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CHEN et al.

(54) VENT PROTECTION FOR MODULAR AND SCALABLE BATTERY PACKS

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§ 371 (c)(1),
(2) Date: **Jan. 9, 2025**

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Publication Classification

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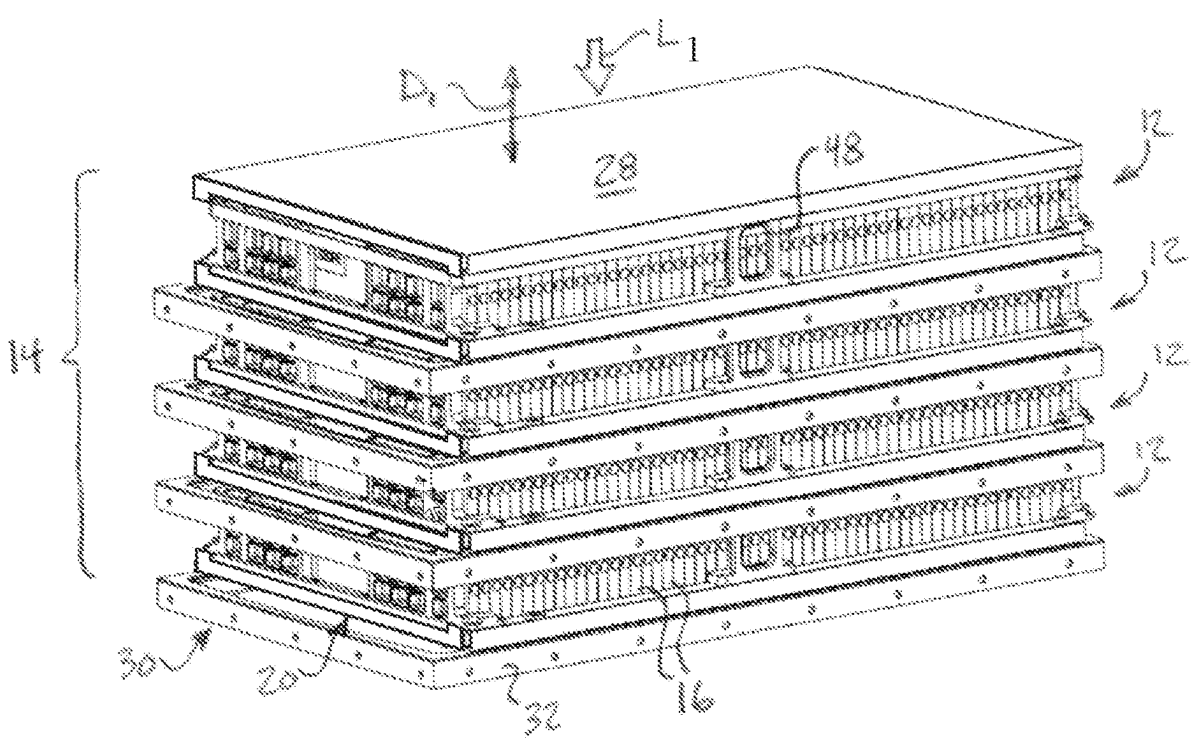
H01M 10/613 (2014.01)
H01M 10/6557 (2014.01)

(52) **U.S. Cl.**
CPC ***H01M 50/30*** (2021.01); ***H01M 10/613*** (2015.04); ***H01M 10/6557*** (2015.04); *H01M 2220/20* (2013.01)

(57) **ABSTRACT**

A battery pack includes battery cells arranged in an array to form a battery module layer. Multiple layers are vertically stacked with thermal management devices, such as active heat exchangers in the form of battery cold plates, above and below each layer to form a multi-layer battery stack that may be held in compression by a battery pack frame. The multi-layer battery stack and battery pack frame are surrounded by a battery enclosure, which has flat sealing surfaces to ensure robust sealing. The battery pack is associated with a thermal management system for cooling and heating the battery cells of the battery pack. The battery thermal management system provides cooling and heating by alternating cooling flow directions to achieve uniform temperature distribution.



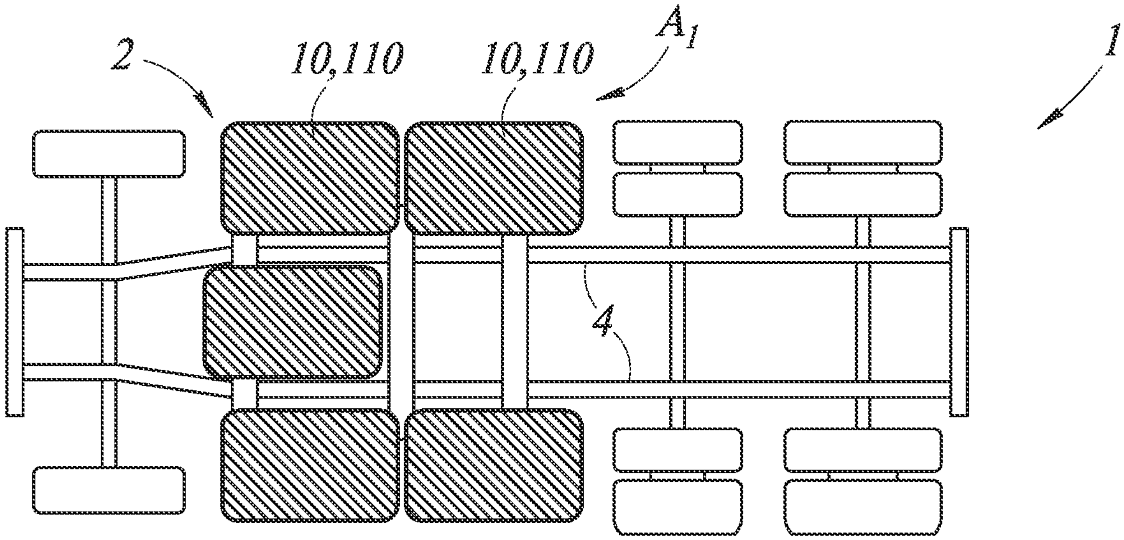


FIG. 1

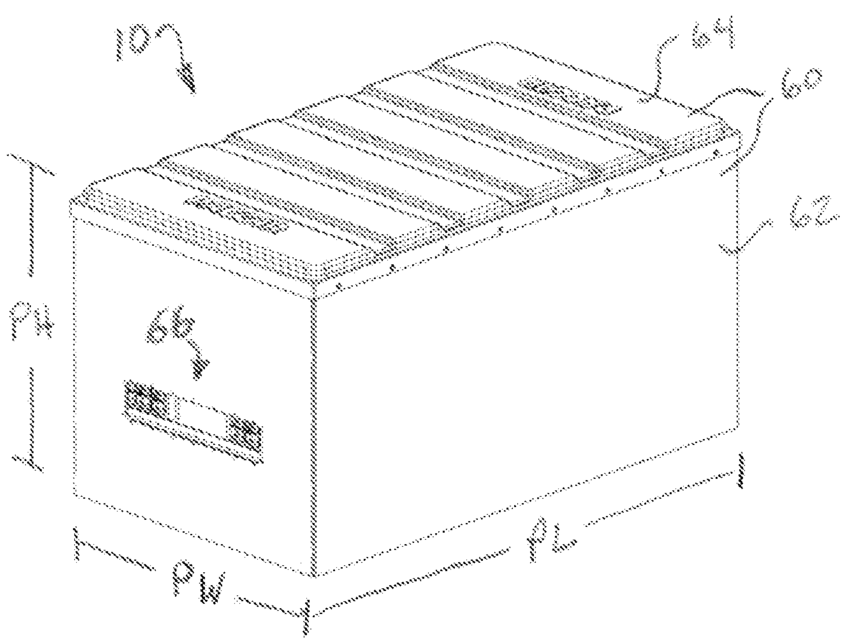


FIG. 2

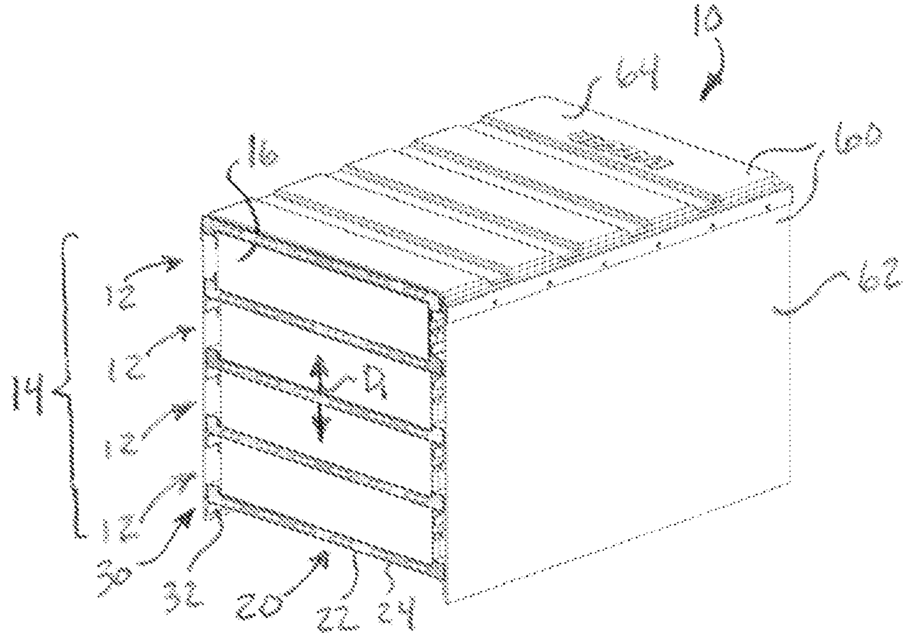
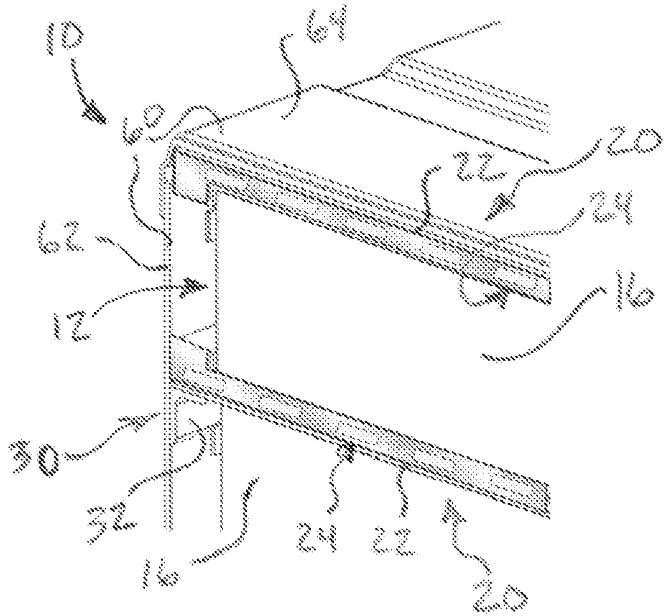

10
64
60
16
12
62
12
D
14
12
12
30
32
20
22
24

FIG. 3


10
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60
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22
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62
12
16
30
32
24
22
16
20

