises a ceramic sheet.

42. The cell carrier according to any one of claims 38 to 41 wherein the heat spreader sheet comprises a flexible graphite sheet.

43. The cell carrier according to any one of claims 38 or 42 wherein the heat spreader sheet extends to and contacts the frame.

44. The cell carrier according to any one of claims 38 to 43 wherein the frame comprises a pipe, the pipe having a bore for receiving the liquid coolant.

45. The cell carrier according to claim 44 wherein the pipe is formed of stainless steel and/or copper.

46. The cell carrier according to any one of claims 38 to 45 wherein the backing plate and the frame are formed of aluminum.

47. Apparatus or systems according to any one of claims 1 to 23 or claims 38 to 46 comprising any new, inventive, and useful feature, combination of features, or sub-combination of features, described or clearly inferred herein.

48. Methods according to any one of claims 24 to 37 comprising any new, inventive, and useful feature, combination of features, or sub-combination of features, described or clearly inferred herein.

49. An apparatus, system or method comprising any new, inventive, and useful feature, combination of features, or sub-combination of features, described or clearly inferred herein.

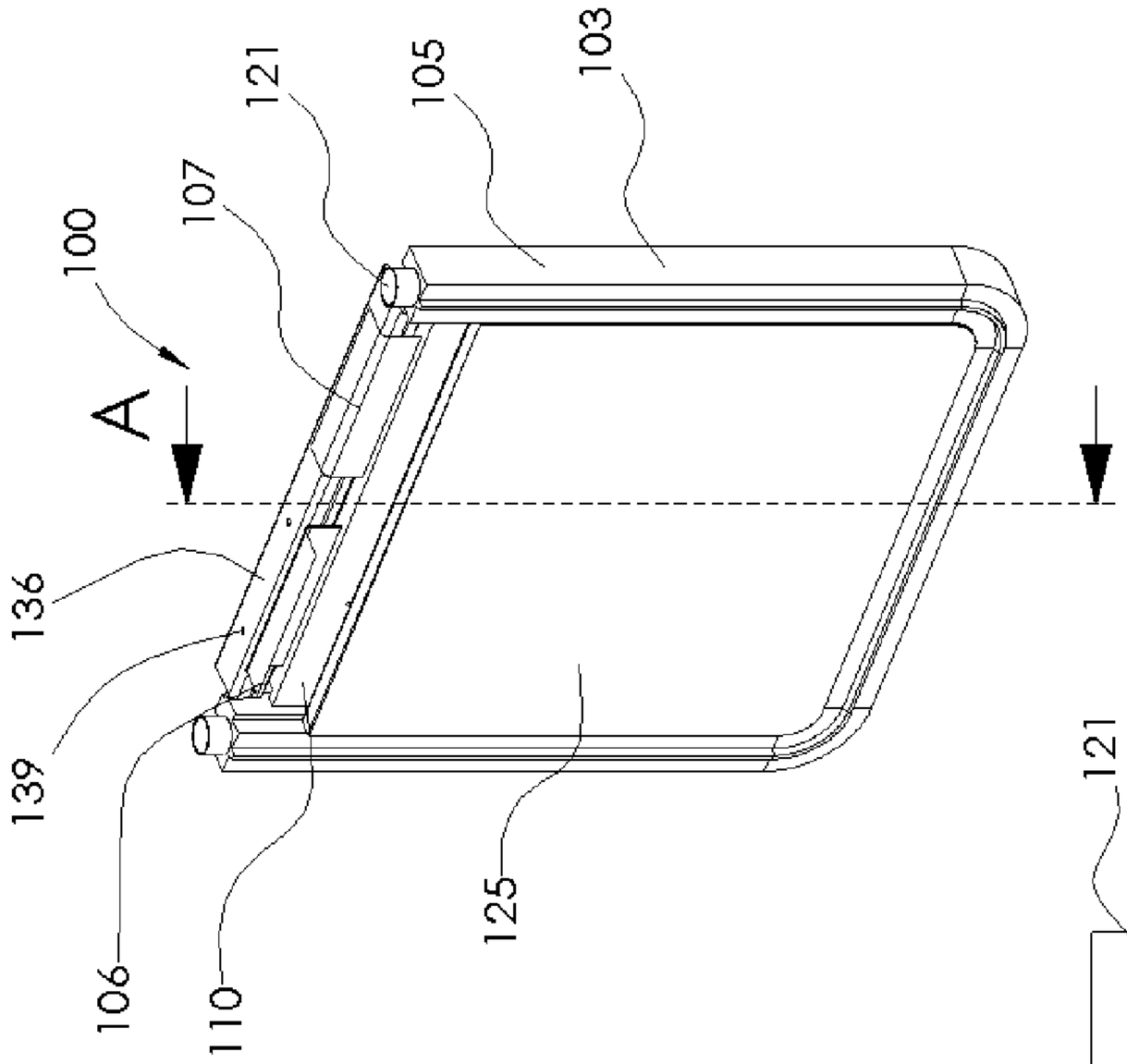


FIG. 1

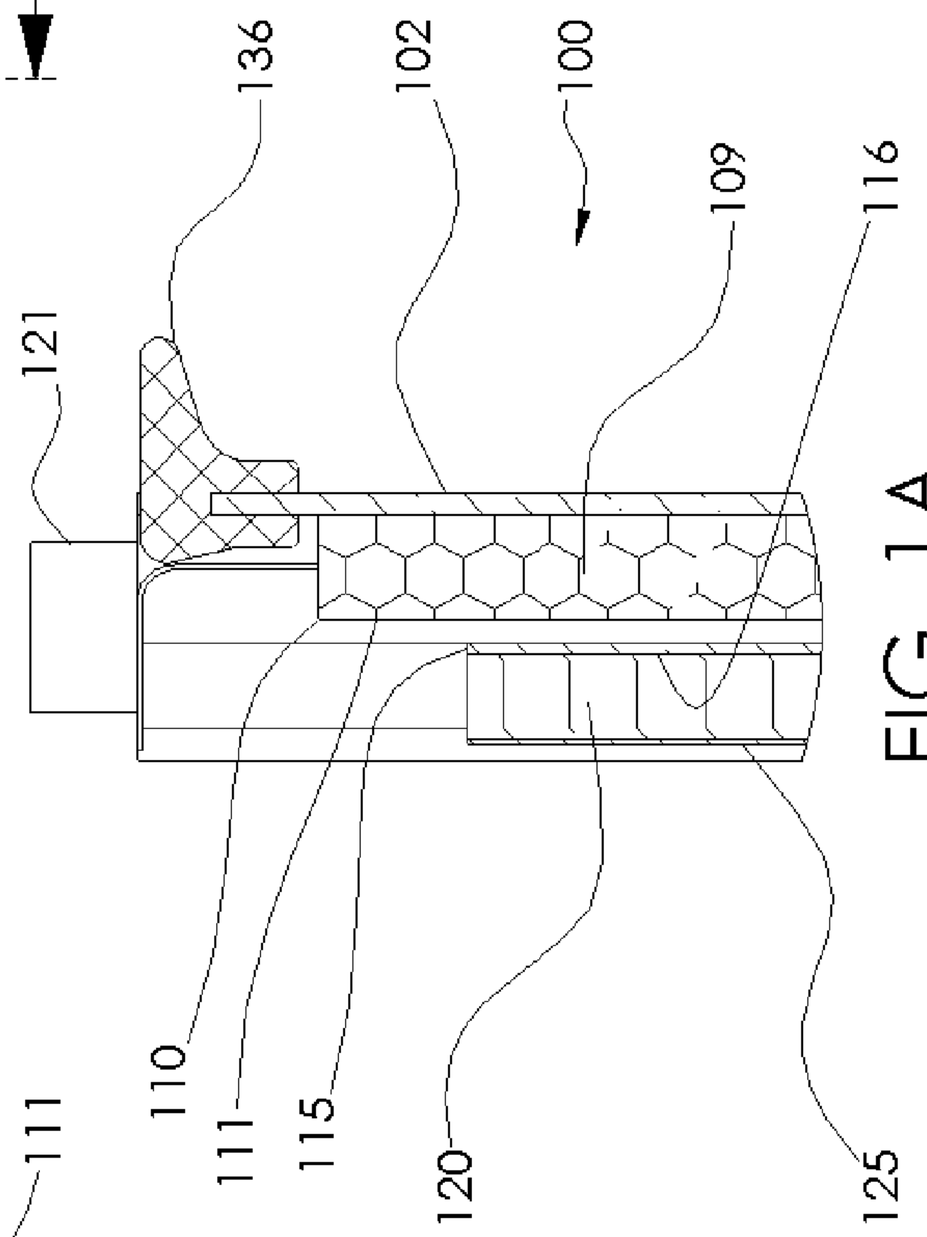


FIG. 1A

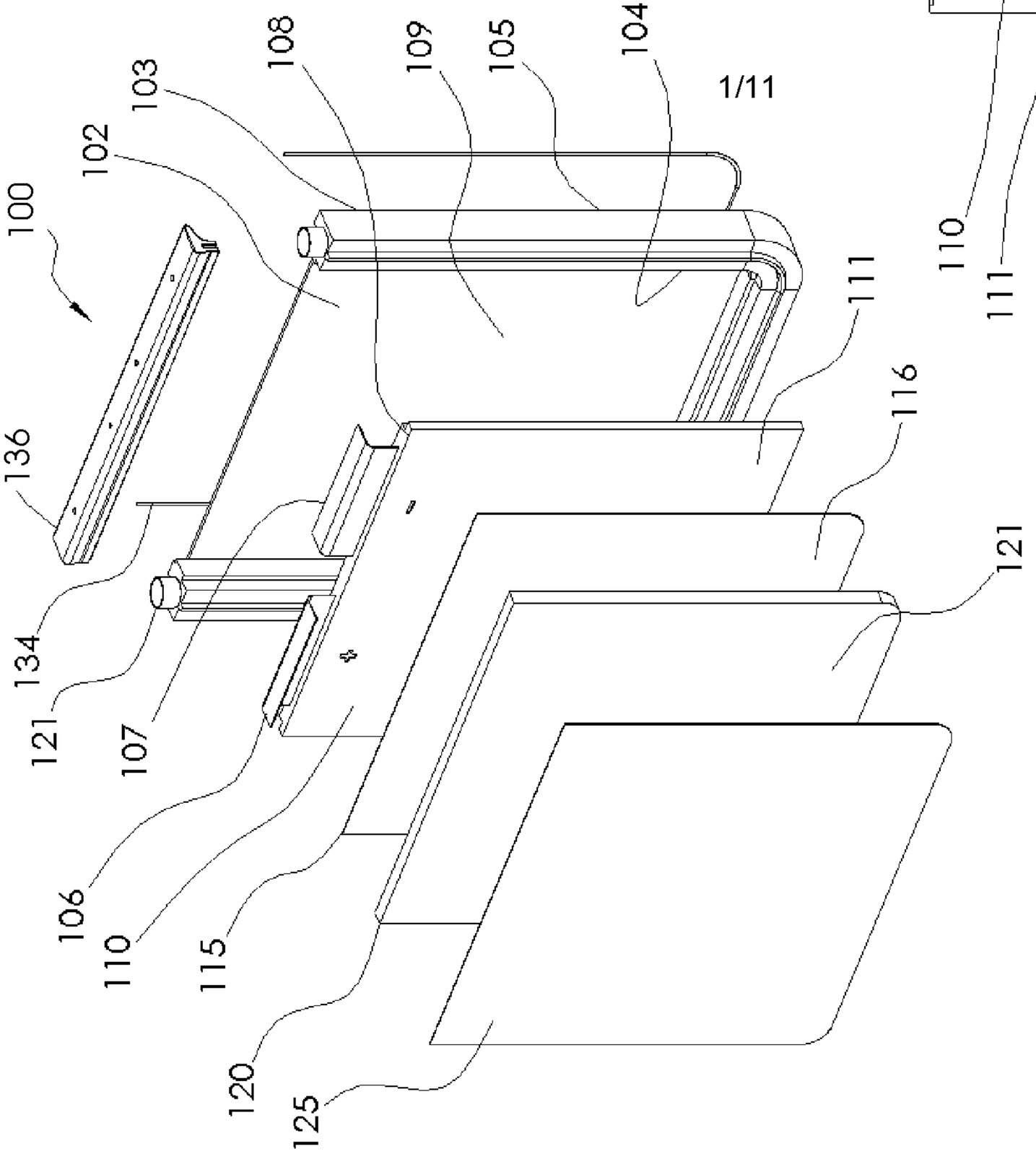
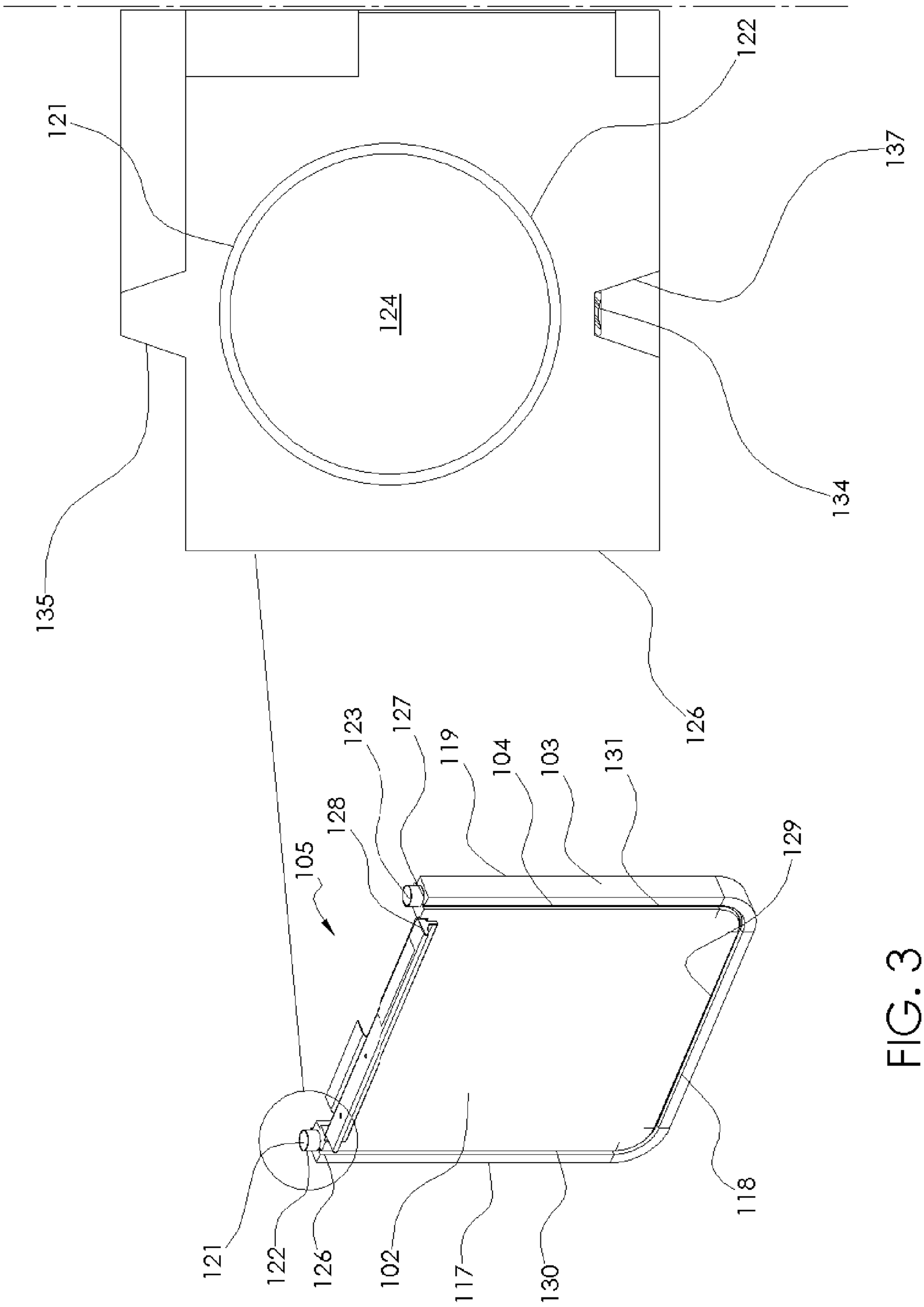