FIG. 4

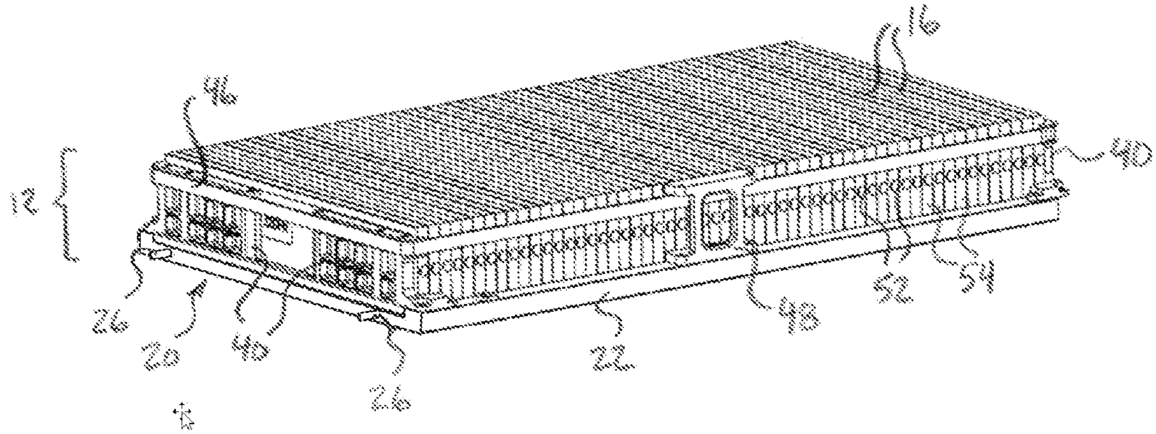

16
46
12
40
26
20
40
48
52
54
22
26

FIG. 5

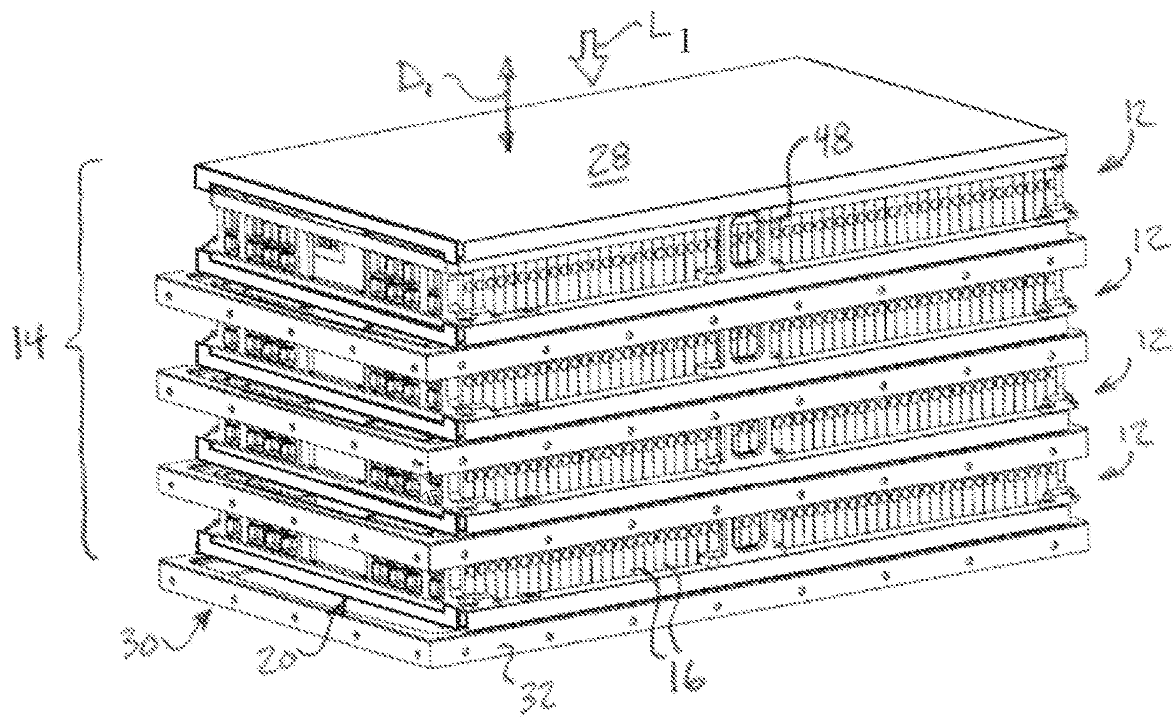

L1
D1
28
48
12
12
12
12
14
30
20
32
16

FIG. 6

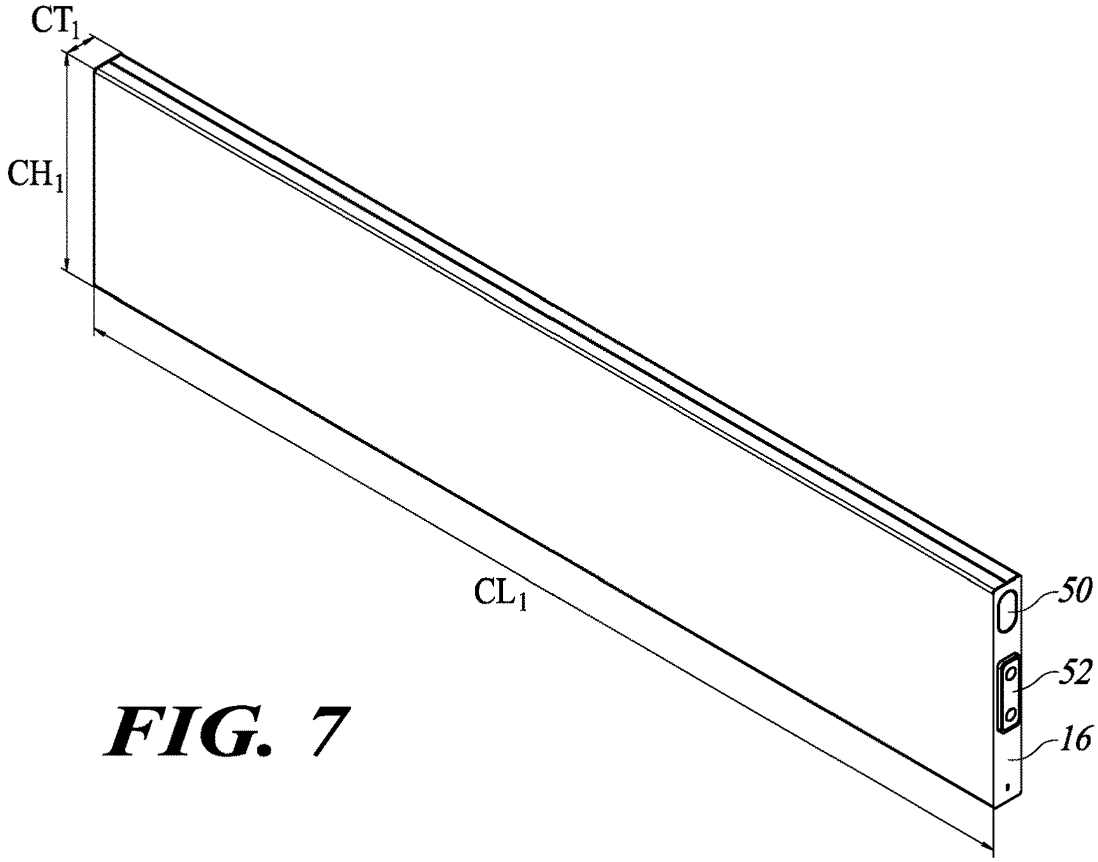


FIG. 7

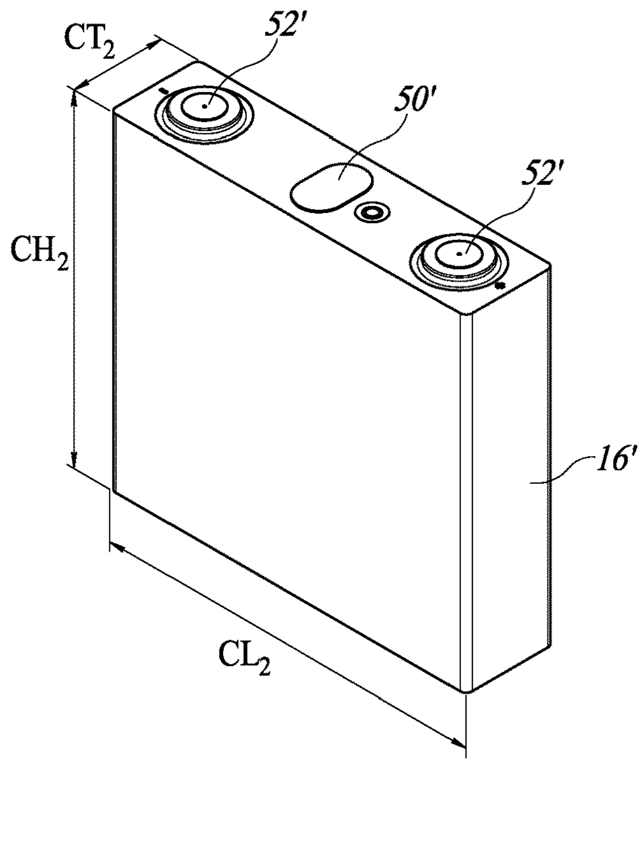


FIG. 8

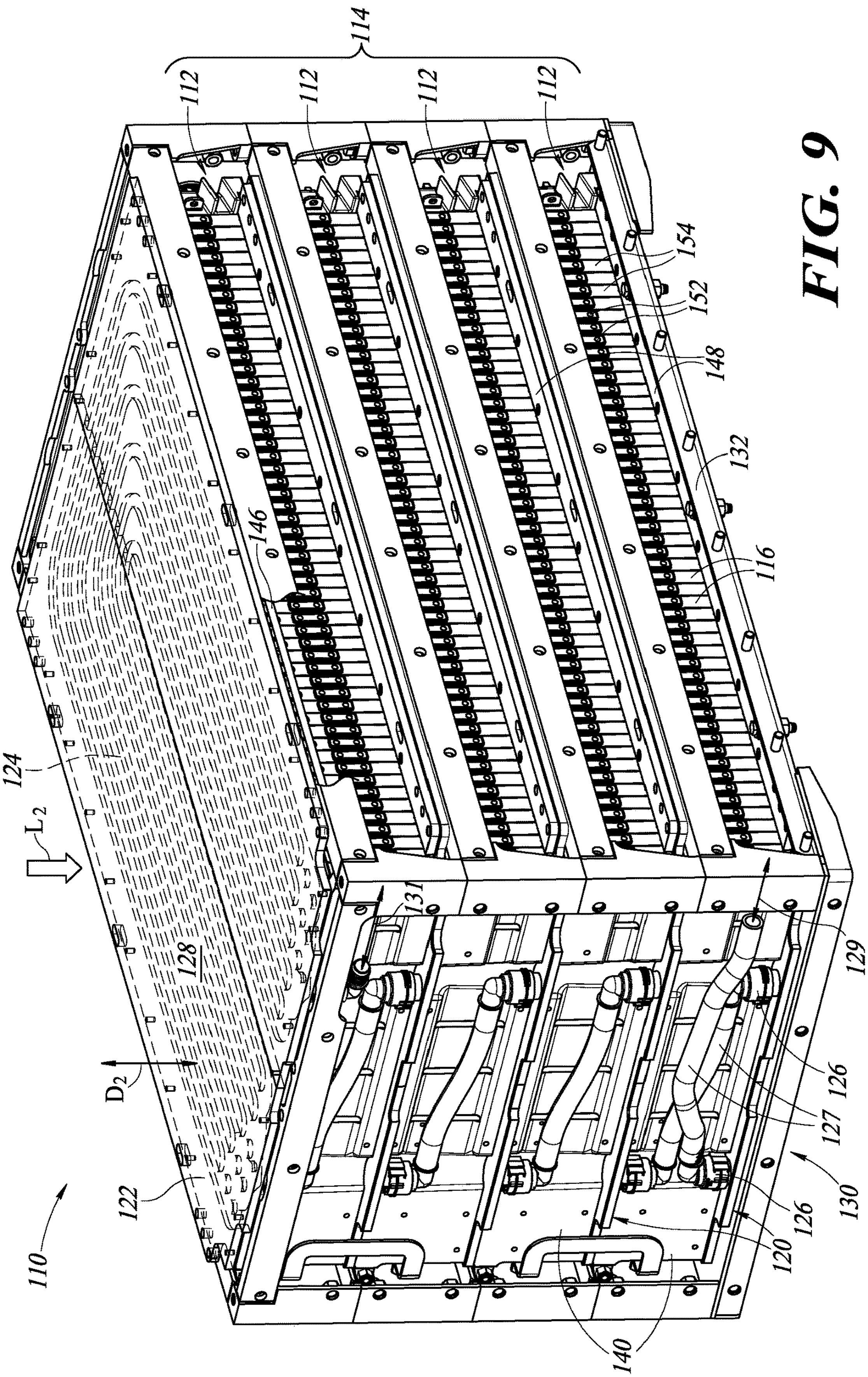
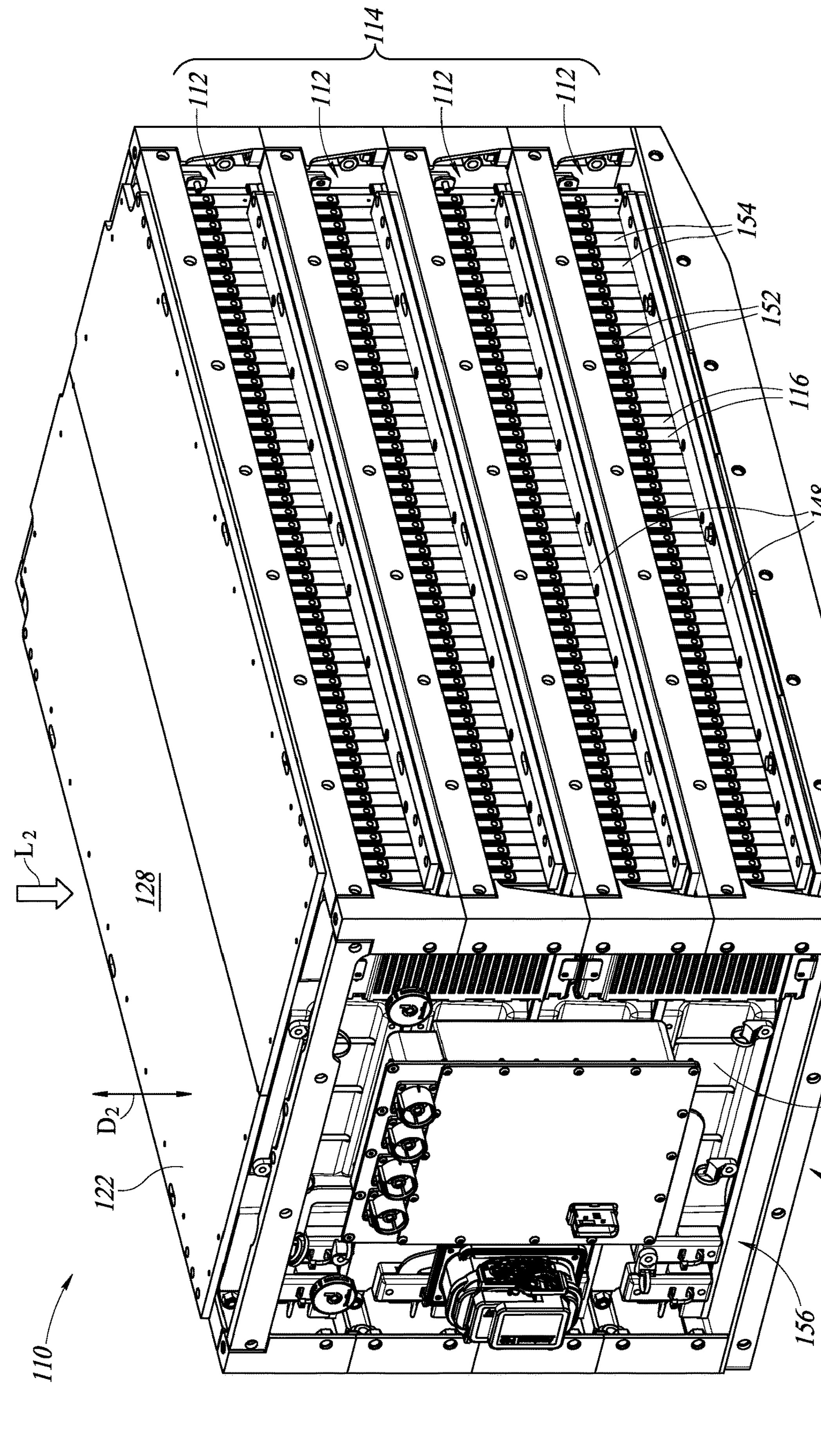

114
112
112
112
112
154
152
148
132
116
146
124
L_2
128
D_2
122
110
131
129
126
127
127
126
130
120
140

FIG. 9


114
112
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112
154
152
116
148
132
L2
128
D2
122
110
140
130
156

FIG. 10

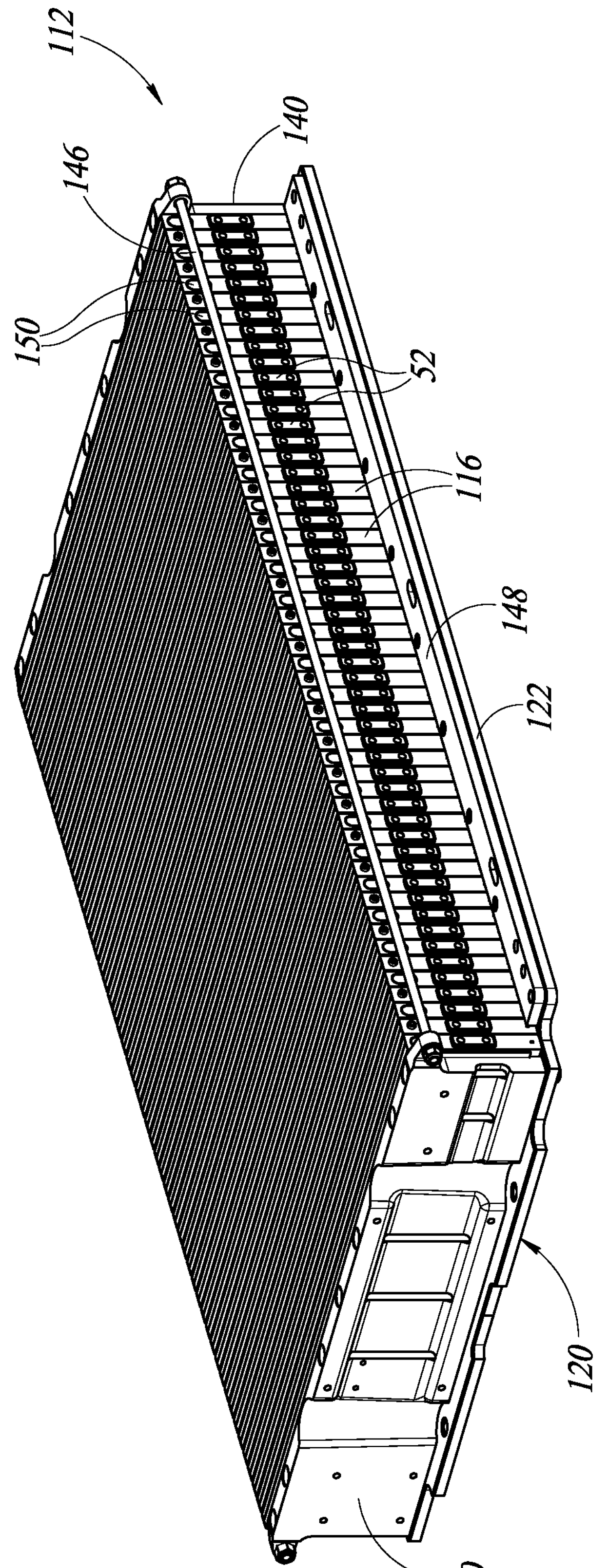

FIG. 11

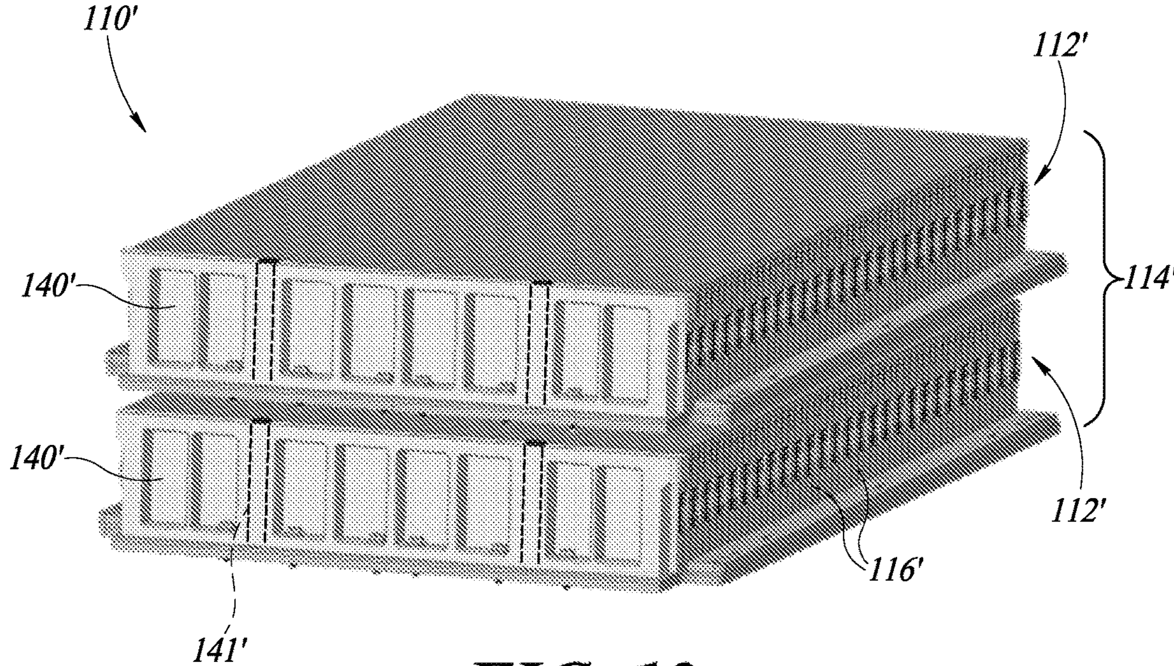

FIG. 12

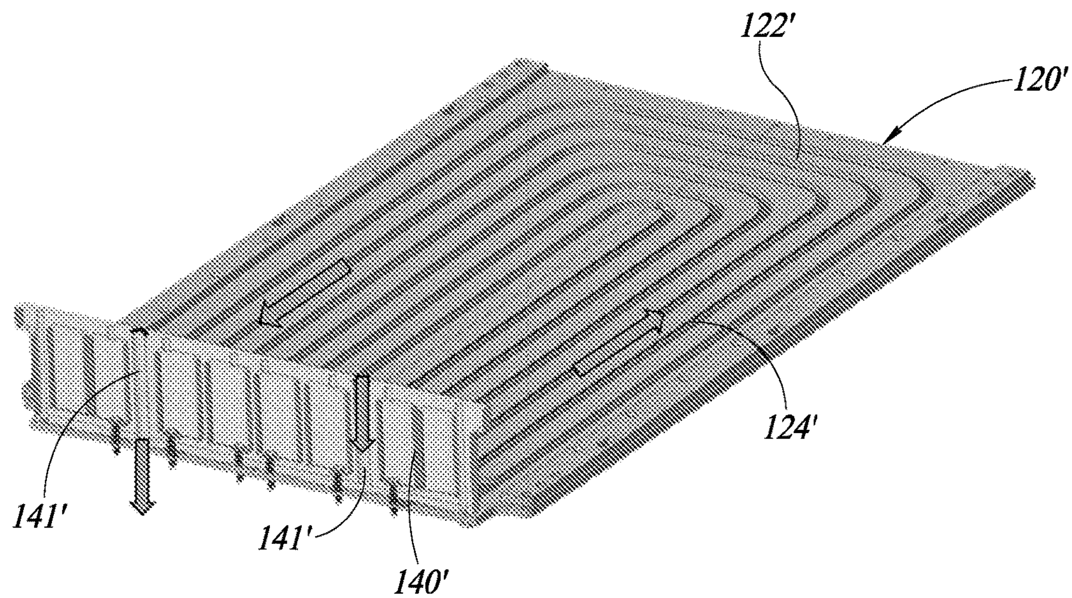

FIG. 13

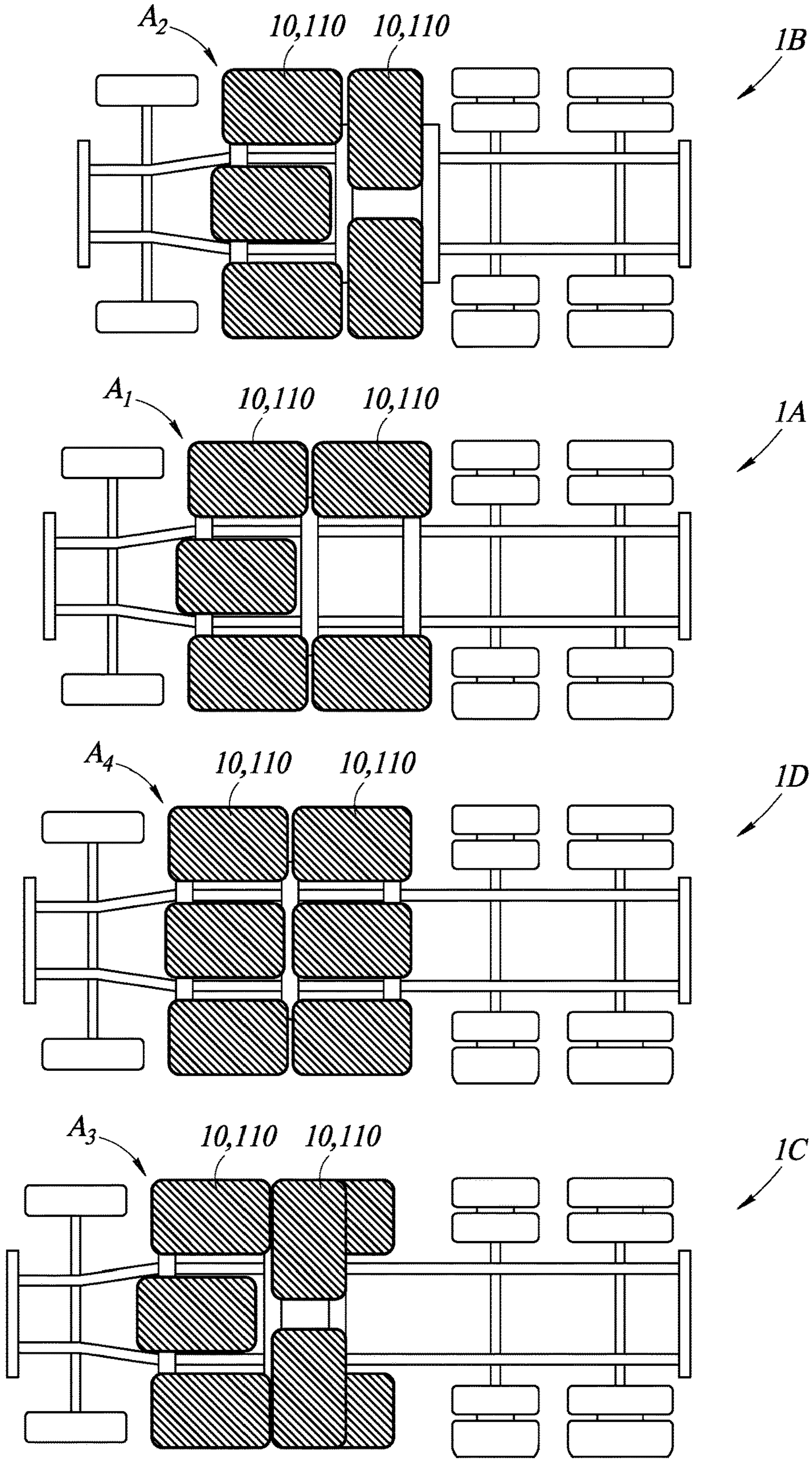
A2
10,110
10,110
1B
A1
10,110
10,110
1A
A4
10,110
10,110
1D
A3
10,110
10,110
1C

FIG. 14

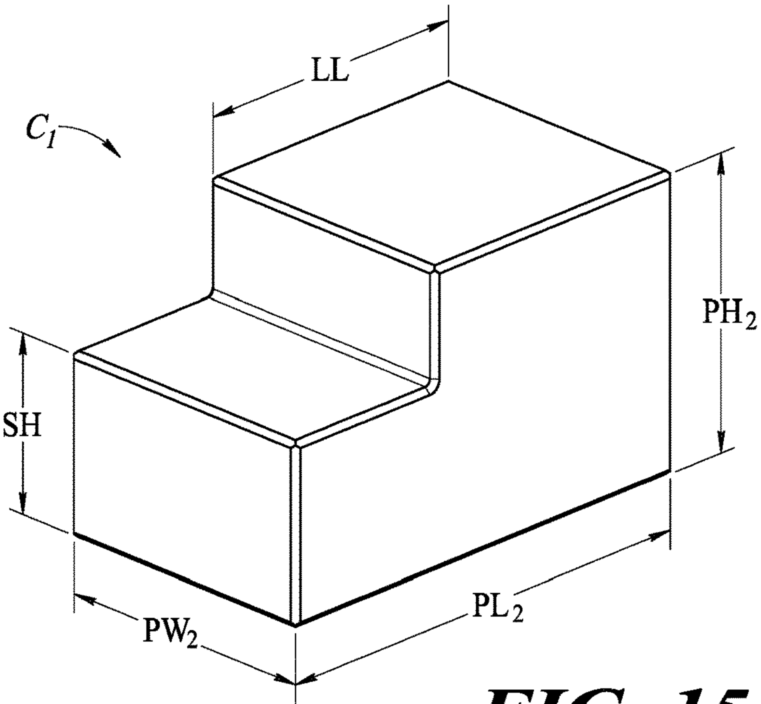

FIG. 15

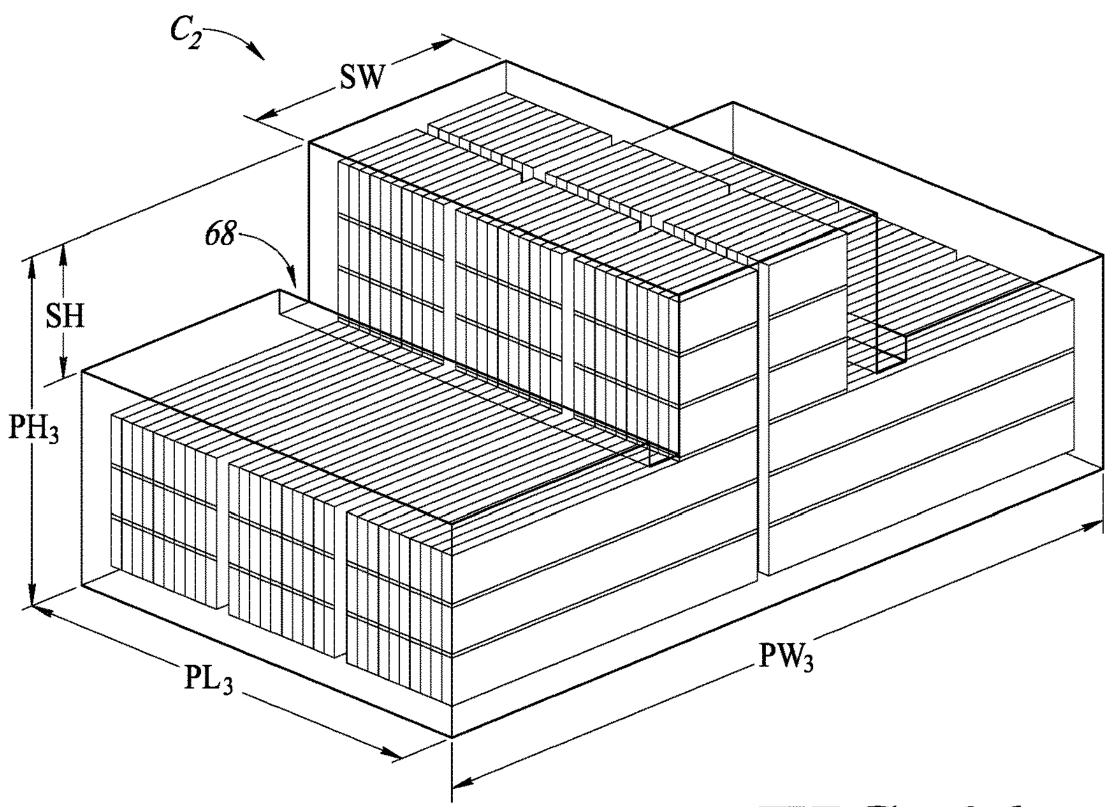

FIG. 16

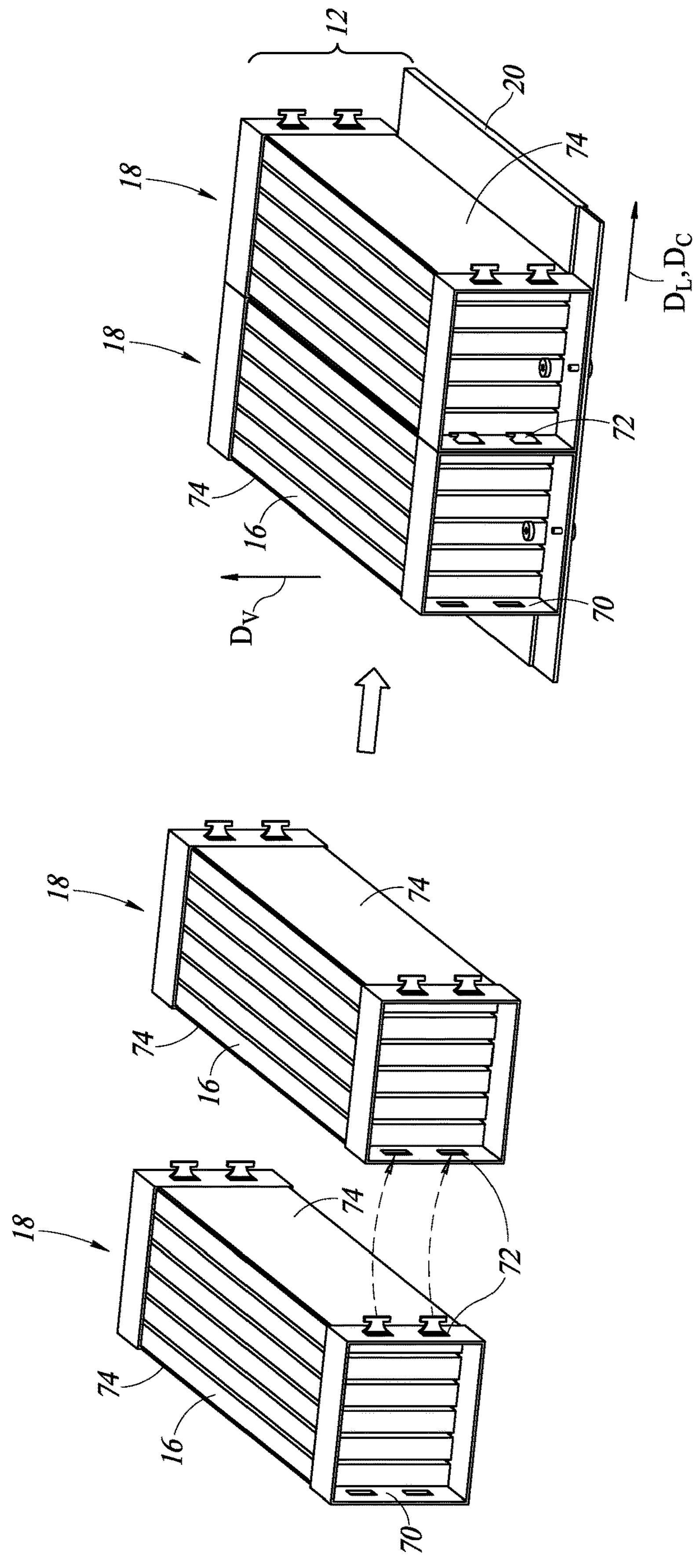

FIG. 17

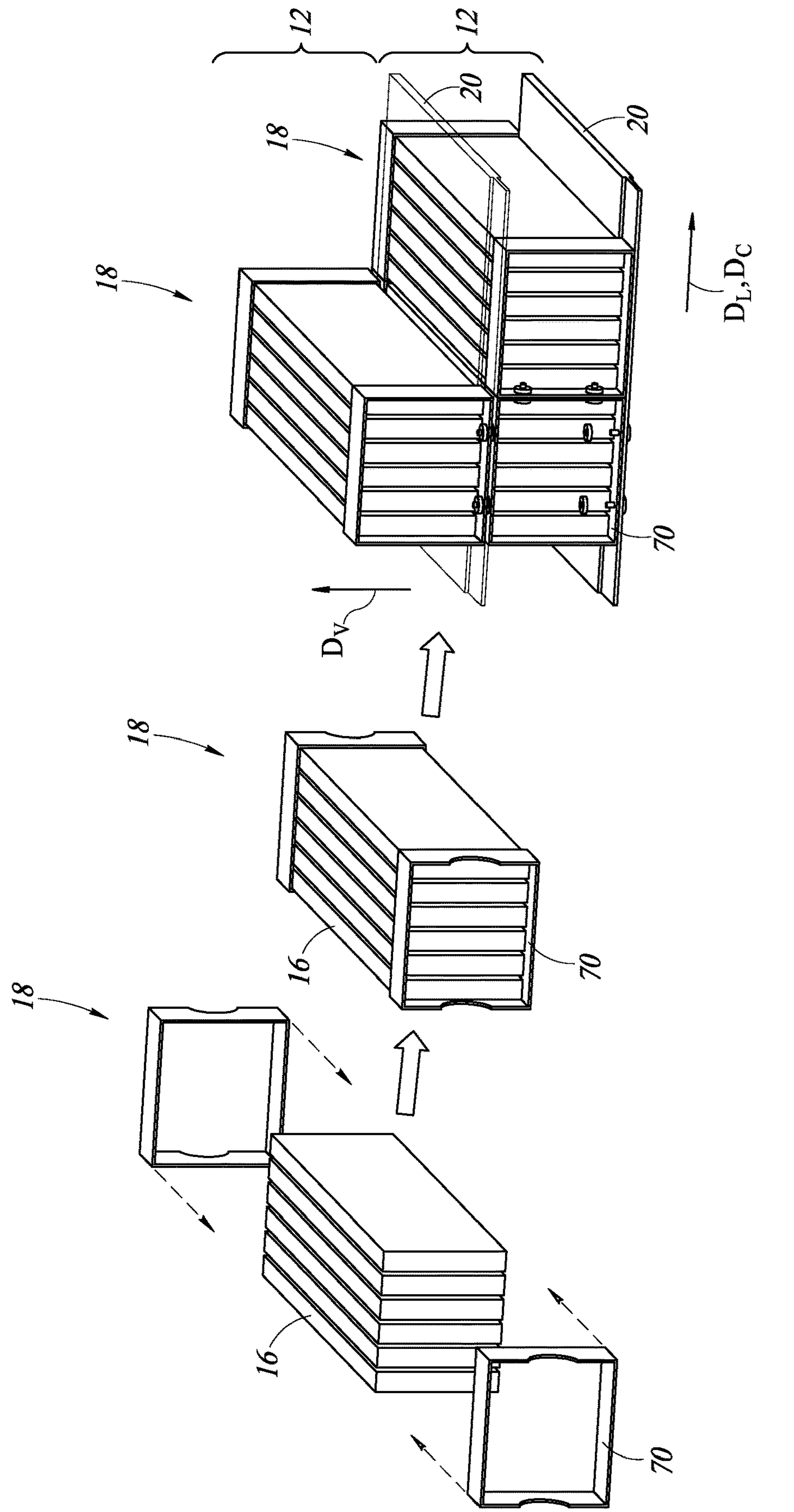

FIG. 18

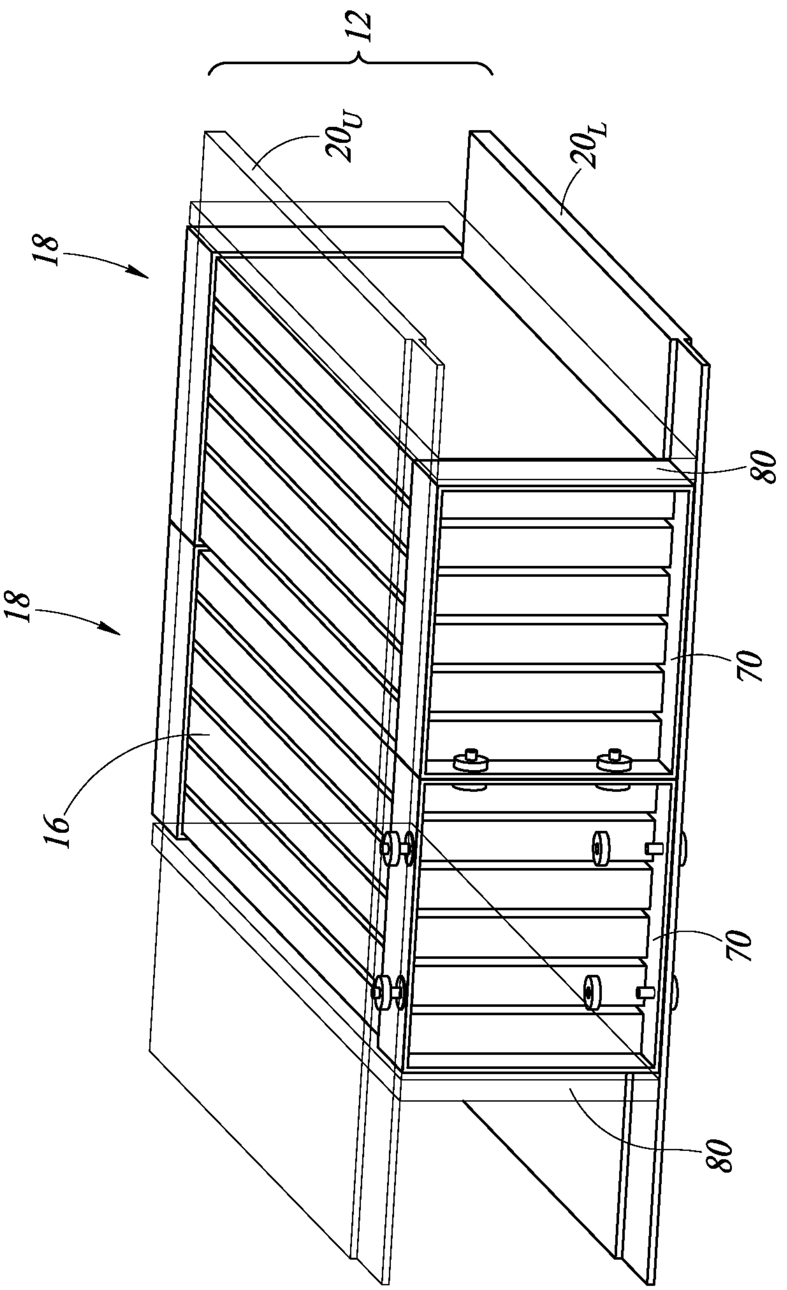

FIG. 19

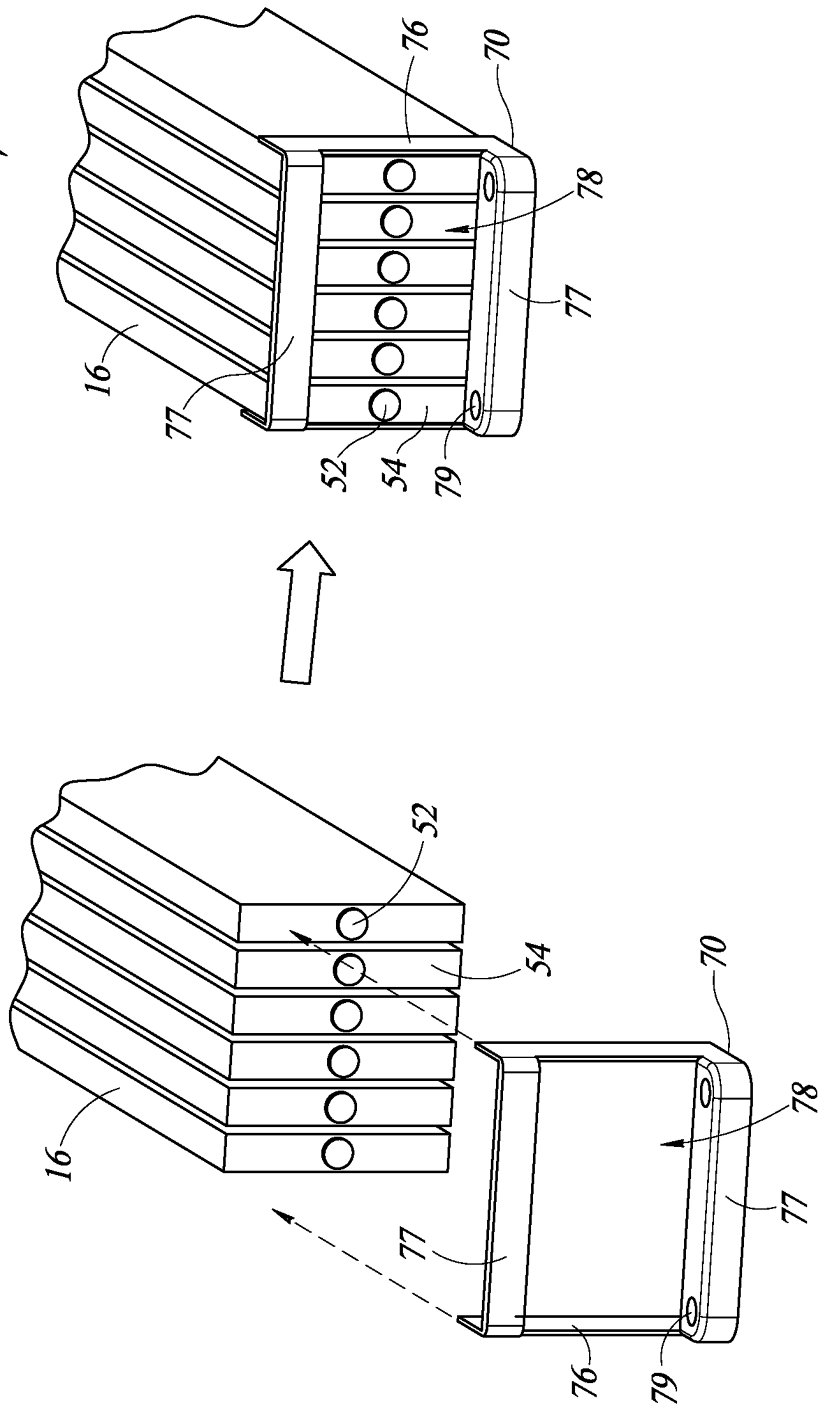

FIG. 20

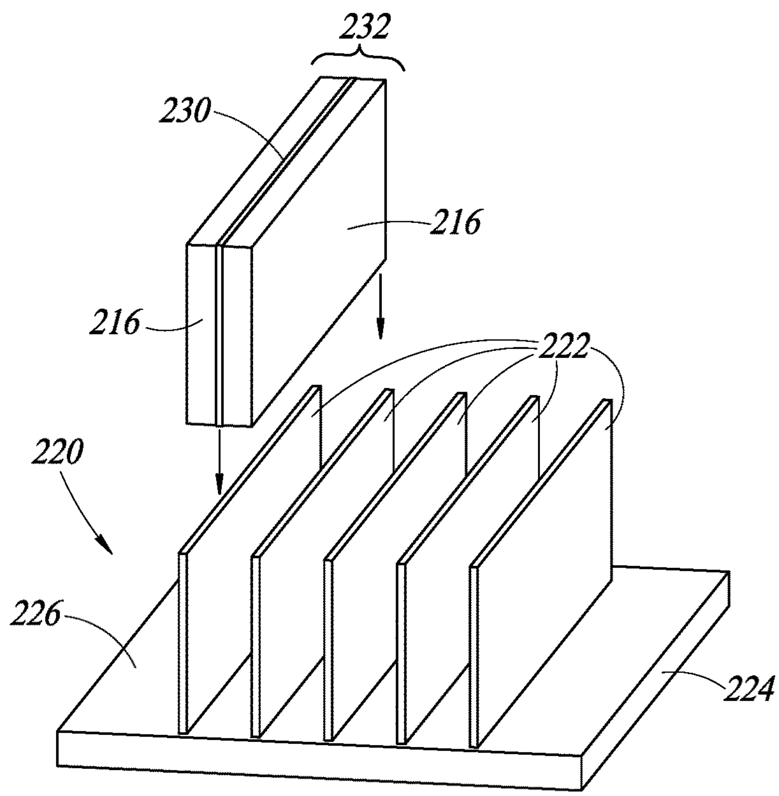
232
230
216
216
222
220
226
224

FIG. 21

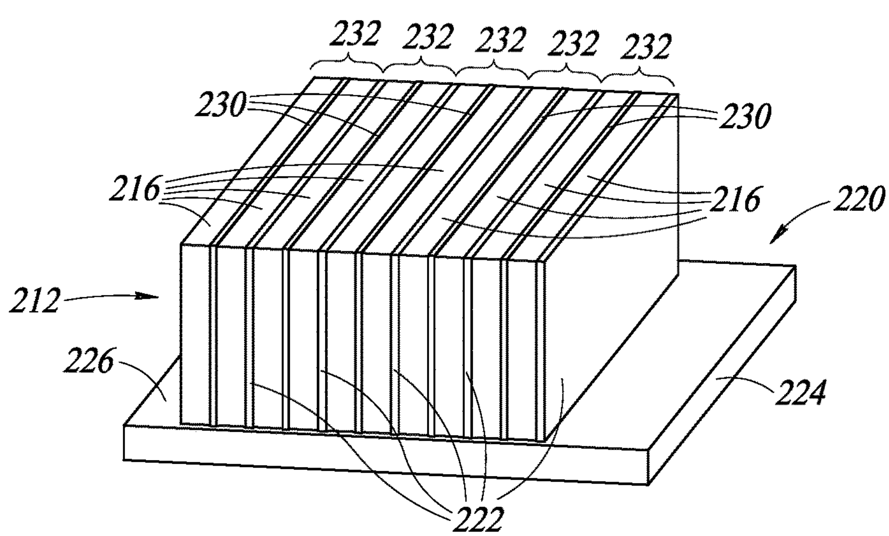
232
232
232
232
232
230
230
216
216
220
212
226
224
222

FIG. 22

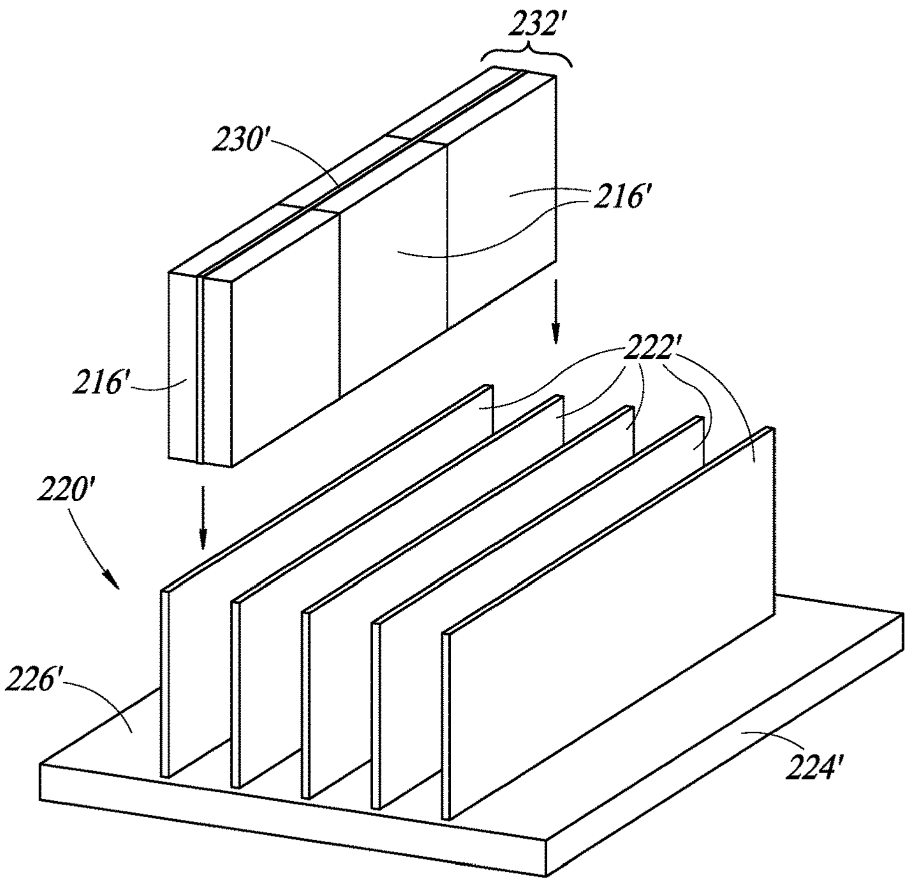
232'
230'
216'
216'
222'
220'
226'
224'

FIG. 23

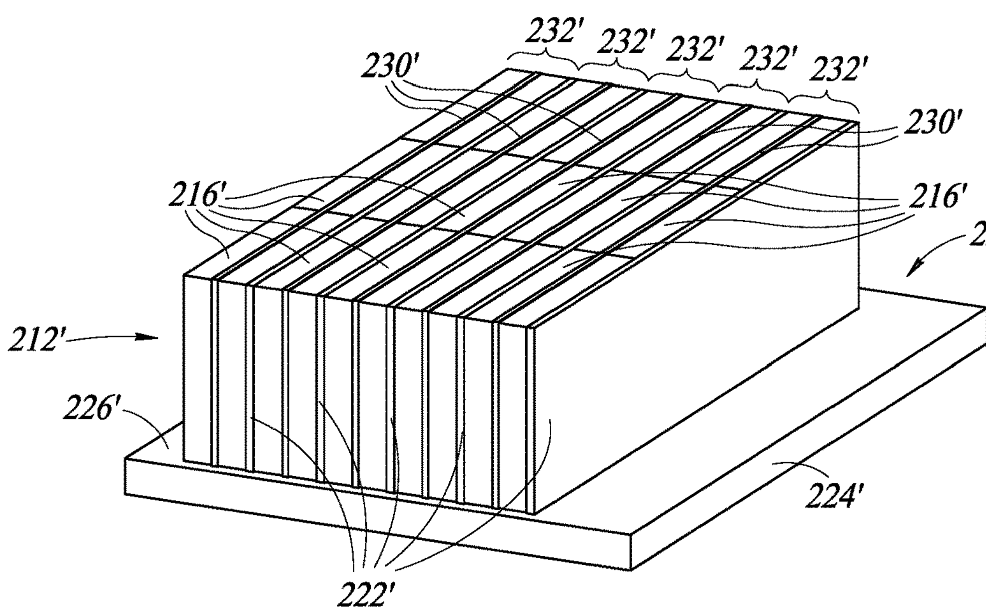
232'
232'
232'
232'
232'
230'
230'
216'
216'
220'
212'
226'
224'
222'

FIG. 24

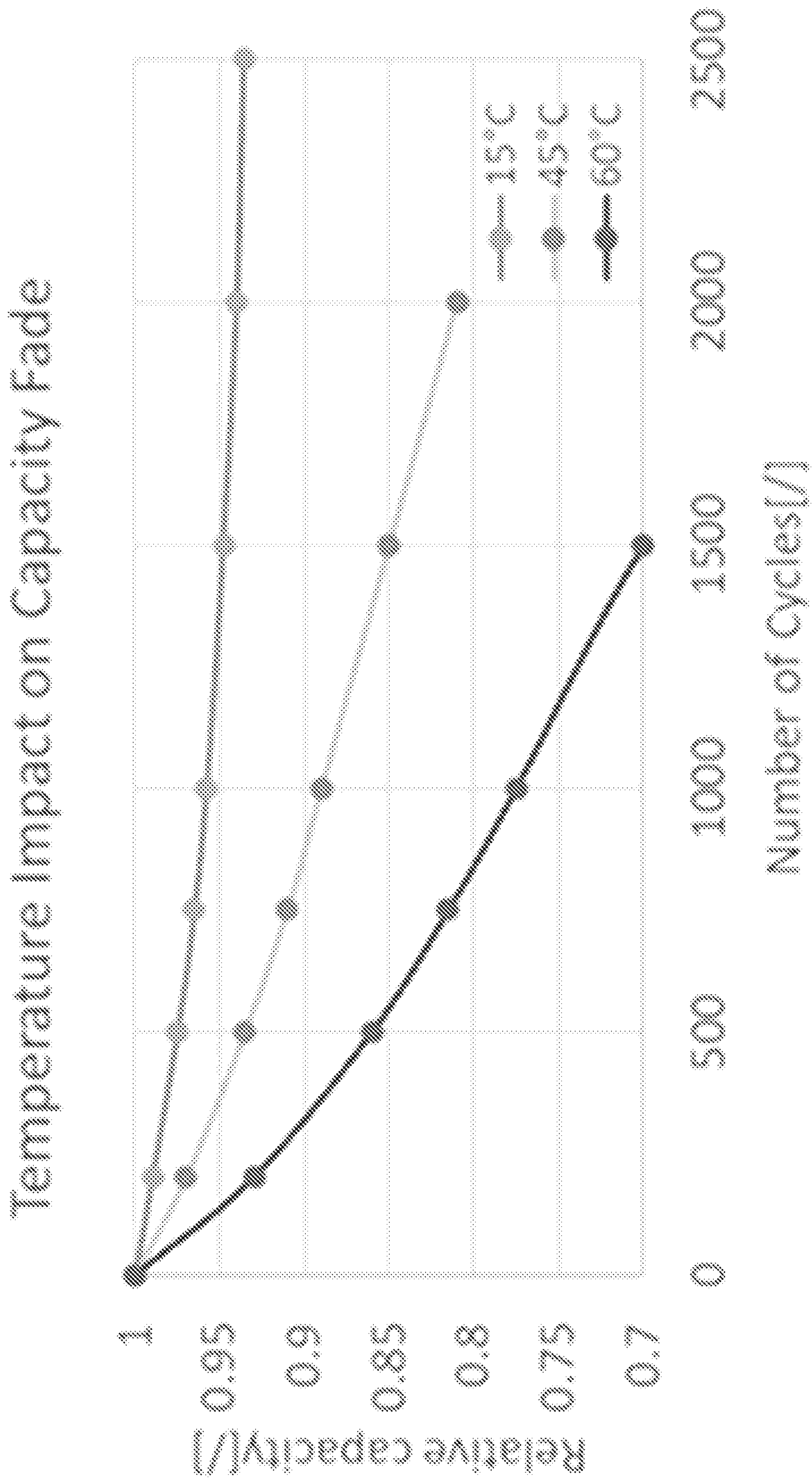
Temperature Impact on Capacity Fade
Relative capacity[/]
1
0.95
0.9
0.85
0.8
0.75
0.7
0
500
1000
1500
2000
2500
Number of Cycles[/]
15°C
45°C
60°C