FIG. 2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121
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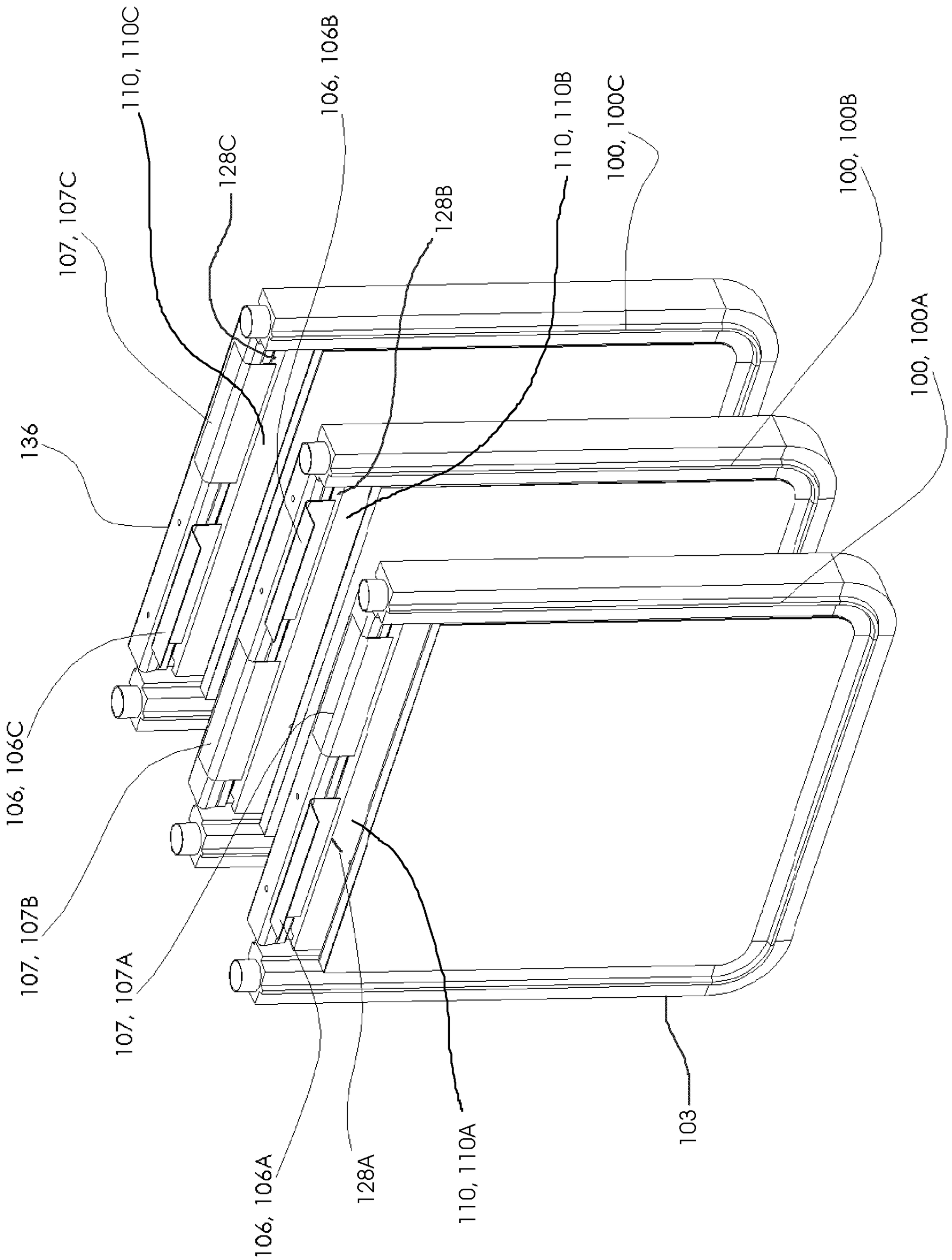
117
130
118

FIG. 3A

FIG. 3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128C
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128B
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106, 106A
128A
110, 110A
103

FIG. 4

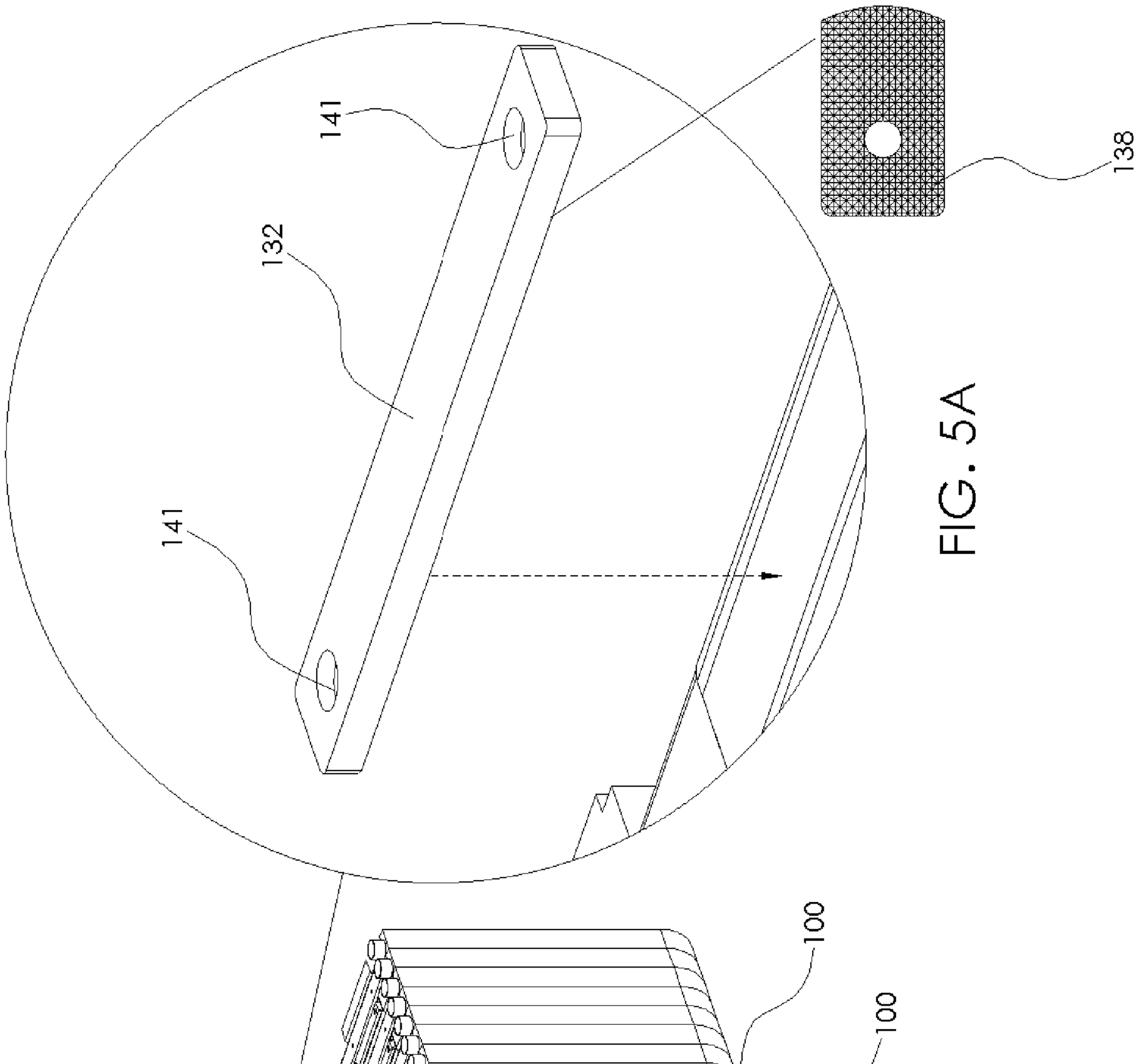


FIG. 5A

FIG. 5

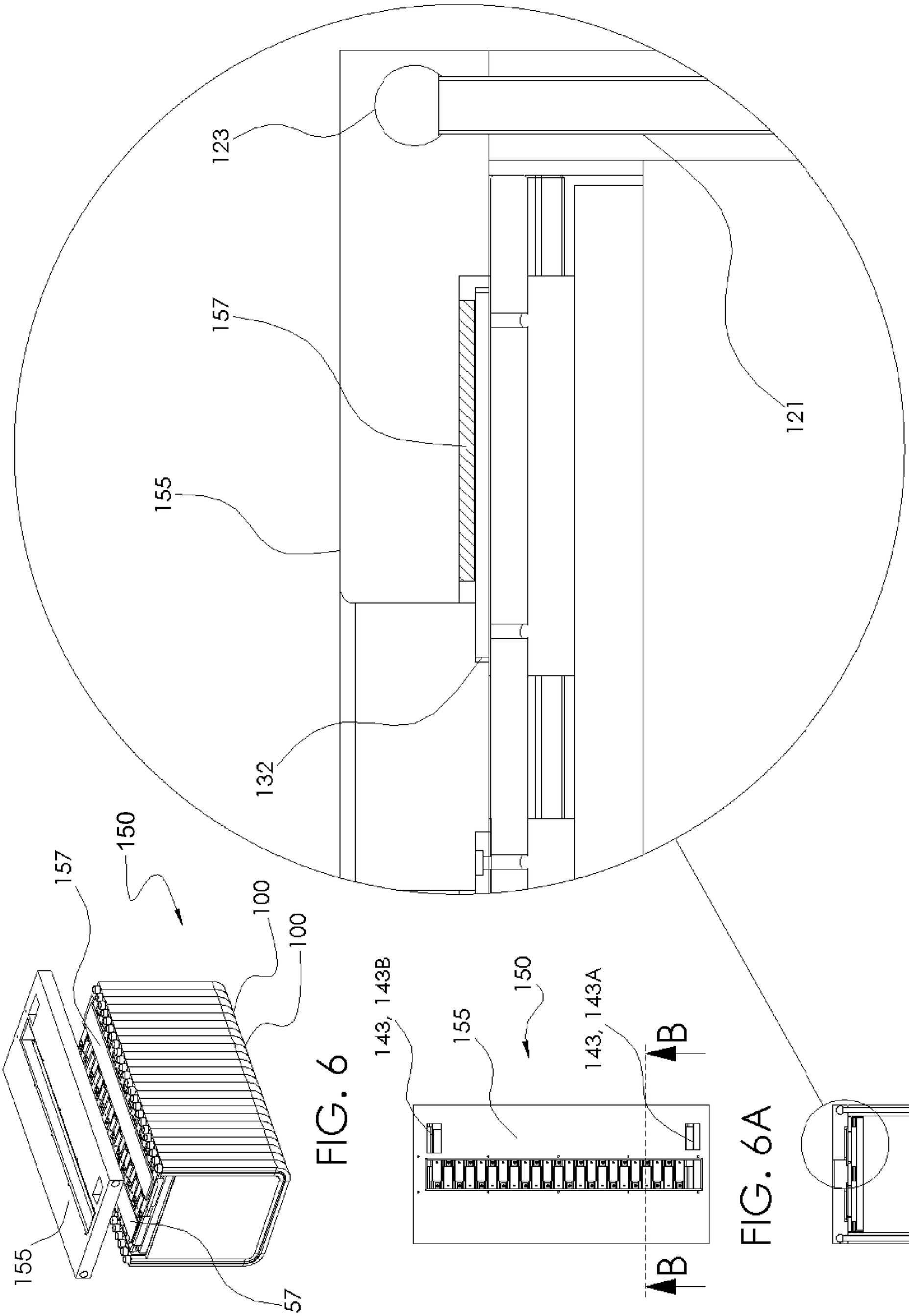
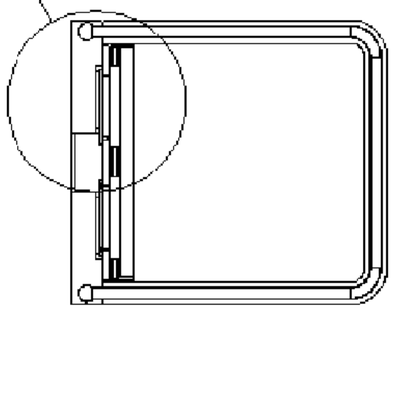