FIG. 25

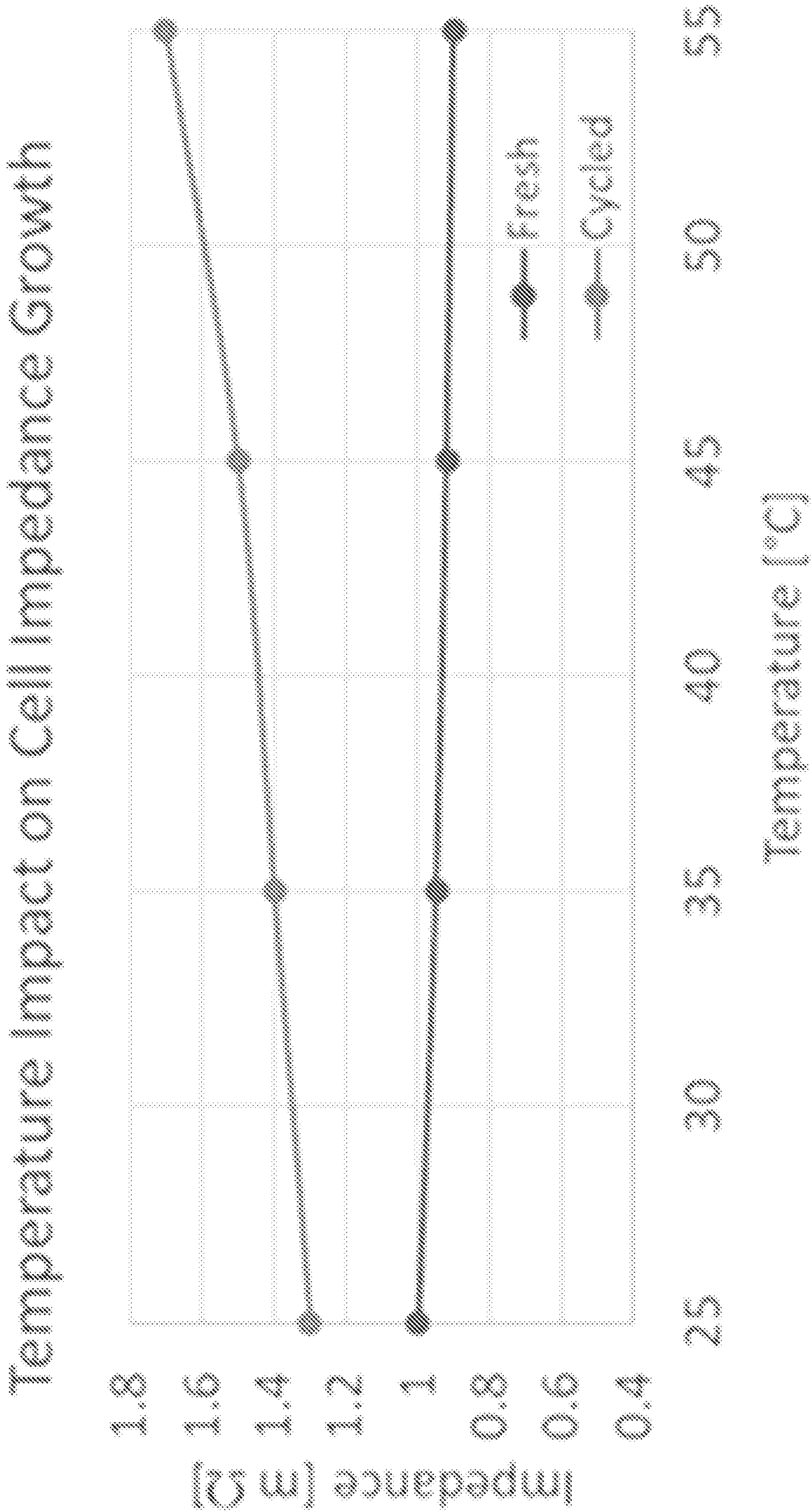
Temperature Impact on Cell Impedance Growth
Impedance [m Ω]
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
25
30
35
40
45
50
55
Temperature [°C]
Fresh
Cycled

FIG. 26

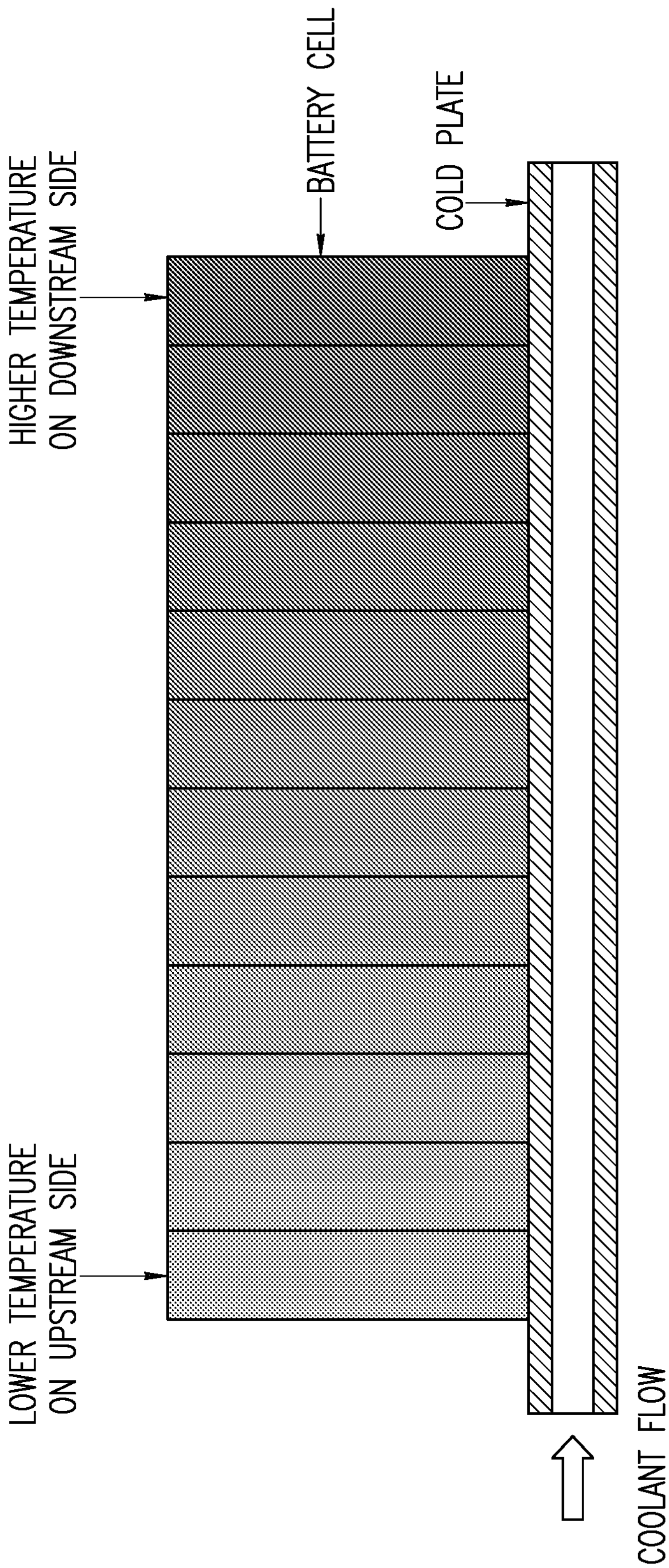
HIGHER TEMPERATURE
ON DOWNSTREAM SIDE
BATTERY CELL
COLD PLATE
LOWER TEMPERATURE
ON UPSTREAM SIDE
COOLANT FLOW

FIG. 27

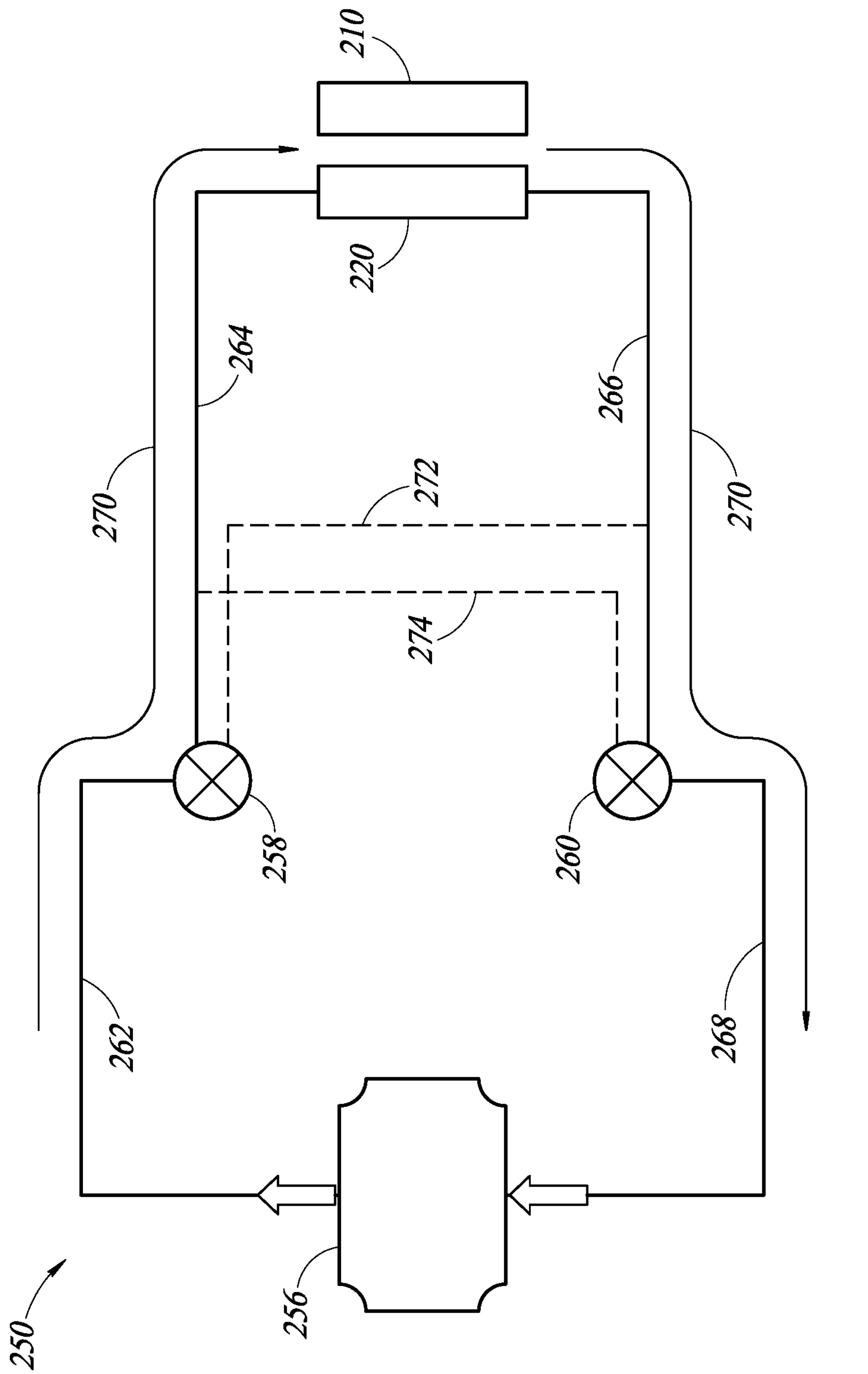

FIG. 28A

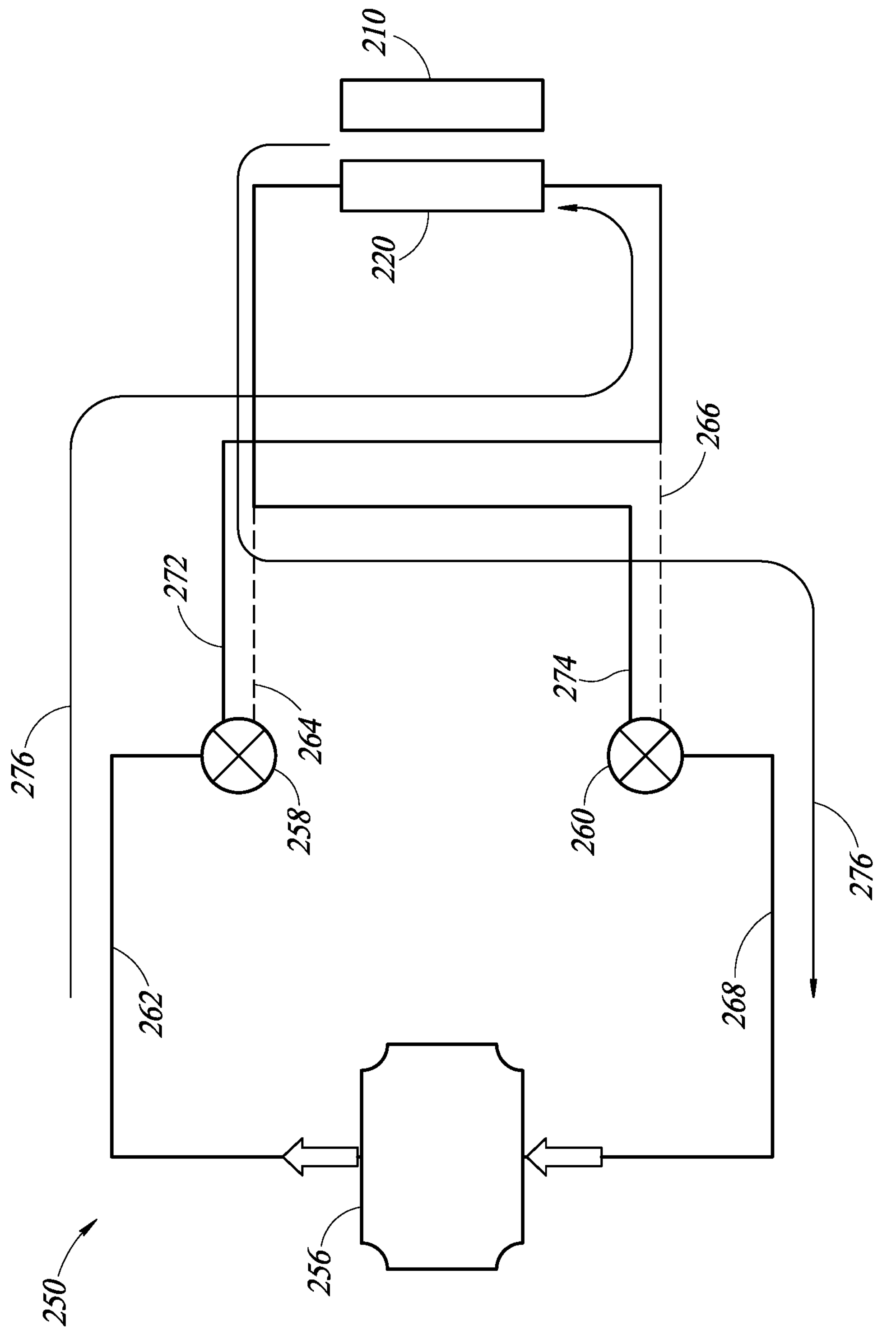

FIG. 28B

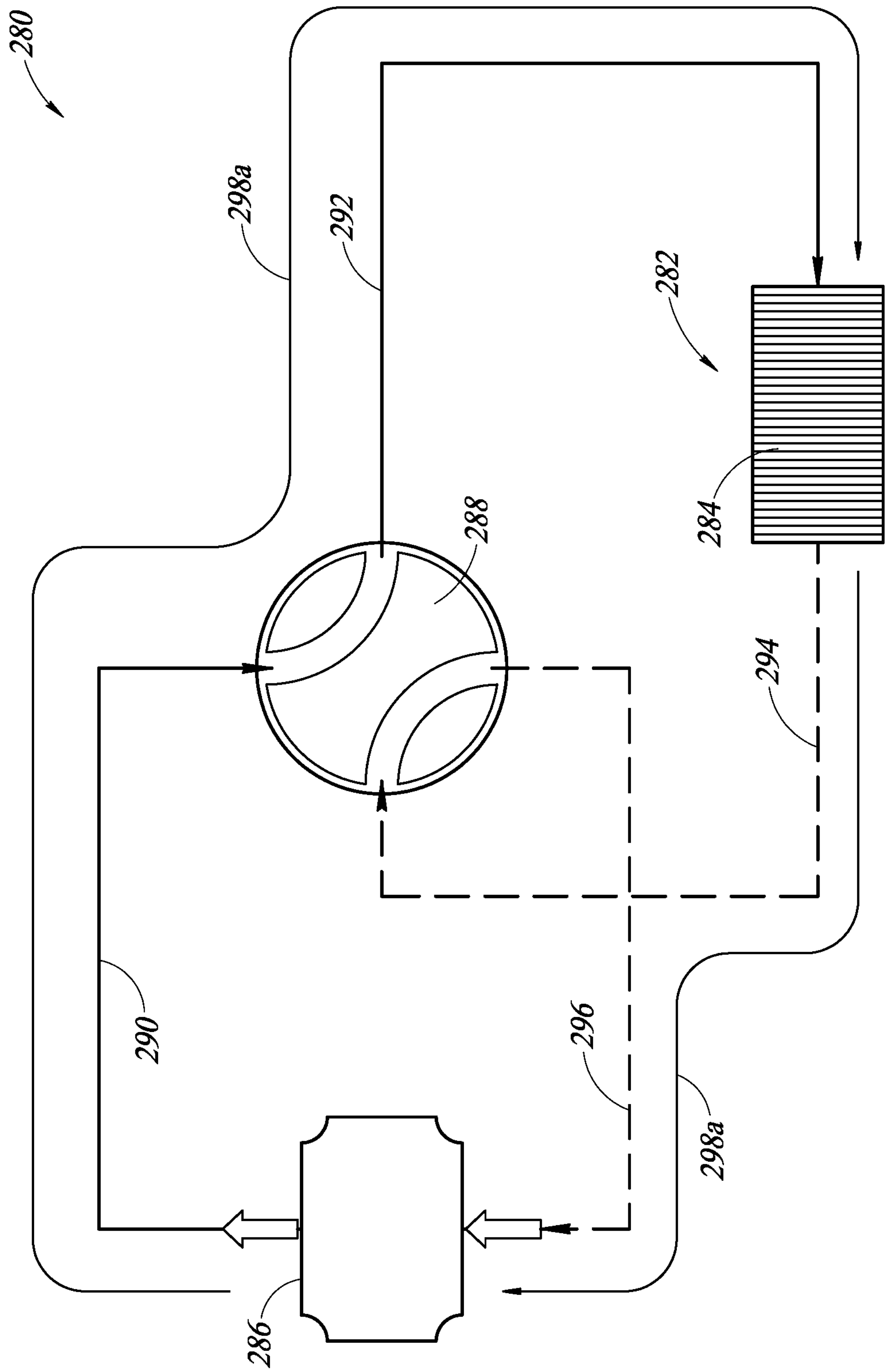

FIG. 29A

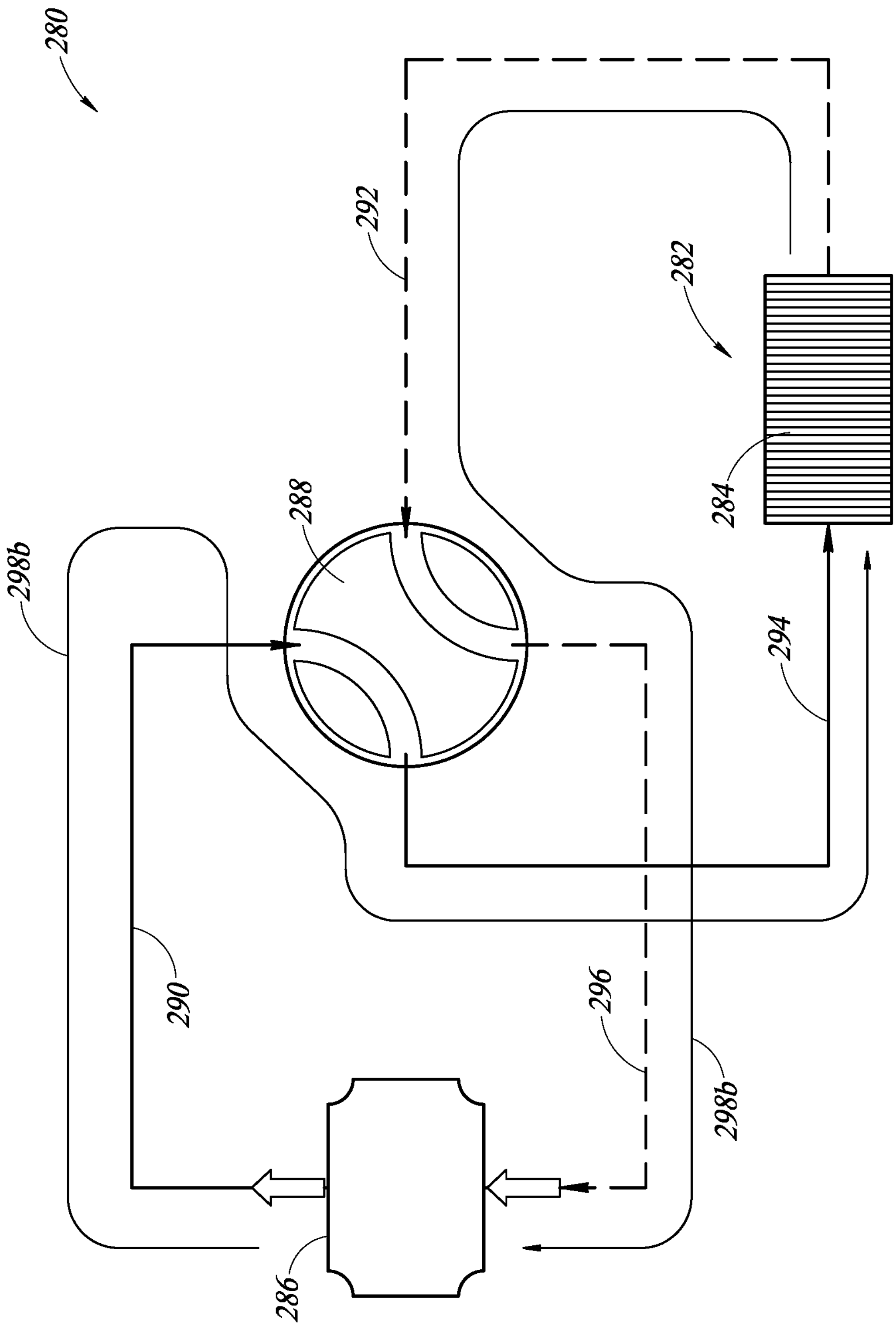

FIG. 29B

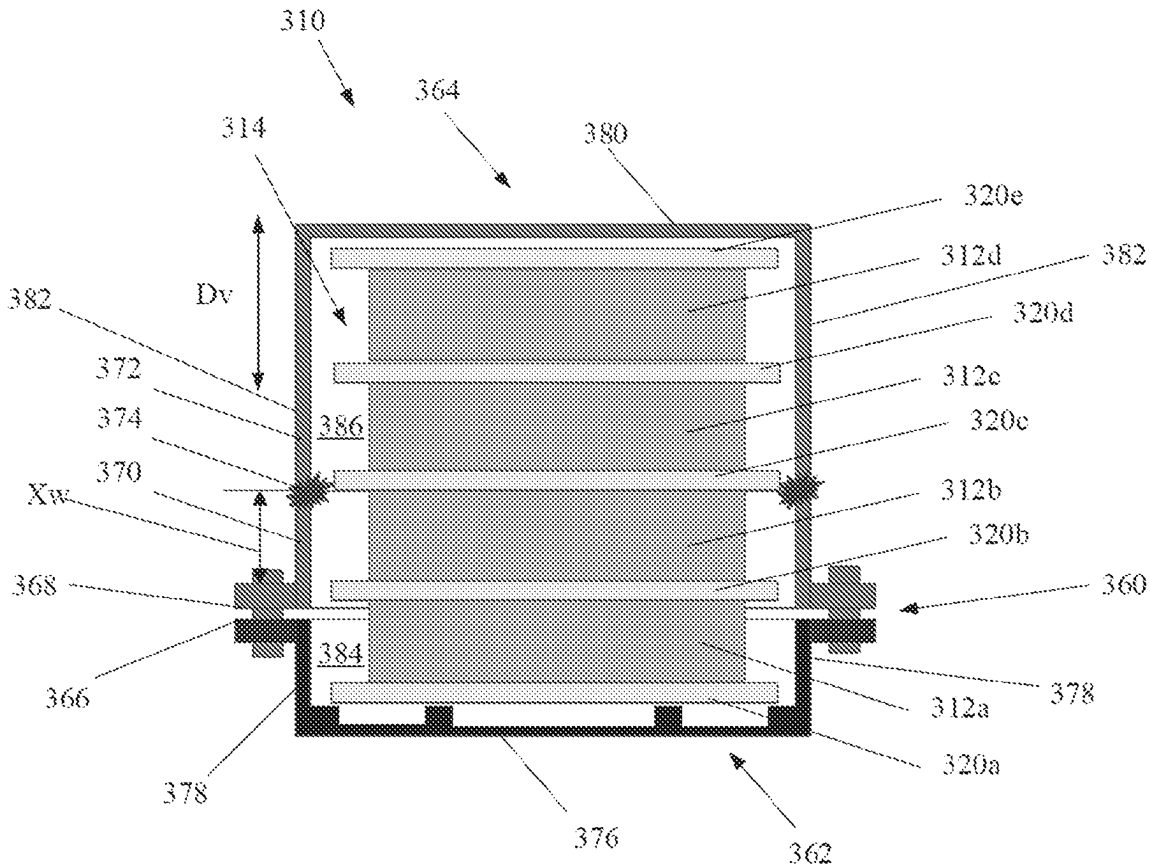
310
364
314
380
320e
312d
382
Dv
382
320d
372
312c
386
374
320c
370
Xw
312b
320b
368
360
384
366
378
312a
378
320a
376
362

FIG. 30

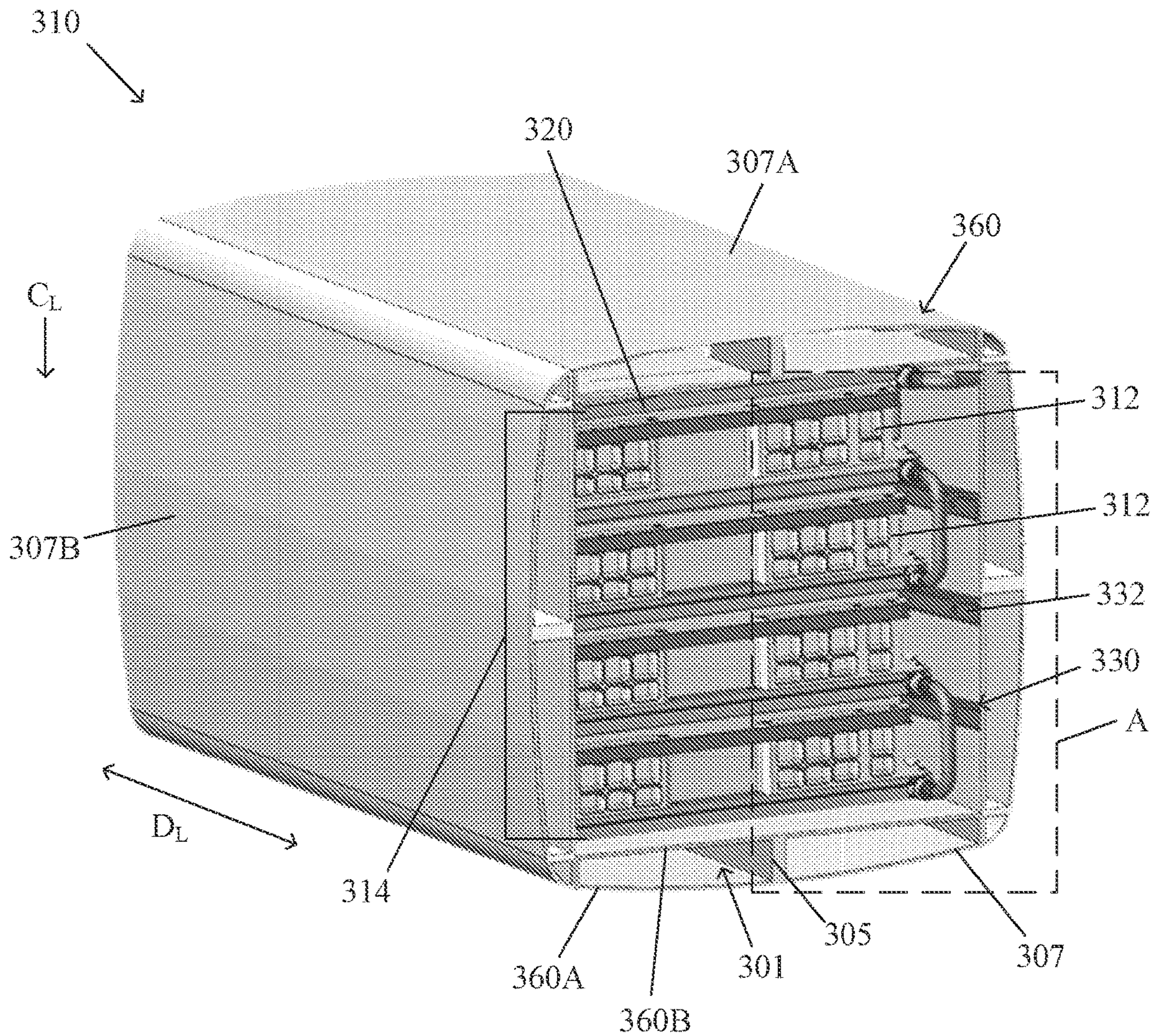
310
320
307A
360
C_L
312
312
307B
332
330
A
D_L
314
305
307
360A
301
360B

FIG. 31

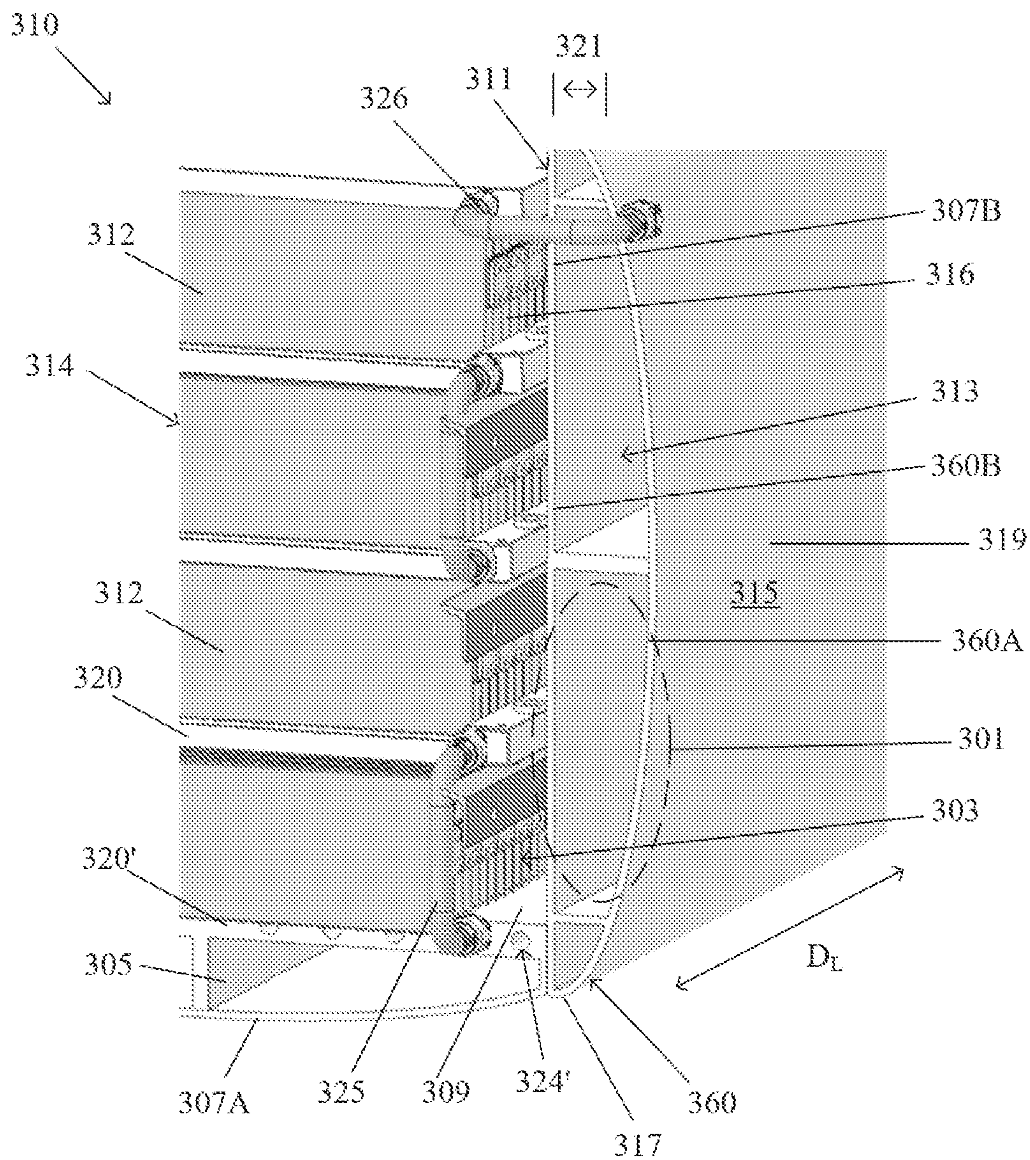
310
321
311
326
307B
312
316
314
313
360B
319
312
315
360A
320
301
303
320'
D_L
305
307A
325
309
324'
360
317