FIG. 6B

FIG. 6

FIG. 6A



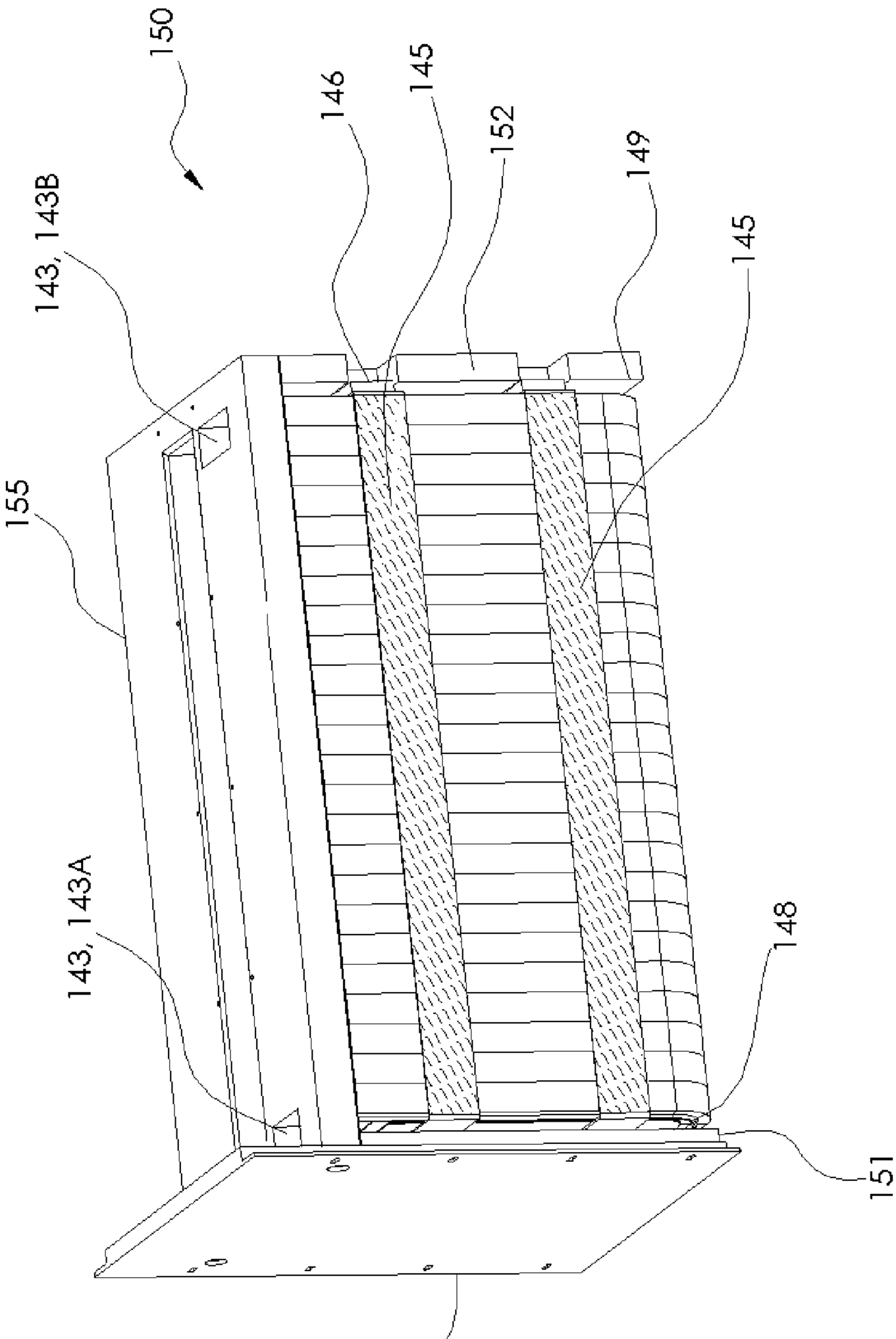


FIG. 7

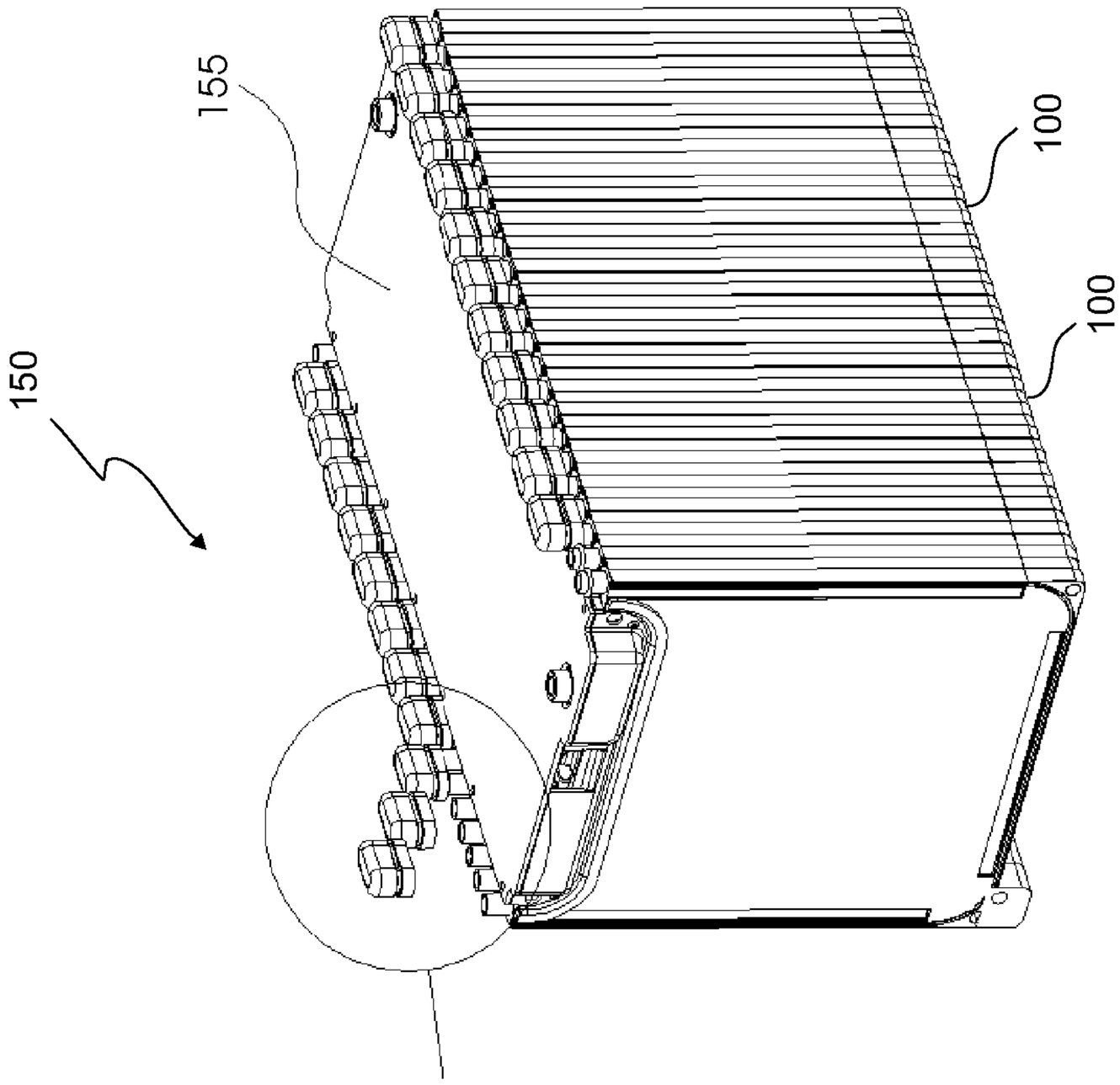


FIG. 8

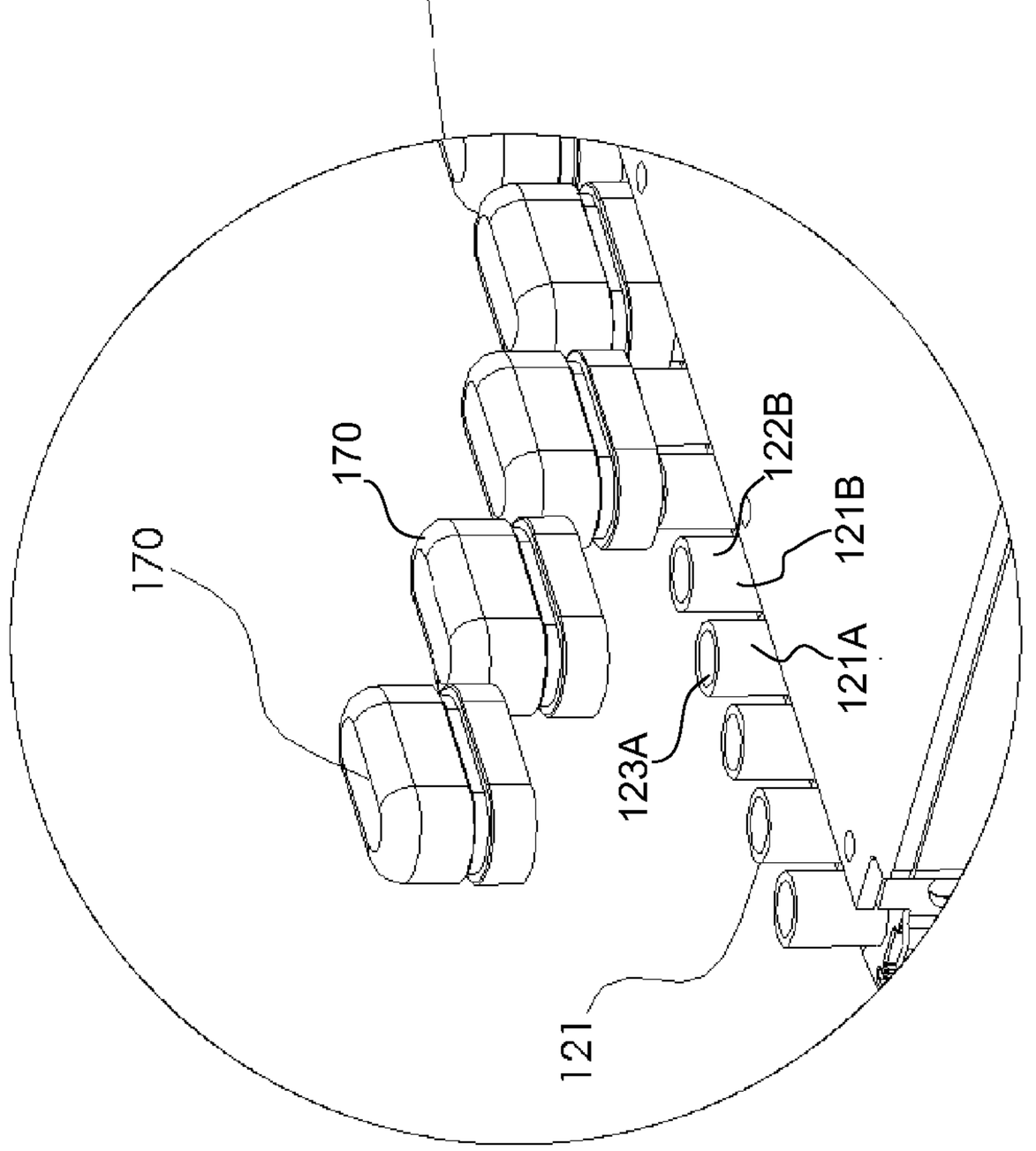


FIG. 8A

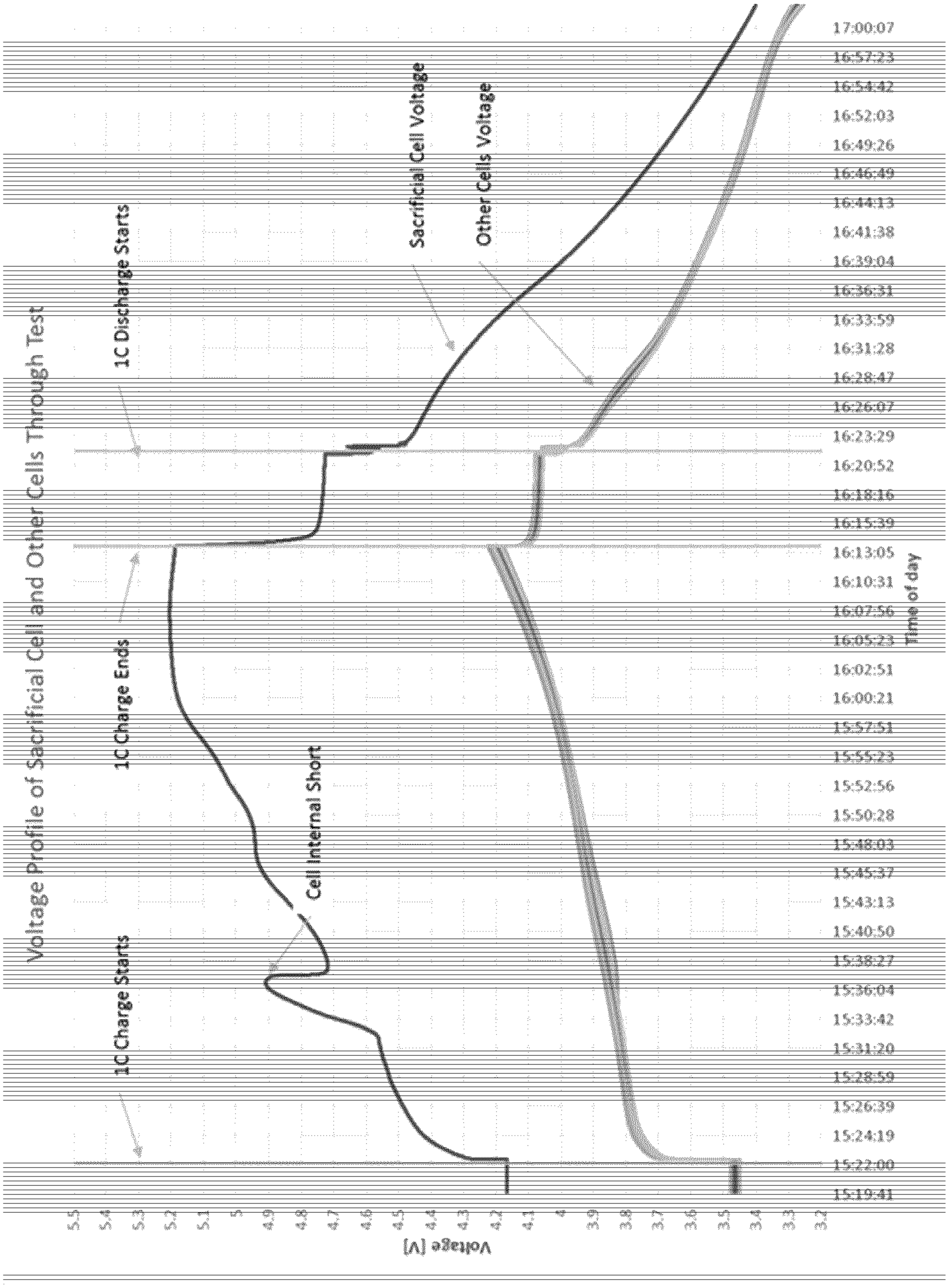

Voltage Profile of Sacrificial Cell and Other Cells Through Test
1C Charge Starts
1C Charge Ends
1C Discharge Starts
Cell Internal Short
Sacrificial Cell Voltage
Other Cells Voltage
Voltage (V)
Time of day
17:00:07
16:57:23
16:54:42
16:52:03
16:49:26
16:46:49
16:44:13
16:41:38
16:39:04
16:36:31
16:33:59
16:31:28
16:28:47
16:26:07
16:23:29
16:20:52
16:18:16
16:15:39
16:13:05
16:10:31
16:07:56
16:05:23
16:02:51
16:00:21
15:57:51
15:55:23
15:52:56
15:50:28
15:48:03
15:45:37
15:43:13
15:40:50
15:38:27
15:36:04
15:33:42
15:31:20
15:28:59
15:26:39
15:24:19
15:22:00
15:19:41