FIG. 32

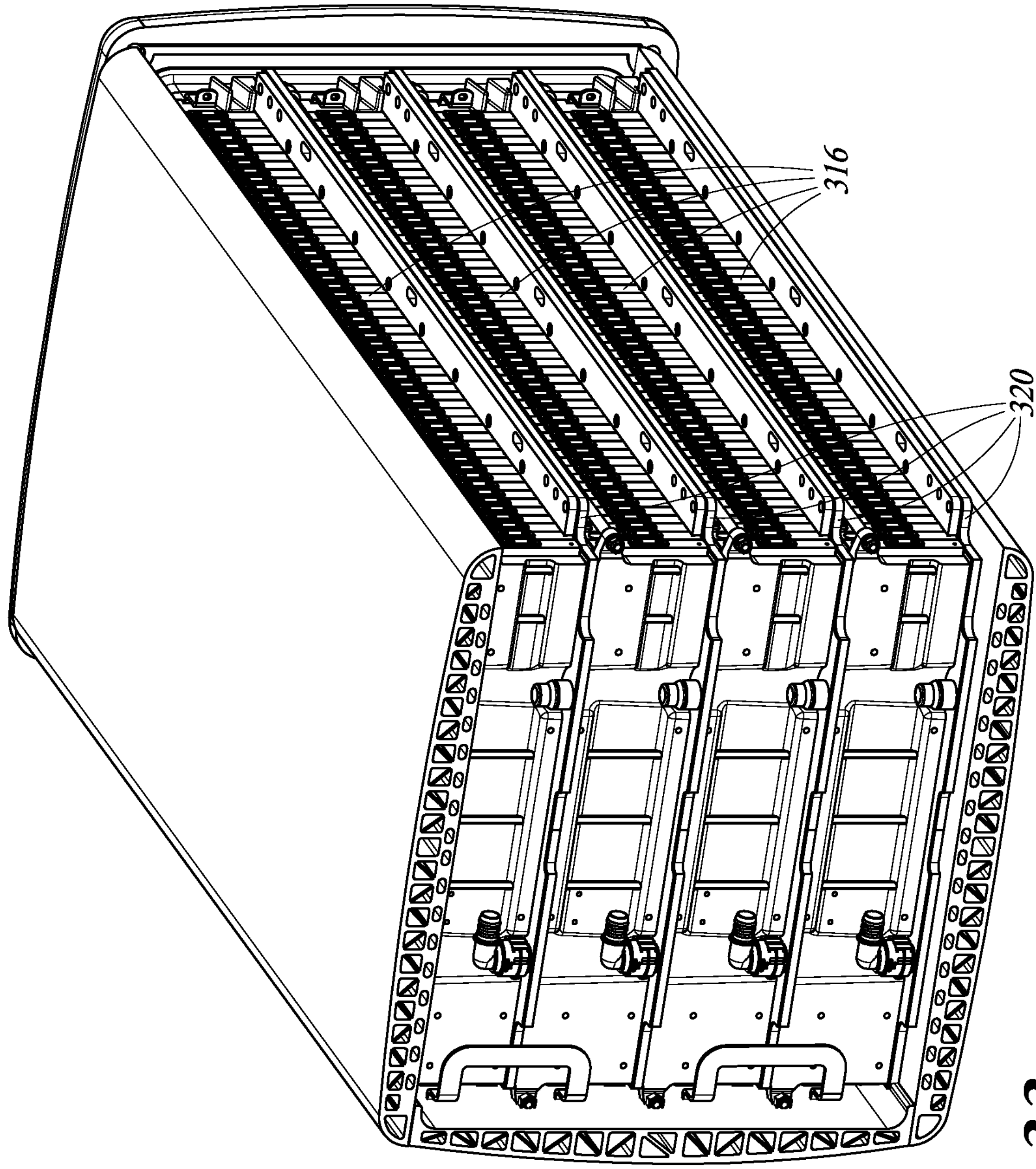

FIG. 33

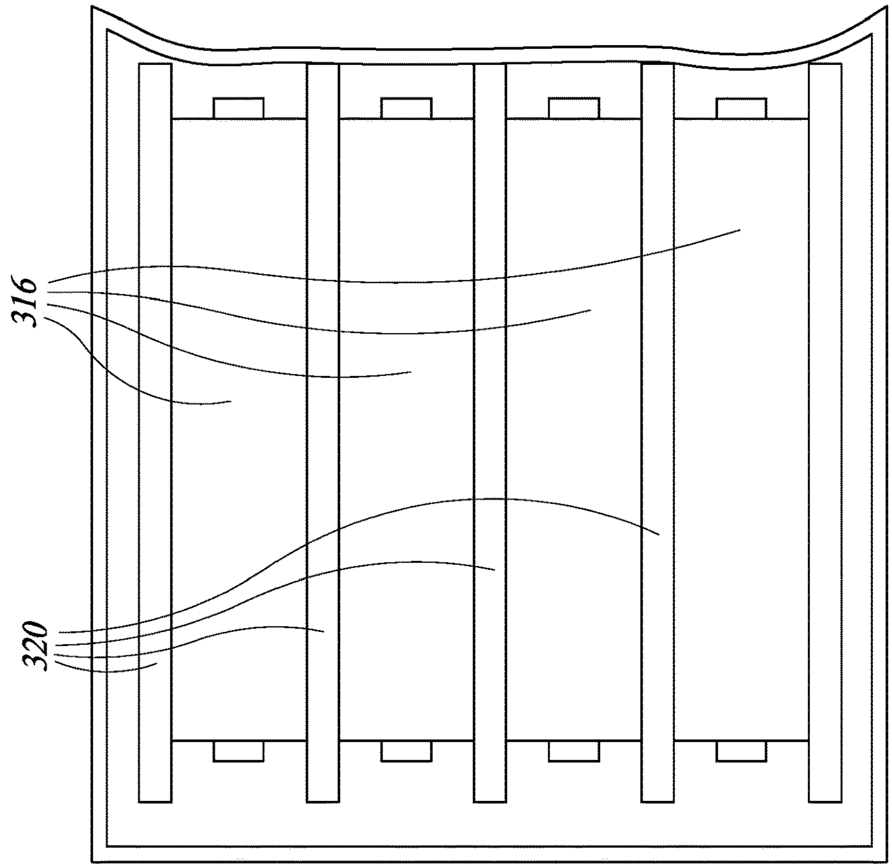

FIG. 34B

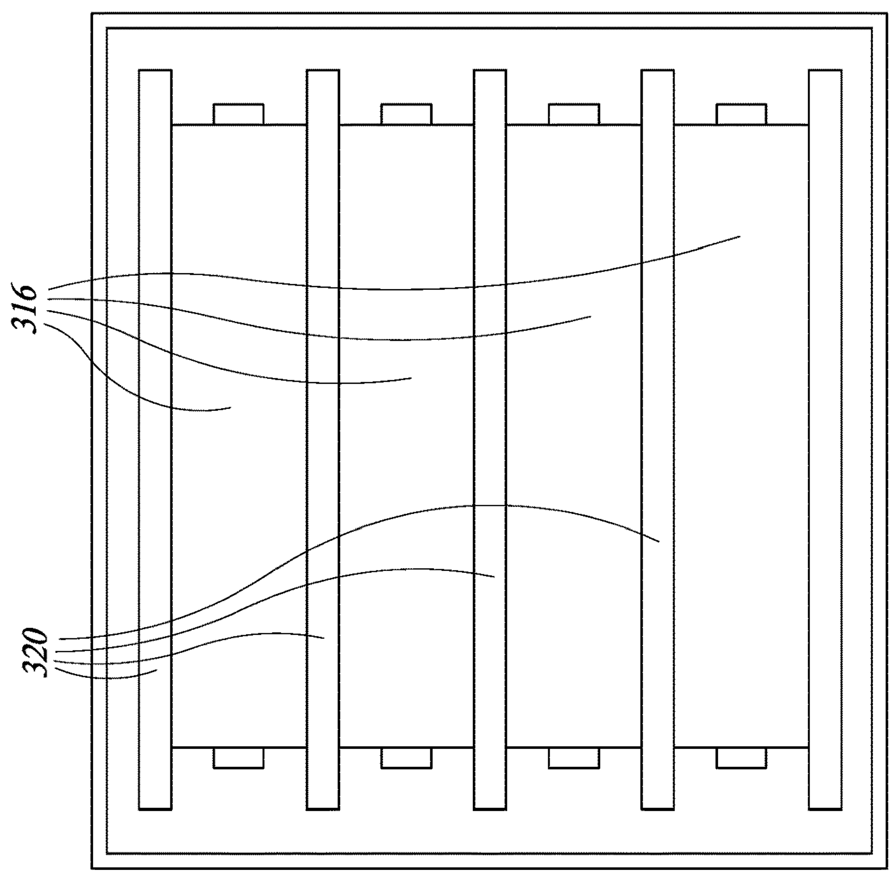

FIG. 34A

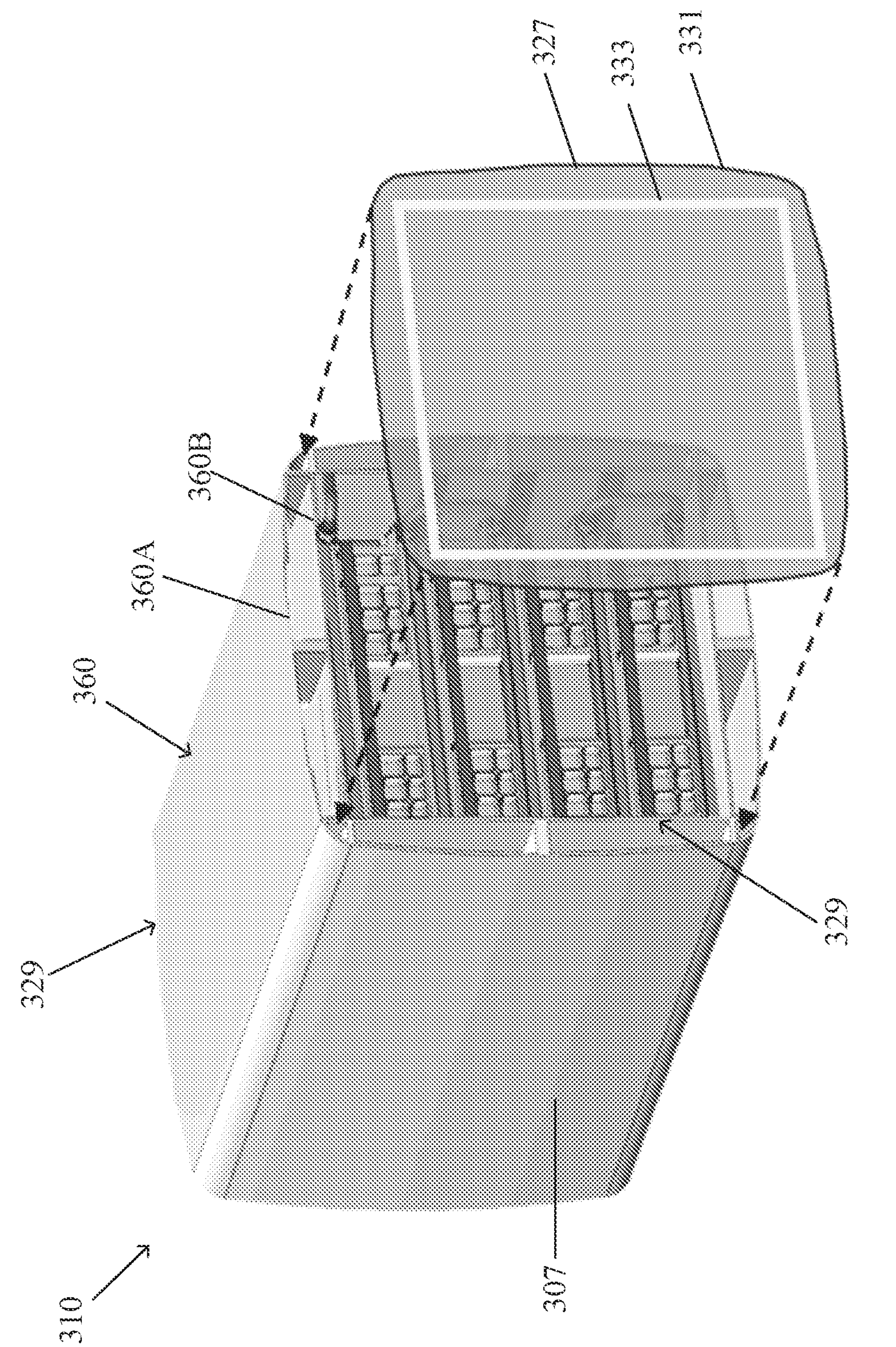

FIG. 35

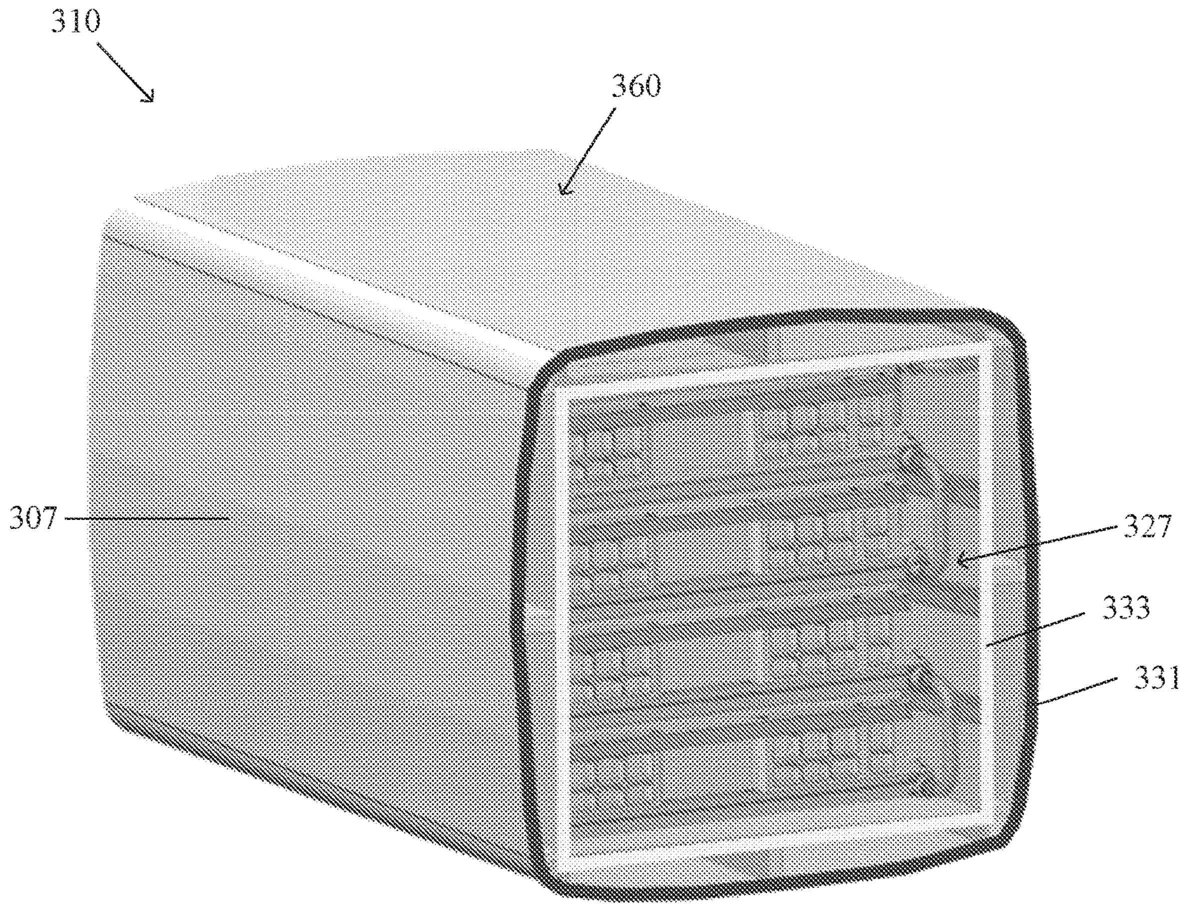

FIG. 36

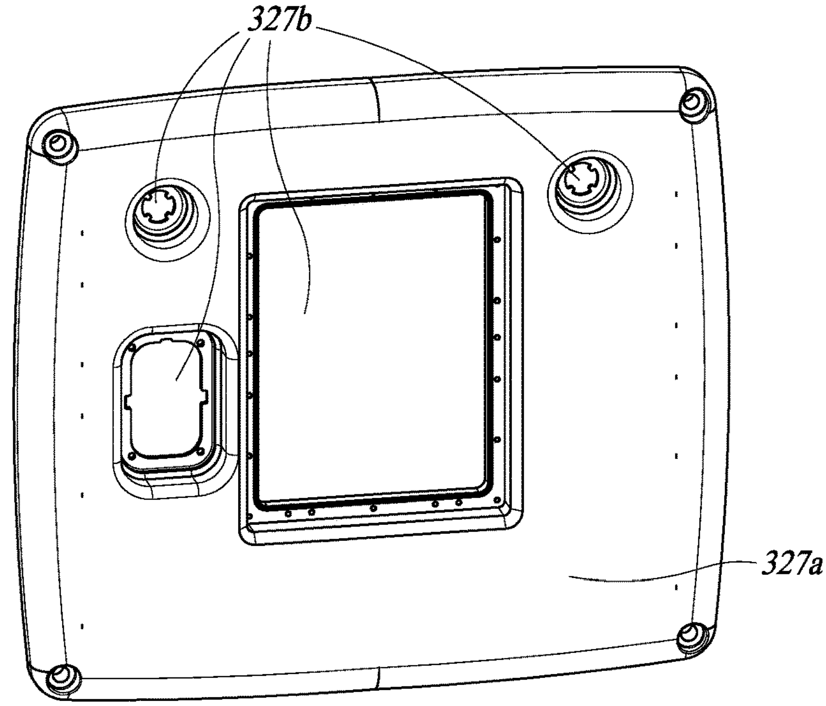

FIG. 37

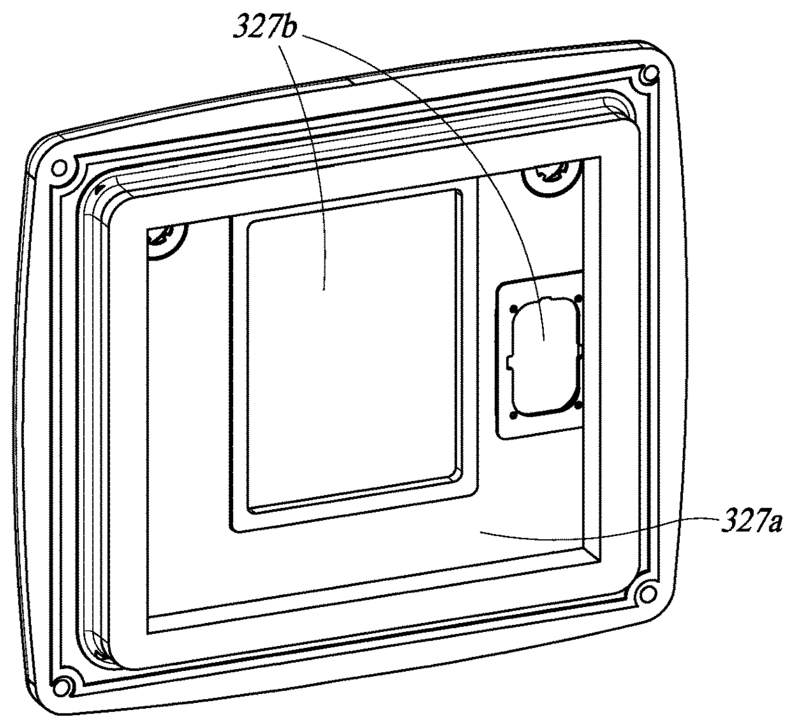

FIG. 38

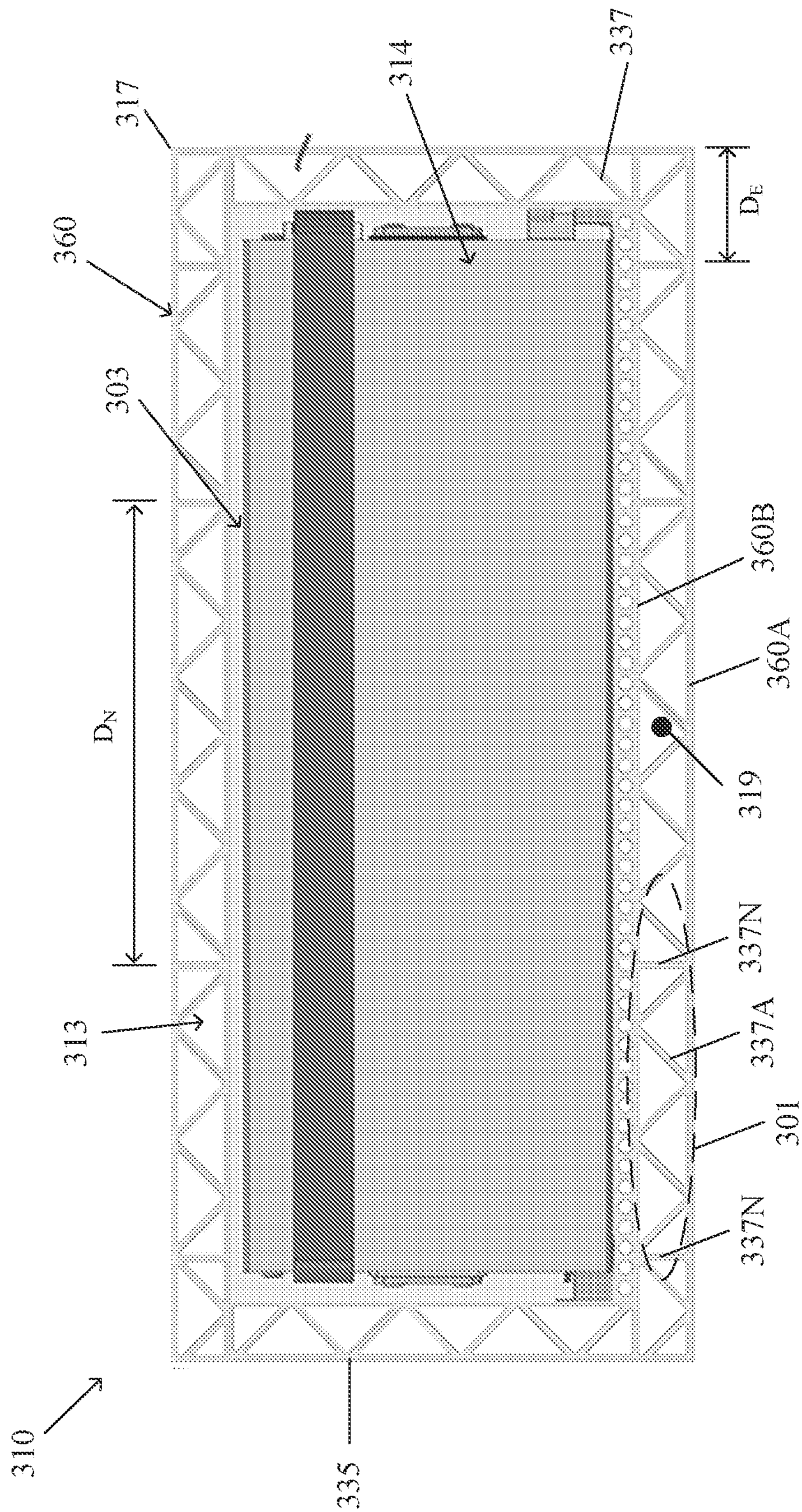
317
360
303
313
310
335
314
337
D_E
D_N
360B
360A
319
337N
337A
301
337N

FIG. 39

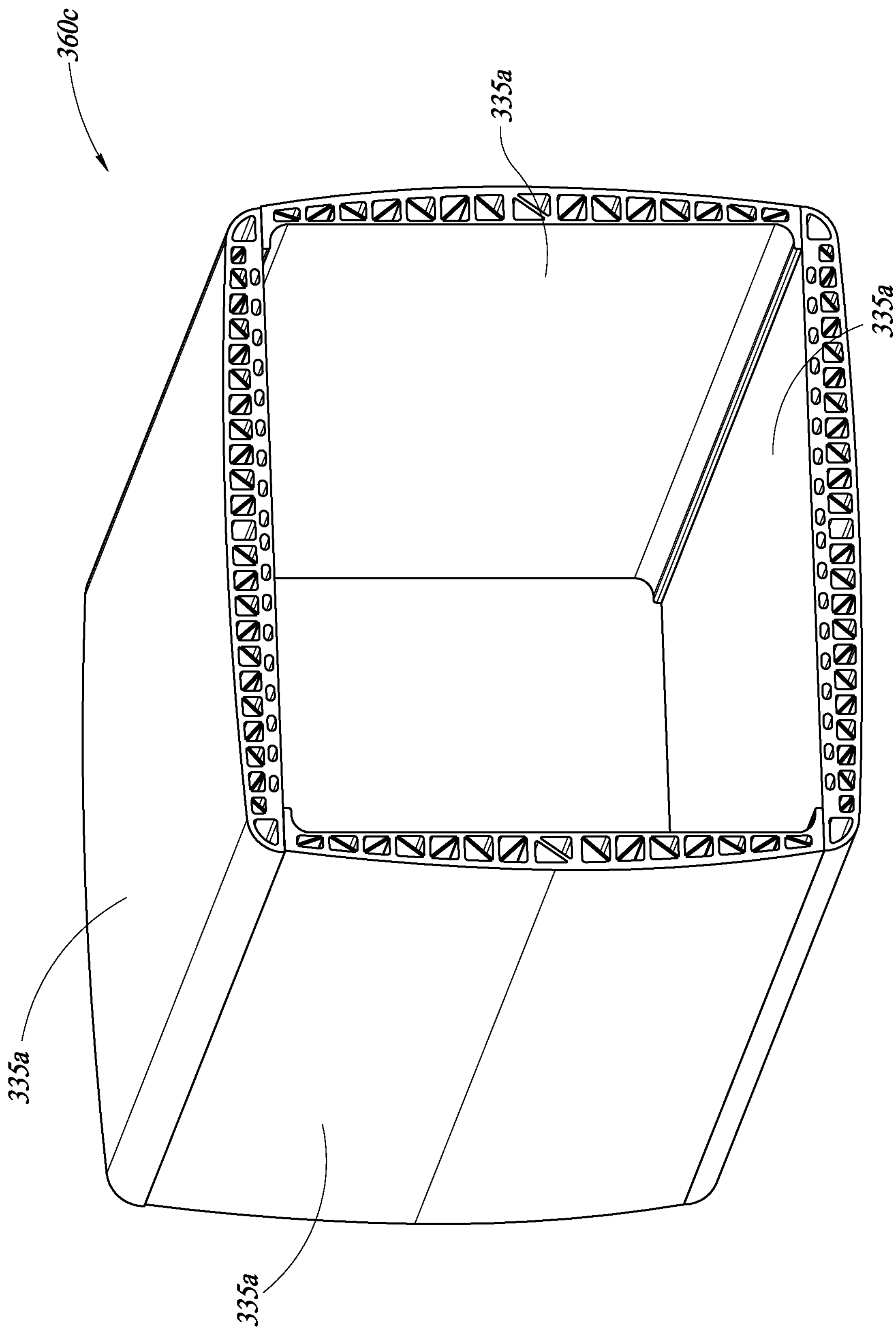

FIG. 40

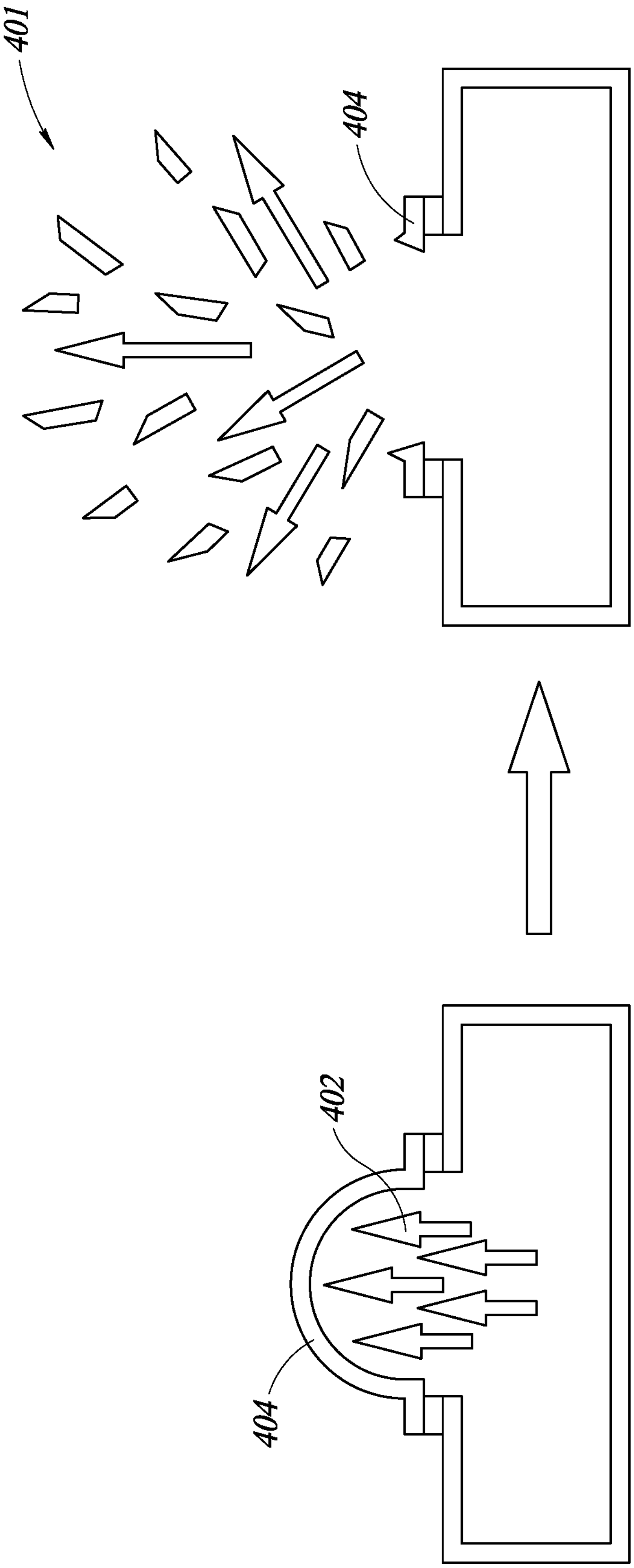

FIG. 41

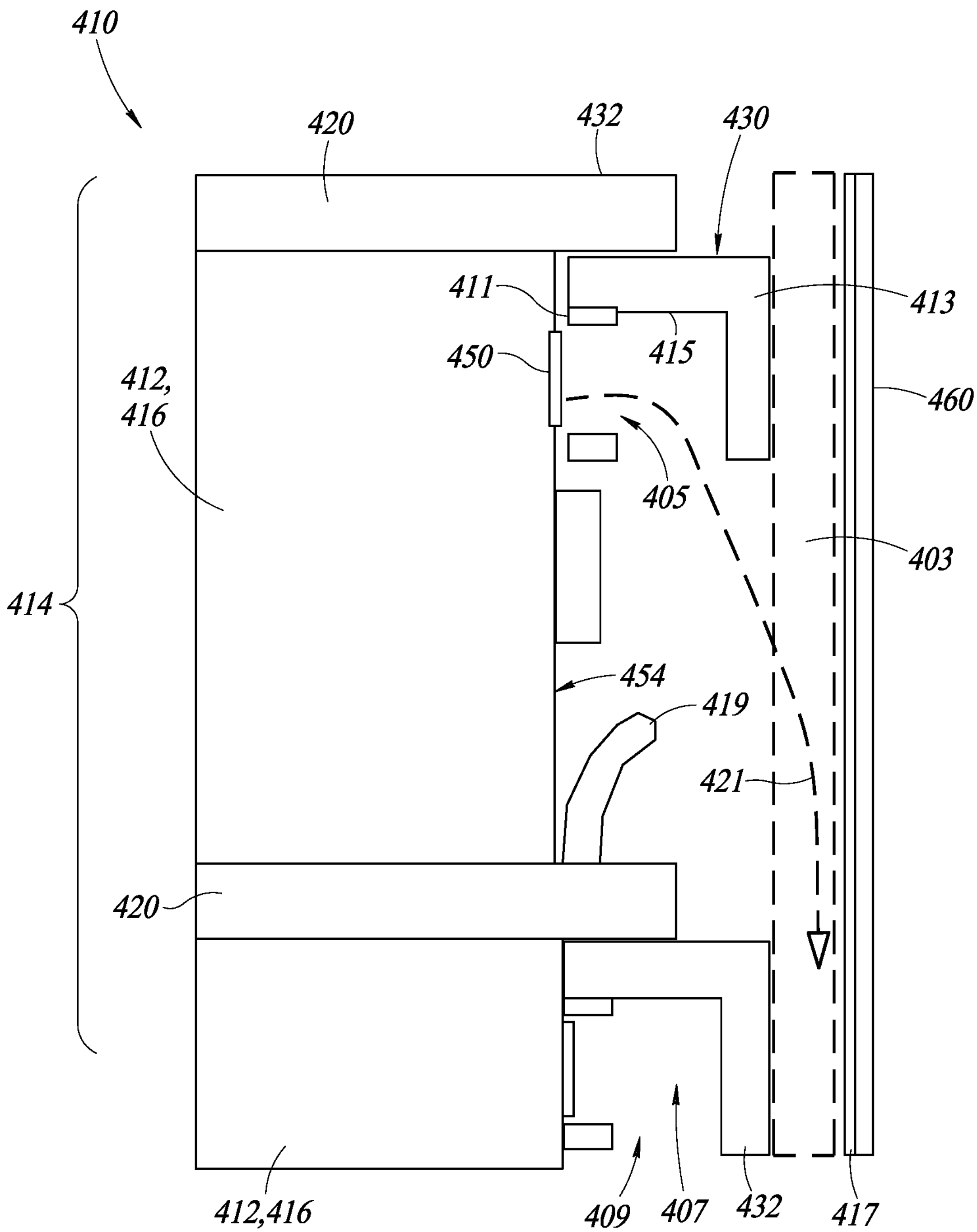
410
420
432
430
411
413
415
450
460
412,
416
405
403
414
454
419
421
420
412,416
409
407
432
417

FIG. 42

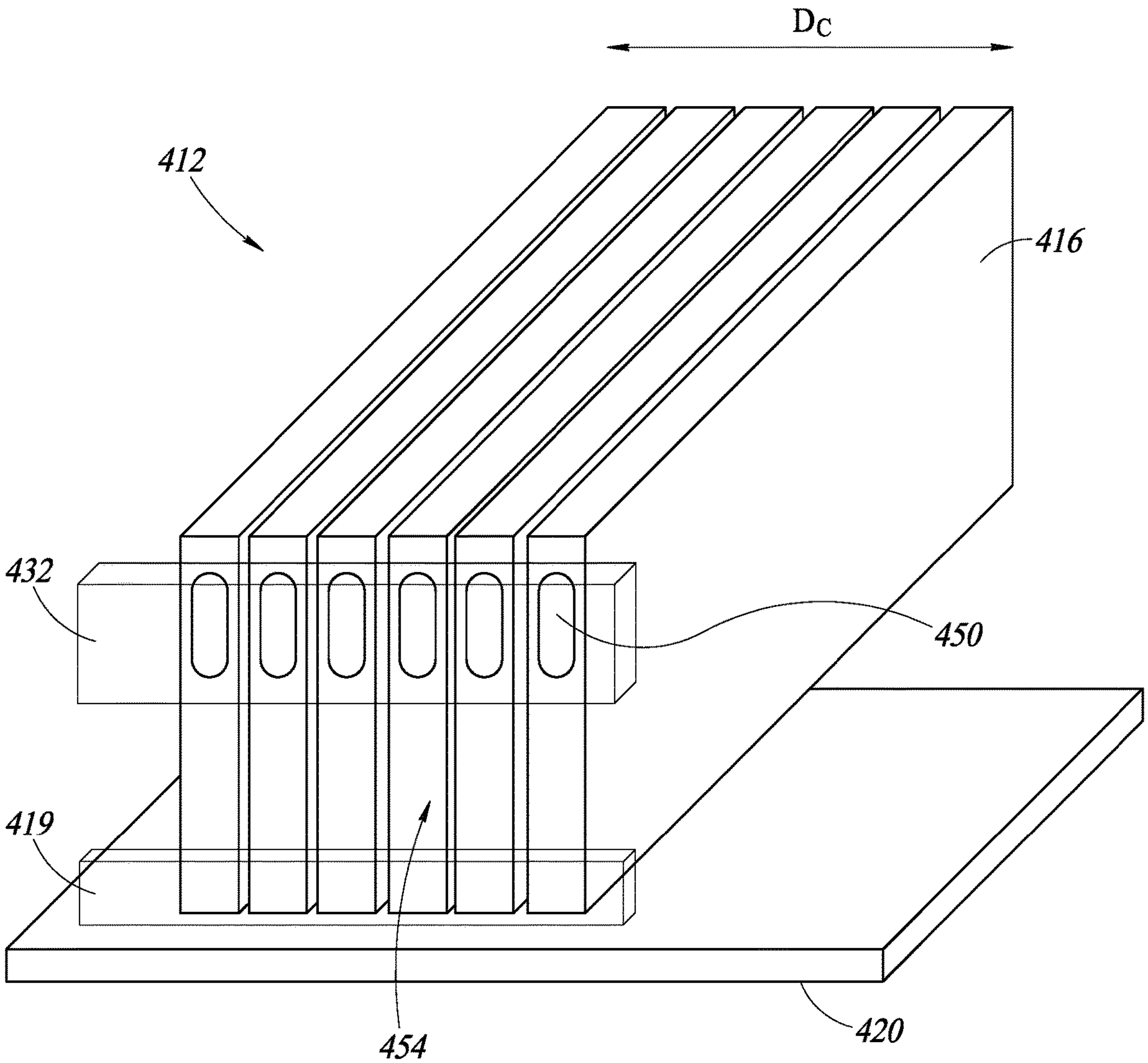

FIG. 43

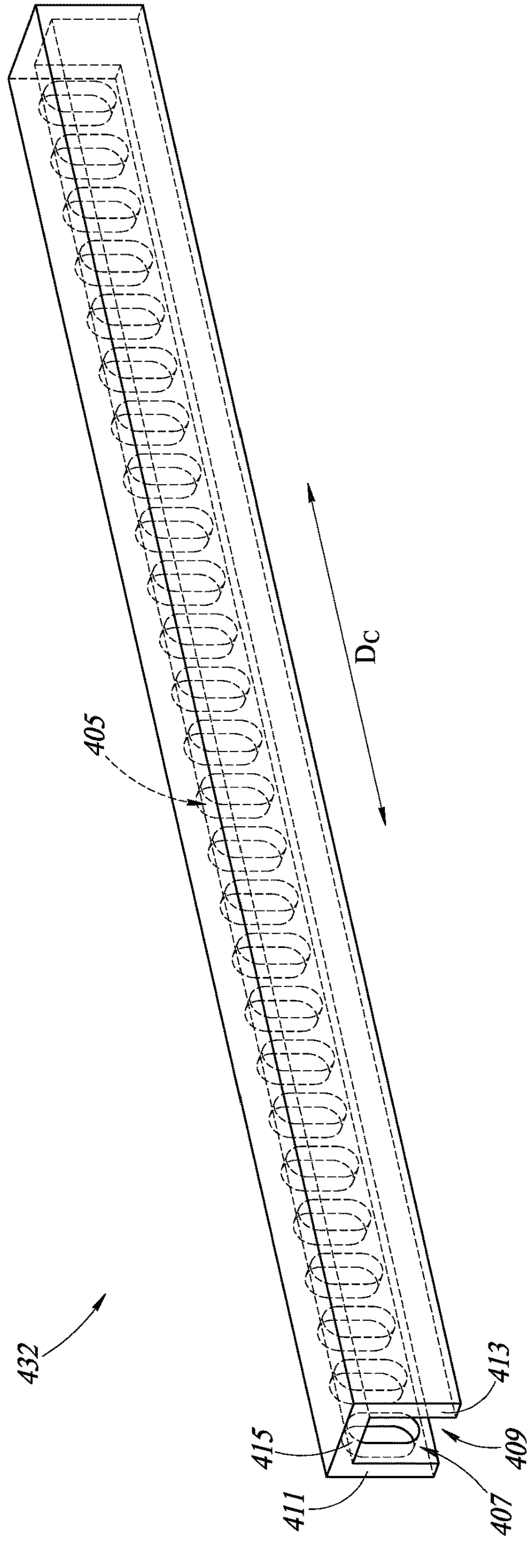

FIG. 44

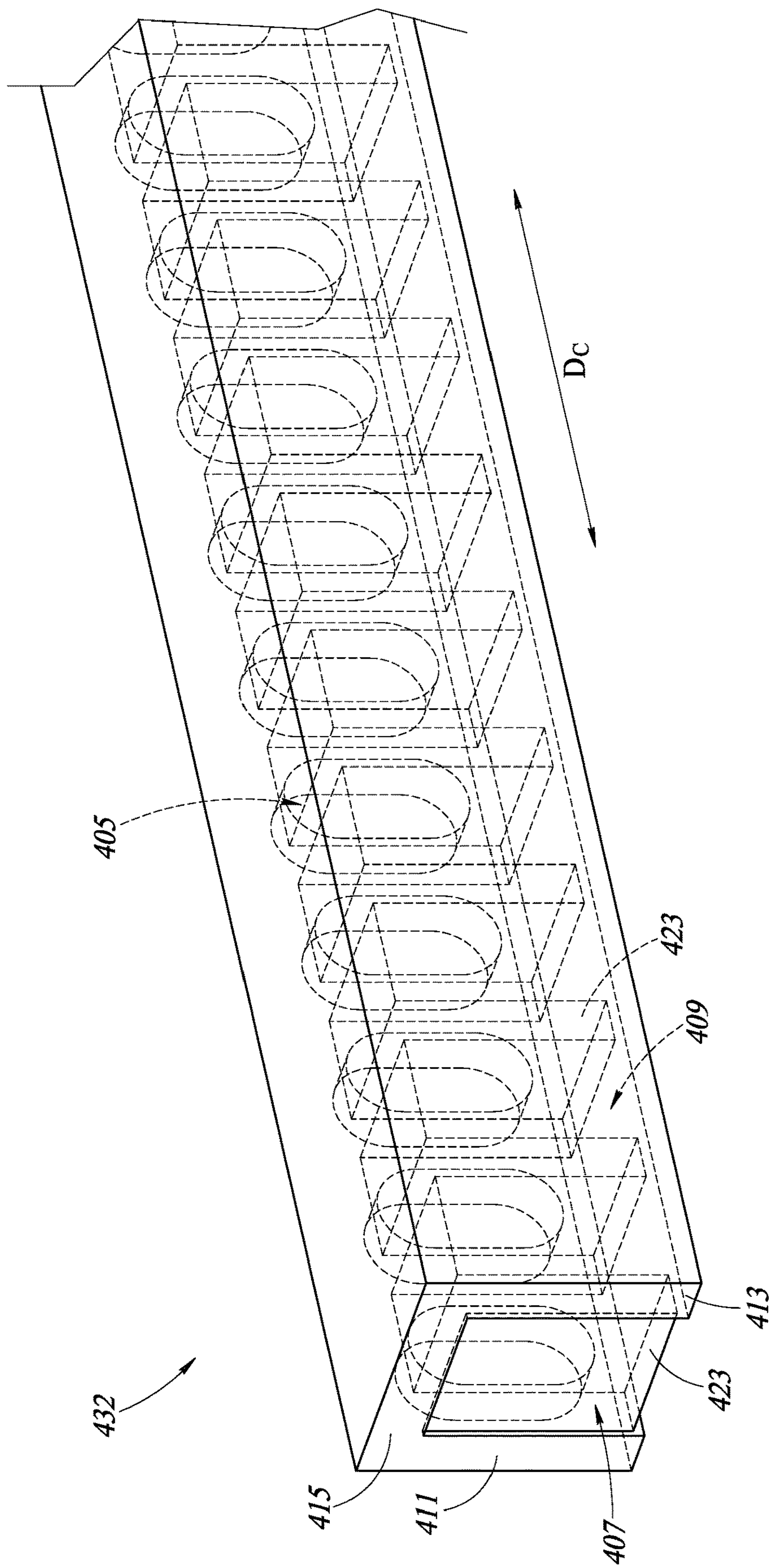

FIG. 45

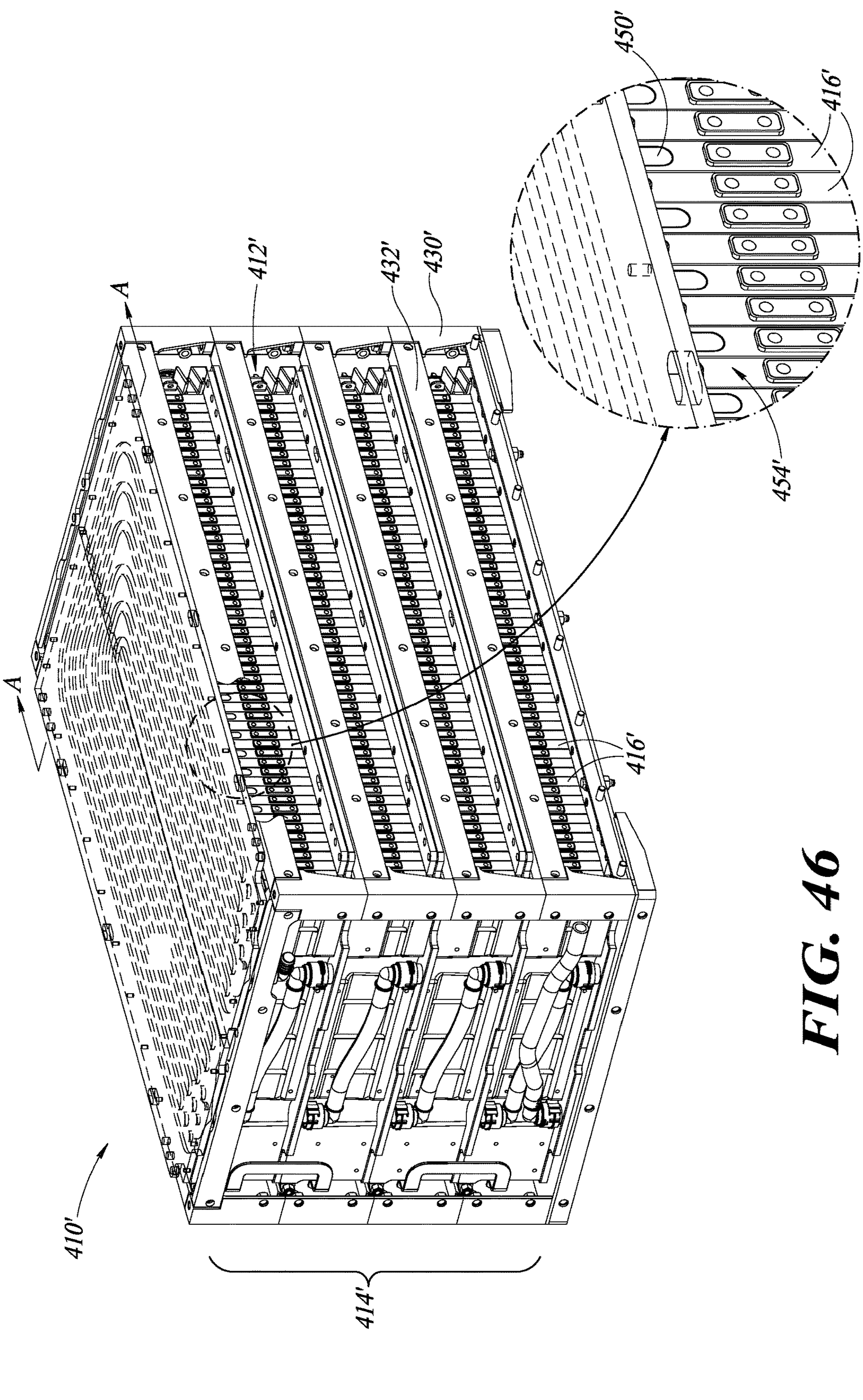

FIG. 46

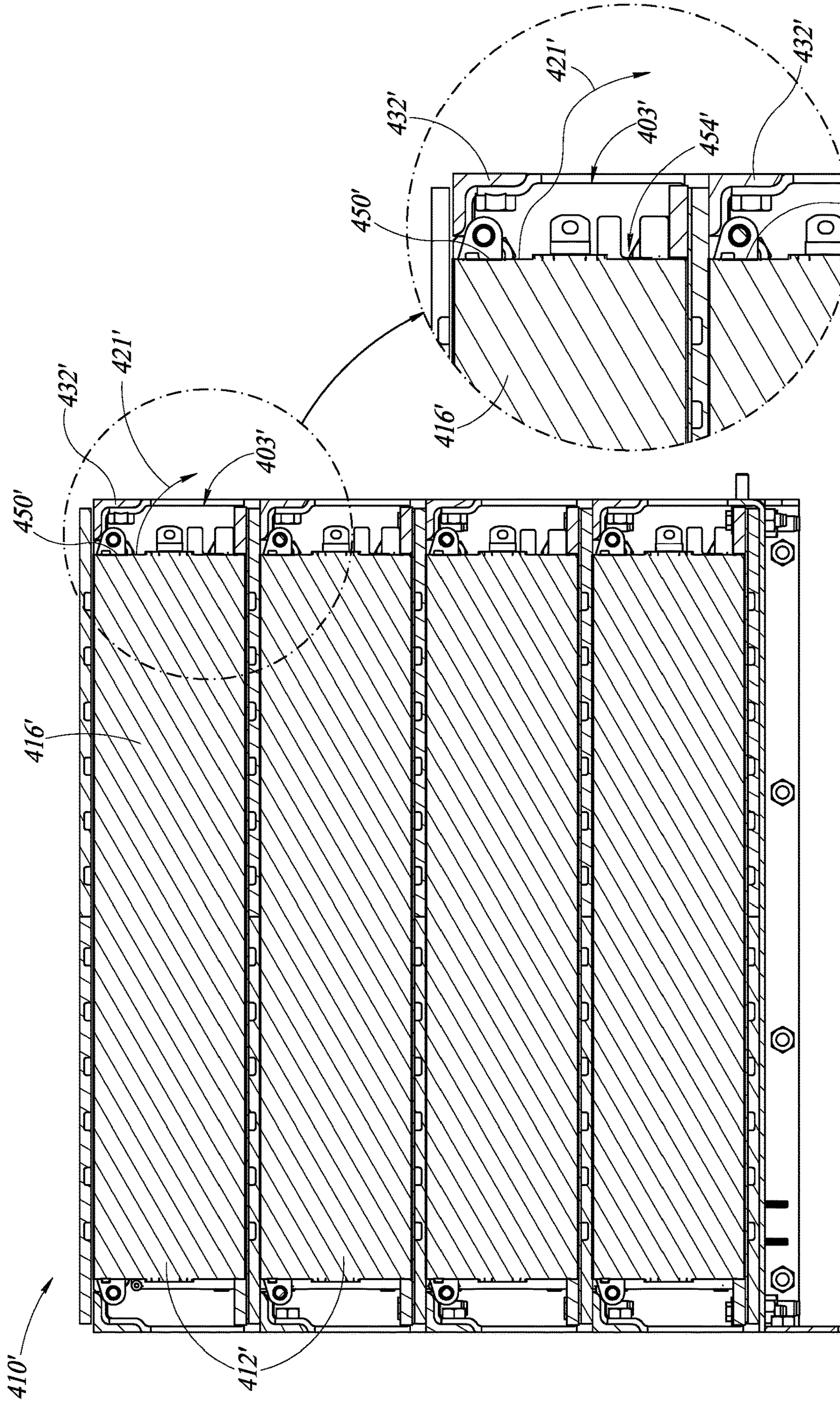

FIG. 47

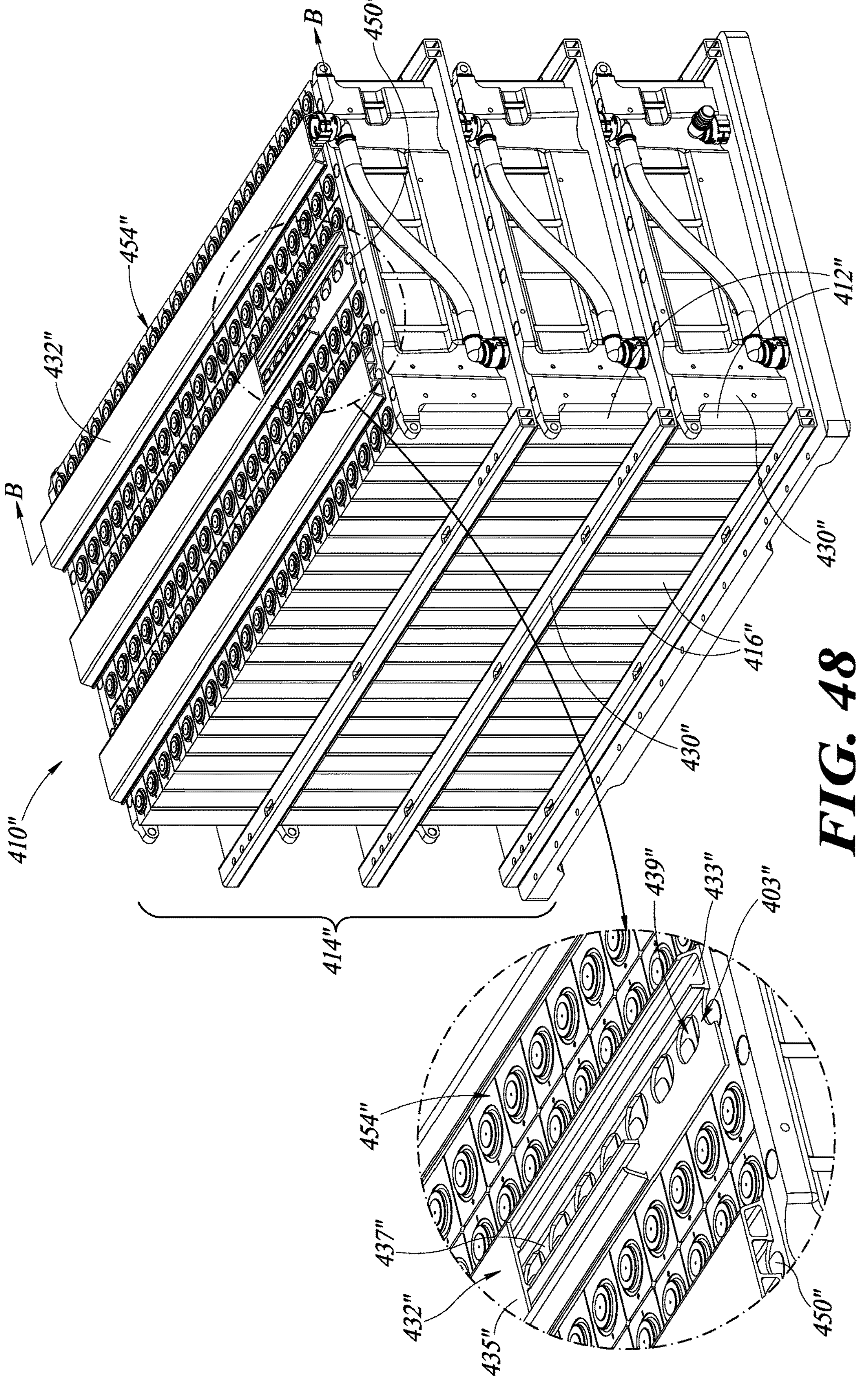
410"
432"
454"
B
B
450"
412"
430"
416"
430"
414"
439"
433"
403"
454"
437"
432"
435"
450"