FIG. 9

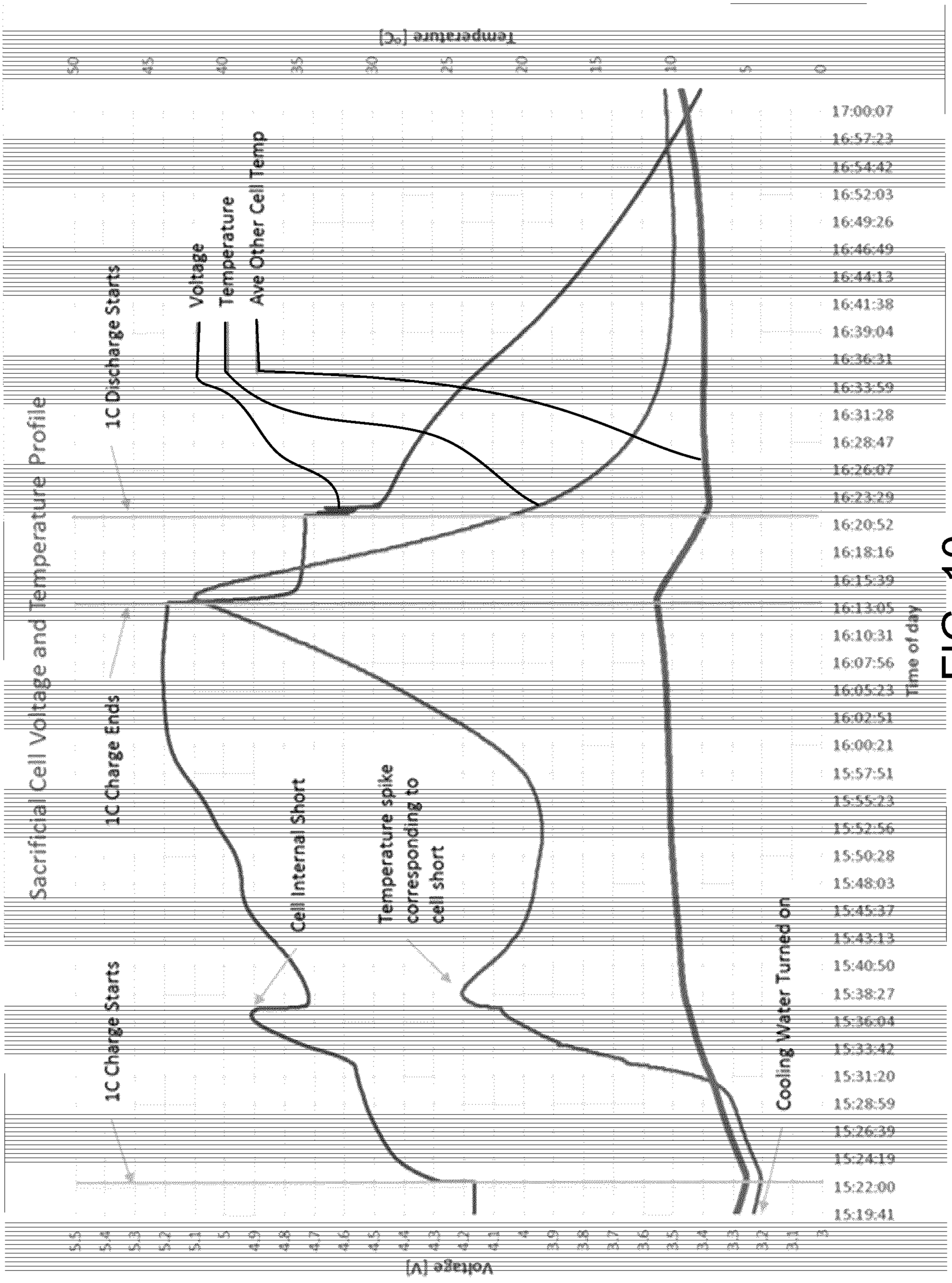

Temperature [°C]
Voltage [V]
Time of day
Sacrificial Cell Voltage and Temperature Profile
1C Discharge Starts
1C Charge Ends
1C Charge Starts
Cell Internal Short
Temperature spike corresponding to cell short
Cooling Water Turned on
Voltage
Temperature
Ave Other Cell Temp

FIG. 10

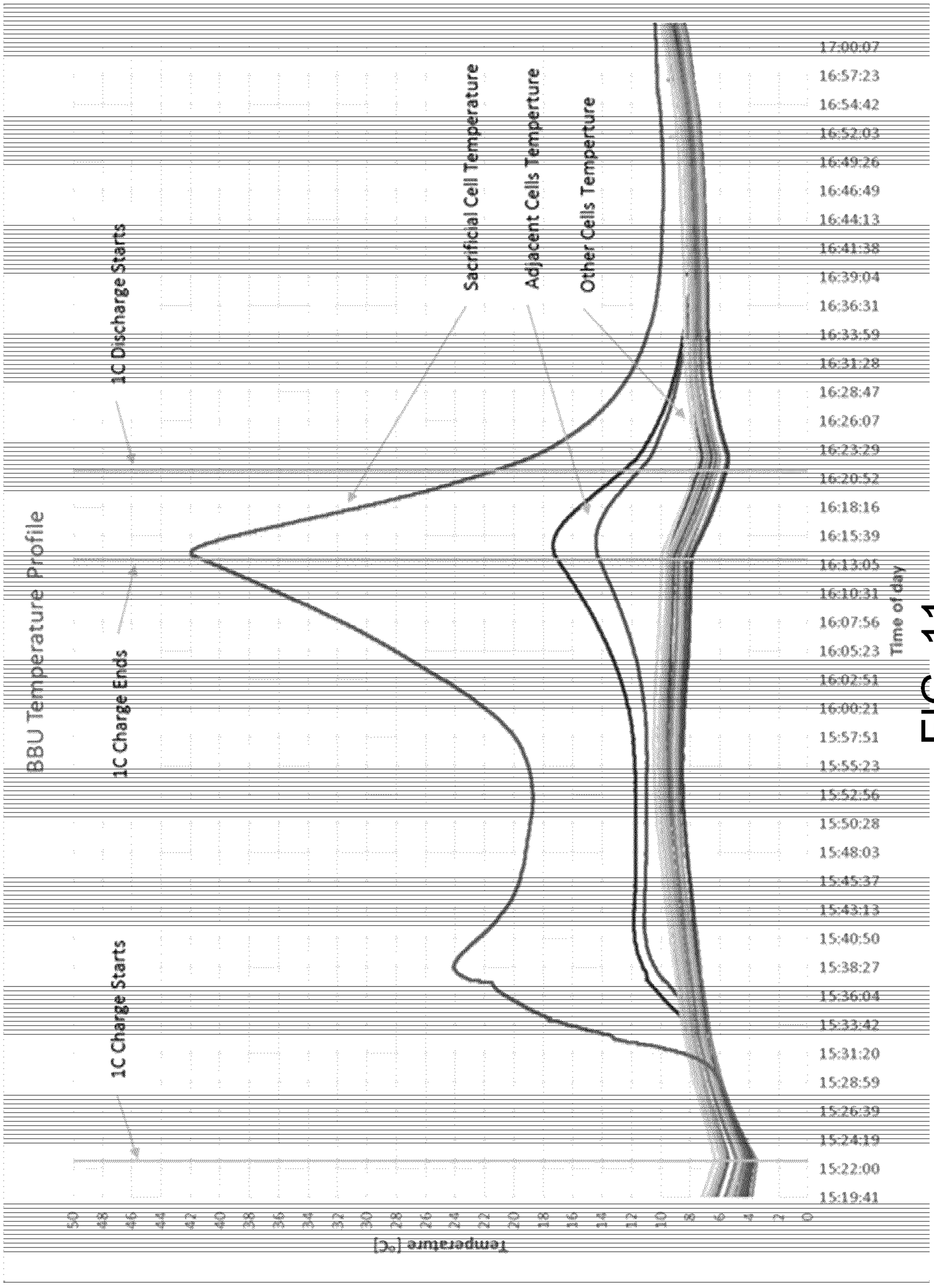
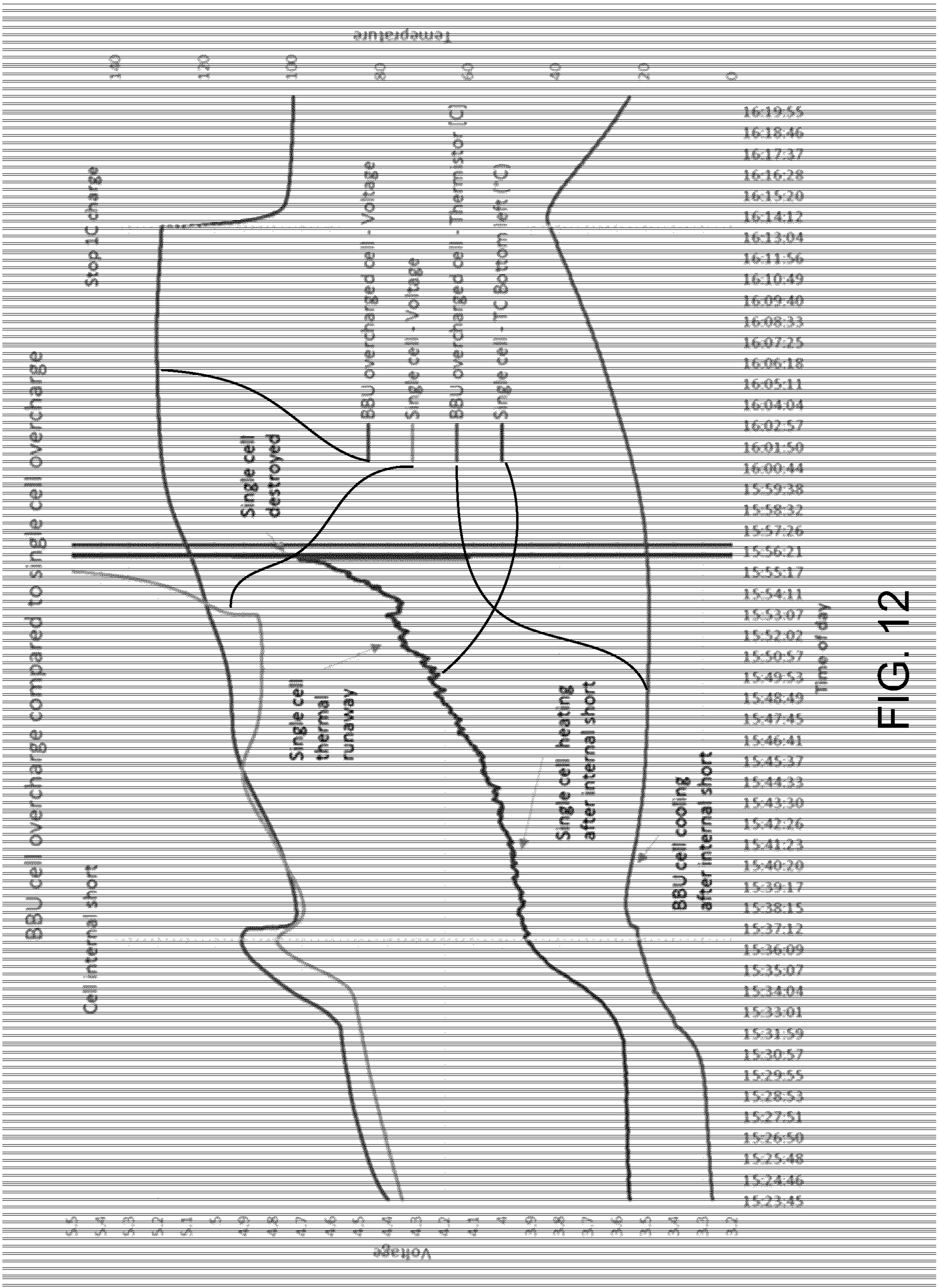

1C Discharge Starts
1C Charge Ends
1C Charge Starts
BBU Temperature Profile
Sacrifical Cell Temperature
Adjacent Cells Temperture
Other Cells Temperture
Time of day
17:00:07
16:57:23
16:54:42
16:52:03
16:49:26
16:46:49
16:44:13
16:41:38
16:39:04
16:36:31
16:33:59
16:31:28
16:28:47
16:26:07
16:23:29
16:20:52
16:18:16
16:15:39
16:13:05
16:10:31
16:07:56
16:05:23
16:02:51
16:00:21
15:57:51
15:55:23
15:52:56
15:50:28
15:48:03
15:45:37
15:43:13
15:40:50
15:38:27
15:36:04
15:33:42
15:31:20
15:28:59
15:26:39
15:24:19
15:22:00
15:19:41
Temperature [°C]

FIG. 11


temperature
Cell overcharge compared to single cell
Single cell thermal runaway
Subsequent delayed cell thermal runaway
Single cell thermal runaway
Central cell short
BU cell cooling after internal short
time of day
16:19:55
16:18:46
16:17:37
16:16:28
16:15:20
16:14:12
16:13:04
16:11:56
16:10:49
16:09:40
16:08:33
16:07:25
16:06:18
16:05:11
16:04:04
16:02:57
16:01:50
16:00:44
15:59:38
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15:57:26
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15:39:17
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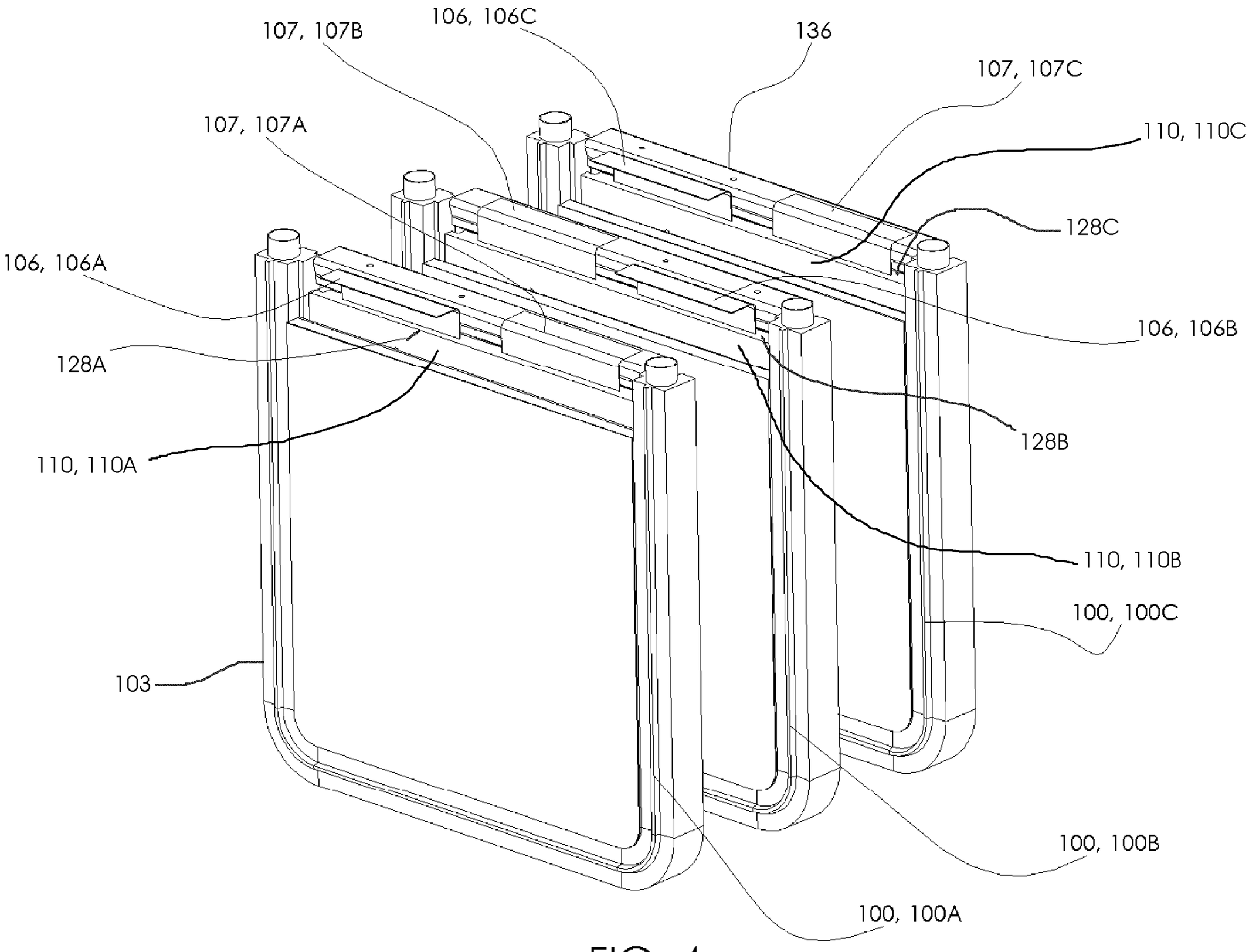
15:23:45

FIG. 12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100, 100C
103
100, 100B
100, 100A

FIG. 4