FIG. 48

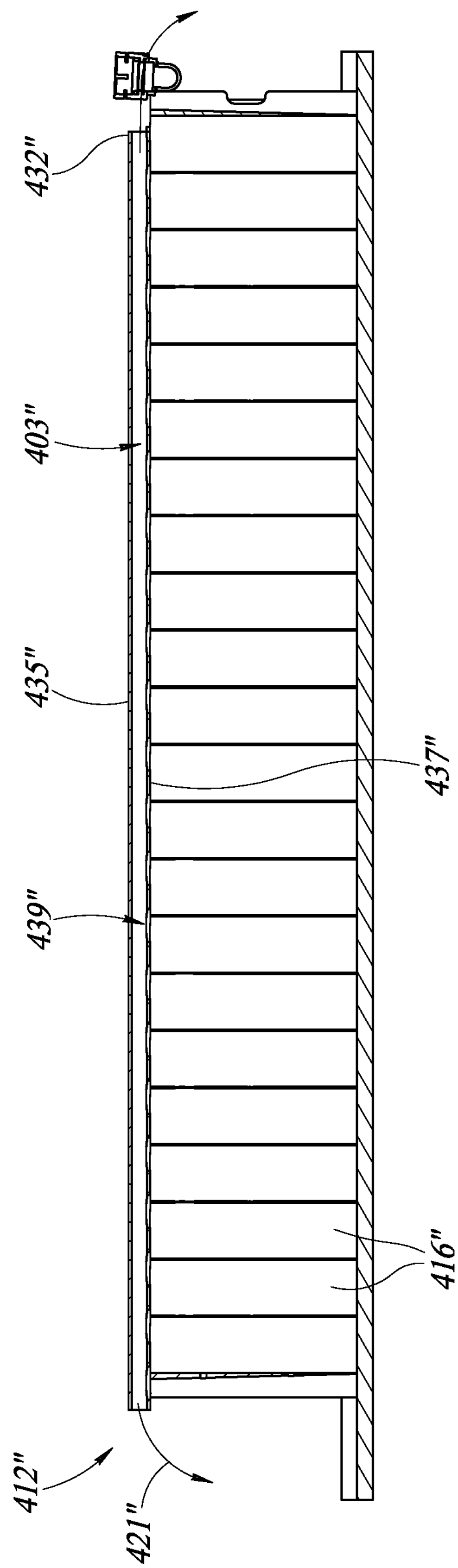

FIG. 49

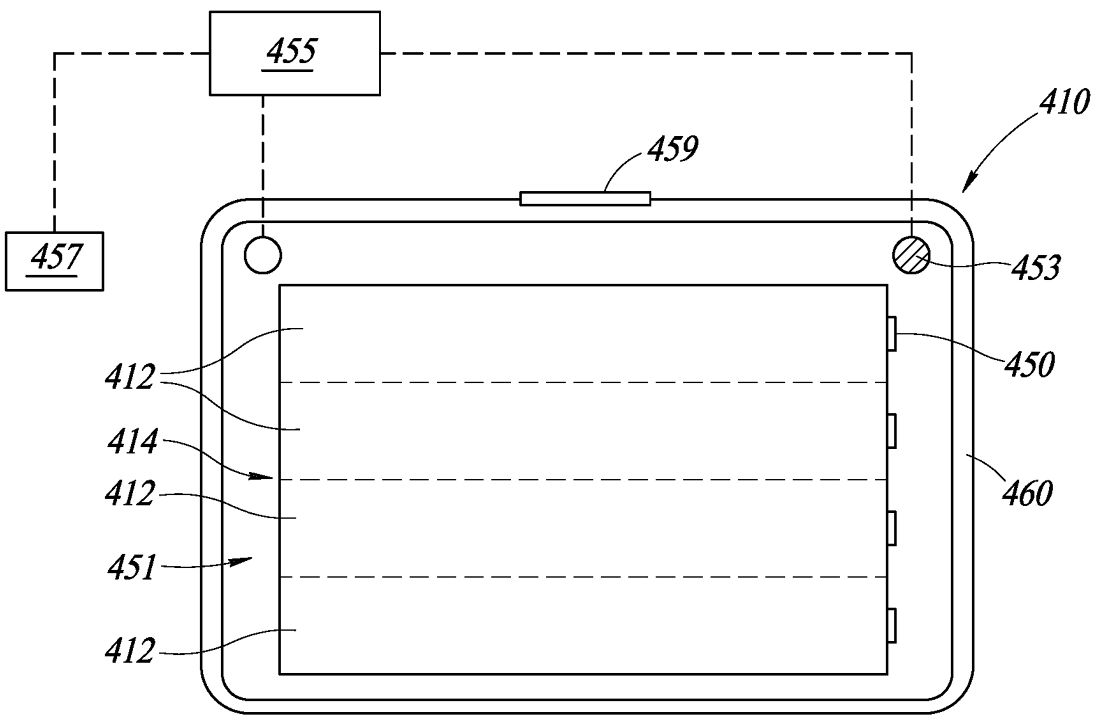

FIG. 50

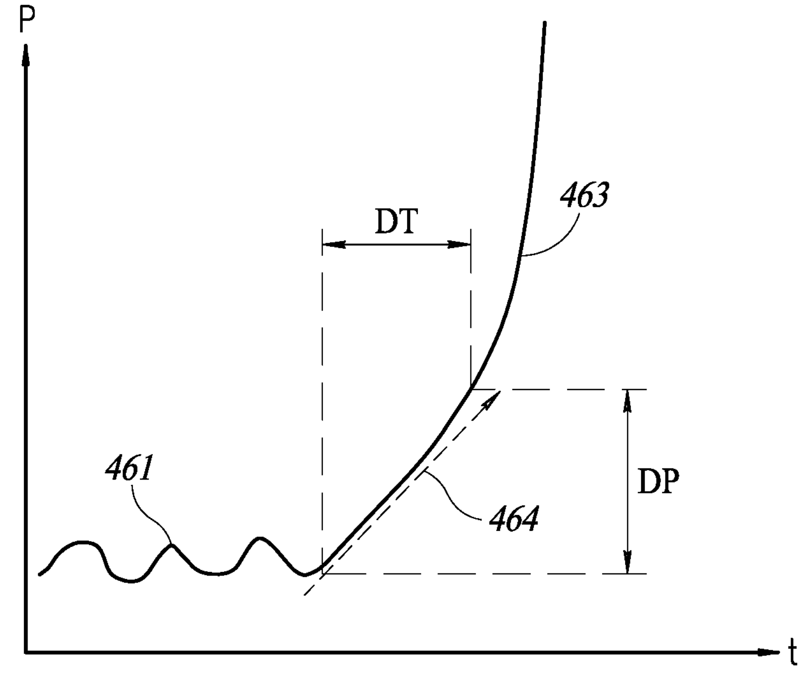

FIG. 51

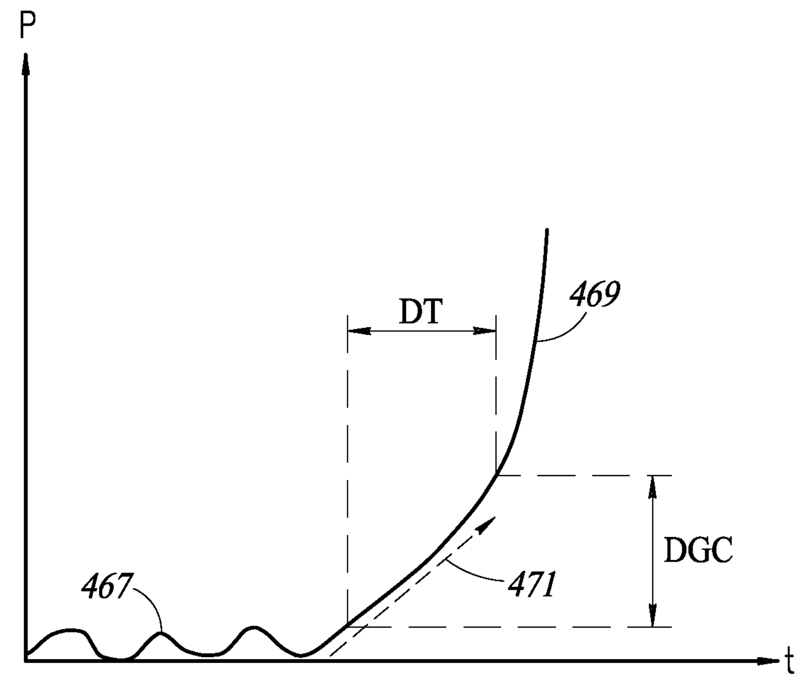

FIG. 52

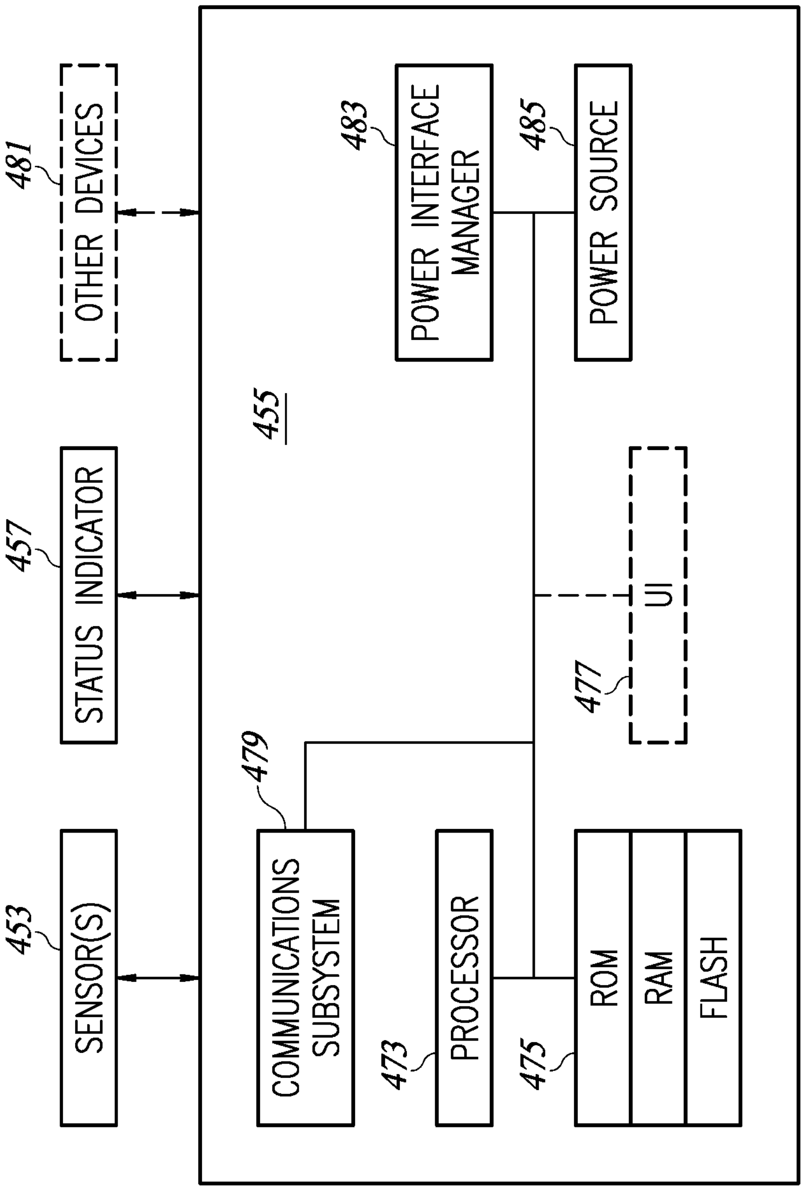
481
OTHER DEVICES
457
STATUS INDICATOR
453
SENSOR(S)
455
483
POWER INTERFACE MANAGER
485
POWER SOURCE
477
UI
479
COMMUNICATIONS SUBSYSTEM
473
PROCESSOR
475
ROM
RAM
FLASH

FIG. 53

VENT PROTECTION FOR MODULAR AND SCALABLE BATTERY PACKS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Patent Application Nos. 63/388,608, 63/388,609, 63/388,610, 63/388,612, 63/388,613, 63/388,615, 63/388,616, 63/388,618, 63/388,619, each filed on Jul. 12, 2022, the entire disclosures of which are herein incorporated by reference for all purposes.

BACKGROUND

Technical Field

[0002] The present disclosure generally relates to battery packs, such as, for example, modular and scalable battery packs to meet energy requirements of different applications including battery packs that feature multi-layer battery stacks that effectively utilize space and increase energy density of the battery packs.

[0003] The present disclosure also generally relates to internal and external aspects of battery pack form factors, such as, for example, aspects of battery cell stacks, battery pack frames, battery enclosures, and the like.

[0004] The present disclosure also generally relates to techniques for heating and cooling battery packs, including, but not limited to, heating and cooling form factors, systems, arrangements, and techniques to provide effective cooling functionality during use of the battery pack or effective heating functionality during, for example, cold starts of the battery pack.

[0005] The present disclosure also generally relates to techniques associated with battery cell and/or battery enclosure venting, including but not limited to techniques for detecting an occurrence of a battery thermal runaway event and for mitigation of venting gas and debris of the battery pack following the battery thermal runaway event.

Description of the Related Art

[0006] Electric vehicles have seen a rapid increase in popularity in recent years based on environmental concerns associated with internal combustion engines, and other factors. A known electric vehicle includes a battery to power an electric motor that is mechanically coupled to the wheels of the vehicle to generate vehicle movement via electric power provided by the battery pack. Electric vehicles range is limited by the capacity of the battery pack and the capacity of charging stations. This becomes particularly prominent for long-haul commercial vehicles.

[0007] Further, during cooling processes of a known battery, battery cells located on an upstream side of the flow of the heat exchange media can have a lower temperature than other battery cells in the battery pack, while batteries on the downstream side of the flow can have a higher temperature than other battery cells in the battery pack. This has a significant impact on battery cell capacity fade and impedance growth. The battery cells located on the downstream side are exposed to higher temperature and therefore the capacity fades more quickly. This creates a challenge for battery balancing and shortens battery life.

[0008] In addition, batteries for electric vehicles undergo temperature and pressure changes during operation that can lead to problems without proper venting. For example, if battery cells are damaged by overcharging, manufacturing defects, or other causes, the cells vent matter, such as hot gas and debris, during a thermal runaway event. The vented matter from one cell can cause other nearby cells to likewise vent matter, leading to a condition where rapidly increasing temperatures and pressures released by the cells exceed the venting capability of an enclosure around the cells. This can result in failure of the enclosure, as well as potentially more serious and dangerous outcomes such as a battery fire.

[0009] Moreover, for vehicles with various wheelbase and packaging space, a variety of battery packs need to be designed due to the limitation of the existing battery form factors. Frequently, the packaging space cannot be utilized effectively which limits the range of the vehicles.

BRIEF SUMMARY

[0010] The present disclosure is generally directed to battery packs and is particularly, but not exclusively, directed to battery packs and related battery technology for electric vehicles. The battery packs and related technology described herein may be particularly useful for implementation in commercial vehicles, including long-haul tractors, but the concepts discussed herein are not necessarily limited thereto and may be applied equally to other electric vehicles and electric vehicle batteries and related battery systems, as well as potentially other fields.

[0011] A battery pack includes a plurality of battery cells arranged in an array to form a battery module layer. Each battery cell may be a prismatic type battery cell and may have a significantly greater length than thickness. Multiple battery module layers can be stacked in a vertical arrangement with thermal management devices such as active heat exchangers in the form of battery cold plates positioned above and/or below each layer to form a multi-layer battery stack. A battery pack frame includes frame elements that may support the battery cold plates and hold the battery cold plates in compression against the battery cells provided therebetween. The battery pack frame may also apply a compressive force to the multi-layer battery stack generally to hold the battery cells in place. The multi-layer battery stack and battery pack frame are surrounded by a battery enclosure that may be provided in a number of different form factors. For example, the battery enclosure may have a multi-part construction that is joined together in a waterproof seal around the multi-layer battery stack and the frame. In some instances, the battery enclosure may be an at least two-part shell that defines crumple zones to protect the multi-layer battery stack.

[0012] The battery cold plates in the battery pack enable heating and cooling of the battery cells via communication with a thermal management system that feeds a heat transfer medium through internal passages of the cold plates. The thermal management system may include valves or other devices for periodically reversing a direction of flow of the heat transfer medium to assist in balancing a temperature between battery cells located at the upstream and downstream ends of the heat transfer medium path. The battery pack may also include one or more vent detection sensors in the form of a pressure sensor and/or a gas sensor to detect whether a thermal runaway event (i.e., a venting event) has occurred with one or more of the battery cells. Upon detection of the thermal runaway event, the one or more sensors may provide instructions, signals, or data to a status indicator to provide at least one warning indication to a user, such as an occupant and/or driver of the vehicle.

[0013] In some embodiments, the frame members of the battery pack frame have integrated vent isolation functionality to mitigate the effects of a thermal runaway event associated with one or more of the cells. Alternatively, vent isolation functionality may be provided by vent isolators that are separate structures coupled to the frame and in communication with the battery cells. During a thermal runaway event, the vent isolators direct the discharged matter, which may be hot gas and entrained debris, away from the battery cells and towards a debris collection space. The vent isolators prevent the discharged matter from one cell from reaching a vent of an adjacent cell to mitigate damage to adjacent vents. The battery pack may also include one or more dams protecting the battery cells to further mitigate damage thereto during a thermal runaway event.

[0014] Multiple battery packs can be combined in parallel in different arrangements to increase electric vehicle range while also being positionable to optimize weight distribution for different vehicles. The multiple layers of the multi-layer battery stack utilize available space effectively and increase energy density. The battery packs may be associated with a centralized heating and cooling system, or distributed heating and cooling systems, or a combined arrangement (e.g., centralized cooling, distributed heating) to further improve thermal performance. The battery packs may be associated with a centralized battery management system (BMS) for providing centralized monitoring and control functionality for the common battery packs; or a master-slave battery management system (BMS) for providing distributed monitoring and control functionality. Furthermore, the battery packs may be associated with a centralized charging system comprising a single charger for charging the battery packs; or a distributed charging system comprising a plurality of chargers for charging the battery packs. In addition, the modular nature of the battery packs significantly reduces maintenance downtime and potential charging downtime because packs can be switched out without negatively impacting the entire battery pack system.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

[0015] The present disclosure will be more fully understood by reference to the following figures, which are for illustrative purposes only. These non-limiting and non-exhaustive embodiments are described with reference to the following drawings, wherein like labels refer to like parts throughout the various views unless otherwise specified. The sizes and relative positions of elements in the drawings may not necessarily be drawn to scale in some figures. The figures do not describe every aspect of the teachings disclosed herein and do not limit the scope of the claims.

[0016] FIG. **1** is a top plan view of a chassis of a commercial vehicle including an arrangement of common battery packs secured to the chassis.

[0017] FIG. **2** is a perspective view of one of the battery packs of the commercial vehicle of FIG. **1**.

[0018] FIG. **3** shows a cross-sectional view of the battery pack of FIG. **2**.

[0019] FIG. **4** is an enlarged detail view of the cross-section of the battery pack of FIG. **3**.

[0020] FIG. **5** is a perspective view of a battery module layer of the battery pack.

[0021] FIG. **6** is a perspective view of a multi-layer battery stack comprising a plurality of the battery module layers of FIG. **5** stacked together.

[0022] FIG. **7** is a perspective view of an example embodiment of a battery cell of the battery packs.

[0023] FIG. **8** is a perspective view of another example embodiment of a battery cell that may be used in connection with the battery packs disclosed herein.

[0024] FIG. **9** is a perspective view of another embodiment of a battery pack for a commercial vehicle with a battery pack enclosure omitted to reveal underlying details of the battery pack.

[0025] FIG. **10** is another perspective view of the battery pack of FIG. **9**.

[0026] FIG. **11** is a perspective view of a battery module layer of the battery pack of FIG. **9**.

[0027] FIG. **12** is a perspective view of battery module layers of another embodiment of a multi-layer battery stack.

[0028] FIG. **13** is a perspective view of components of the multi-layer battery stack of FIG. **12** with cutaway portions to reveal internal passages thereof.

[0029] FIG. **14** are top plan views of the chassis of a collection of commercial vehicles having different vehicle attributes (e.g., wheelbase) showing different arrangements of battery packs secured thereto to optimize vehicle power and vehicle range of each commercial vehicle.

[0030] FIG. **15** is a perspective view showing an alternative configuration of a battery pack.

[0031] FIG. **16** is a perspective view showing another alternative configuration of a battery pack.

[0032] FIG. **17** shows a sequence of assembling sub-modules of battery cells together to form a battery module layer of a battery stack.

[0033] FIG. **18** shows another sequence of assembling sub-modules of battery cells together to form battery module layers of a battery stack.

[0034] FIG. **19** shows an assembly of sub-modules of battery cells together between opposing cold plates of a battery stack.

[0035] FIG. **20** shows a sequence of assembling a sub-module of battery cells together using a sub-module bracket.

[0036] FIG. **21** shows battery cells being installed on a thermal management device in the form of an active heat exchanger or, more specifically, a battery cold plate.

[0037] FIG. **22** shows the battery cells of FIG. **21** installed on the thermal management device.

[0038] FIG. **23** shows battery cells being installed on a thermal management device in the form of an active heat exchanger or, more specifically, a battery cold plate, according to yet another embodiment.

[0039] FIG. **24** shows the battery cells of FIG. **23** installed on the thermal management device.

[0040] FIG. **25** shows an effect of temperature cycles on battery cell capacity fade.

[0041] FIG. **26** shows an effect of temperature on battery cell impedance growth.

[0042] FIG. **27** shows a schematic of a thermal management system for battery cells.

[0043] FIG. **28**A shows a thermal management system, according to one example embodiment, in a first configuration.

[0044] FIG. **28**B shows the thermal management system of FIG. **28**A in a second configuration.

[0045] FIG. **29**A shows a thermal management system, according to one example embodiment, in a first configuration.

[0046] FIG. **29**B shows the thermal management system of FIG. **29**A in a second configuration.

[0047] FIG. **30** shows a battery pack enclosure according to another example embodiment.

[0048] FIG. **31** shows an embodiment of a battery pack with a battery pack enclosure.

[0049] FIG. **32** is a detail view of area A of the battery pack and battery pack enclosure of FIG. **31**.

[0050] FIG. **33** shows another battery pack within another battery pack enclosure according to another example embodiment.

[0051] FIG. **34**A shows a battery pack enclosure in an ordinary working configuration according to another example embodiment.

[0052] FIG. **34**B shows the battery pack enclosure of FIG. **34**A in the event of a side impact according to another example embodiment.

[0053] FIG. **35** is an exploded view of end parts coupleable to the battery pack enclosure of FIG. **31**.

[0054] FIG. **36** shows the assembled battery pack enclosure with end plates of FIG. **33**.

[0055] FIG. **37** shows a first view of a battery pack end cap according to another example embodiment.

[0056] FIG. **38** shows a second view of the battery pack end cap of FIG. **37**.

[0057] FIG. **39** is a schematic cross-sectional view of an embodiment of a battery pack and battery pack enclosure.

[0058] FIG. **40** shows portions of another battery pack enclosure according to another example embodiment.

[0059] FIG. **41** is a schematic representation of a thermal runaway condition of the battery cell and/or the battery cell enclosure.

[0060] FIG. **42** is a schematic representation of a battery pack with vent protection functionality.

[0061] FIG. **43** shows a vent isolator and an array of battery cells of the battery pack of FIG. **42**.

[0062] FIG. **44** shows the vent isolator of FIG. **43**.

[0063] FIG. **45** shows the vent isolator of FIG. **44** with separators between vent apertures.

[0064] FIG. **46** shows an embodiment of the battery pack of FIG. **42**.

[0065] FIG. **47** is a cross-sectional view of the battery pack of FIG. **46** along line A-A in FIG. **46**.

[0066] FIG. **48** is an isometric view of a further battery pack with vent protection functionality.

[0067] FIG. **49** is a cross-sectional view of an array of battery cells of the further battery pack of FIG. **48** along line B-B in FIG. **48**.

[0068] FIG. **50** shows a battery pack with venting detection aspects.

[0069] FIG. **51** is a graphical representation of detected pressure in a battery enclosure over time.

[0070] FIG. **52** is a graphical representation of detected gas concentration in a battery enclosure over time.

[0071] FIG. **53** is a block diagram of a controller suitable for executing an embodiment of a battery pack that performs at least some techniques described in the present disclosure, as well as various devices and/or computing systems connected thereto.

DETAILED DESCRIPTION

[0072] In the following description, certain specific details are set forth in order to provide a thorough understanding of various disclosed embodiments. However, embodiments may be practiced without one or more of these specific details, or with other methods, components, materials, etc. In other instances, well-known structures associated with battery technology have not been shown or described in detail to avoid unnecessarily obscuring descriptions of the embodiments.

[0073] Persons of ordinary skill in the relevant art will understand that the present disclosure is illustrative only and not in any way limiting. Other embodiments of the presently disclosed battery devices, systems and methods readily suggest themselves to such skilled persons having the assistance of this disclosure.

Modular and Scalable Battery Packs

[0074] With reference to FIG. **1**, a chassis **2** of a commercial vehicle **1** is shown in plan view with an arrangement A_1 of common battery packs **10**, **110** secured to the chassis **2**. Unless the context and language clearly dictates otherwise, the use of "common" herein with respect to a battery pack means multiple battery packs of an identical or nearly identical form factor. In particular, an arrangement of five common battery packs **10**, **110** is shown with a respective pair of the battery packs **10**, **110** secured to each of opposing sides of rails **4** of the chassis **2** and with one of the battery packs **10**, **110** secured in line with a centerline of the chassis **2**. As will be appreciated from a review of the present disclosure, however, the battery packs **10**, **110** may be arranged in a variety of different arrangements (e.g., arrangements A_1, A_2, A_3 A_4, of FIG. **14**) having a varying number of battery packs **10**, **110** to optimize vehicle power and vehicle range of a host commercial vehicle for a particular make of vehicle or a particular desired performance profile. In addition, the battery packs **10**, **110** may be arranged in different configurations to optimize weight distribution. To be clear, the arrangement A_1 of battery packs **10**, **110** in FIG. **1** is a non-limiting example of one arrangement that may be particularly well suited for applications such as long-haul tractors.

[0075] In some instances, for example, a host vehicle may utilize between and including two and ten battery packs for any given application, namely, two, three, four, five, six, seven, eight, nine or ten battery packs. In addition, with respect to a fleet or collection of vehicles, it is appreciated that different configurations may be used for different vehicles, including at least one configuration for one vehicle in which a number of the common battery packs is different than a number of the common battery packs in another one of the configurations for another vehicle.

[0076] According to embodiments disclosed herein, a battery system for a commercial vehicle **1** may be provided that includes one standard size battery pack **10**, **110** that is packaged in a modular arrangement A_1 in the vehicle **1**, with the configuration of the battery packs **10**, **110** in the system providing flexible, scalable capacity to the vehicle **1**. The system provides scalable capacity with the addition of another battery pack **10**, **110** to increase performance and range. Individual battery packs **10**, **110** are made up of battery cells **16**, **116** (see, e.g., FIGS. **3** through **11**) arranged in series to attain a target voltage, for example, from 600V to 1200V. Advantageously, the battery system is modular and can add a battery pack **10**, **110** connected in parallel with each other battery pack **10**, **110** to increase the power, energy storage capability, and the range for the intended duty cycle of the vehicle **1**. In this manner, it is appreciated that the battery pack system may use a common form factor of a battery pack **10**, **110** for each of a plurality of battery packs connected in parallel to form the battery pack system in all arrangements A_1 and vehicles **1** within, for example, a fleet or a collection of vehicles, as described in further detail herein.

[0077] FIGS. **2** through **6** and FIGS. **9** through **11** show additional details of such a common battery pack **10** and a common battery pack **110**, respectively, and FIG. **14** shows additional example arrangements A_1, A_2, A_3, A_4 of such battery packs **10**, **110** on a fleet or a collection of vehicles **1** having different vehicle attributes (e.g., wheelbase).

[0078] With reference to FIGS. **2** through **6**, a battery pack **10** is shown according to an example embodiment that is particularly well suited to serve as a common battery pack **10** that may be combined in parallel together with other like battery packs **10** to optimize vehicle power and vehicle range, as well as to be arranged in different arrangements on a vehicle to optimize weight distribution. As shown in FIG. **2**, the battery pack **10** may be provided in a form factor having a generally rectangular shape with a pack length PL, a pack height PH, and a pack width PW. In one particularly advantageous embodiment for long-haul tractors and other commercial vehicles, the battery pack **10** may be provided in a form factor having a generally rectangular shape with a pack length PL of 1100±150 mm, a pack height PH of 600±100 mm, and a pack width PW of 600±100 mm.

[0079] As shown best in the cross-sectional view of FIG. **3**, the battery packs **10** include a plurality of battery module layers **12** stacked to form a multi-layer battery stack **14**, with each battery module layer **12** including a plurality of battery cells **16** arranged in an array and connected in series with each other and all other battery cells **16** of the battery pack **10**. Again, a sufficient number of the battery cells **16** may be connected together in series to provide a target battery pack voltage, for example, in a range of between and including 600V and 1200V that is common to each of the common battery packs **10**. The common battery packs **10** can then be connected in parallel with each other to increase vehicle power and vehicle range of a host commercial vehicle **1** as desired or required.

[0080] To increase energy density, it is advantageous to provide the battery cells **16** of the battery pack **10** in the plurality of module layers **12**. Unless the context and language clearly dictates otherwise, the term "energy density" should be construed broadly to include both volumetric energy density (i.e., Watt hours per Liter) and gravimetric energy density (i.e., Watt hours per kilogram). While the illustrated embodiment of FIG. **3** shows four stacked battery module layers **12**, it is appreciated that the number of battery module layers **12** may vary and include two, three, four, five or more battery module layers **12**. Further, in some lower capacity applications, a single battery layer **12** may be provided. For a given vehicle, or for a fleet or a collection of vehicles, it is advantageous in some embodiments to provide a same number of battery module layers **12** in the battery packs **10** thereof such that the battery packs **12** have a common form factor for the particular vehicle, or for the fleet or the collection of vehicles.

[0081] With reference to FIGS. **3** to **6**, the plurality of battery module layers **12** may be stacked in a vertical direction D_1 (FIG. **6**) to form a multi-layer battery stack **14** with each battery module layer **12** including a plurality of the battery cells **16** arranged in a linear array. Each battery module layer **12** may further include a thermal management device **20**, such as an active heat exchanger (also referred to as a cold plate), that is in direct thermal engagement with the array of battery cells **16** to provide cooling or heating of the battery cells **16** in operation.

[0082] The battery pack **10** may further include a battery pack frame **30** including a plurality of frame members **32**, wherein each battery module layer **12** is secured to a respective frame member **32** to support the battery module layers within the battery pack **10**. In some advantageous embodiments, the frame members **32** may be arranged to apply a compressive load L_1 (FIG. **6**) on the battery module layers **12** to assist in maintaining the battery module layers **12** of the multi-layer battery stack **14** in thermal contact with each other. In this manner, cooling and heating of the battery cells **16** may be carried out more efficiently via the thermal management devices **20** of the battery pack **10**. As an example, each frame member **32** may be provided in the form of a structural support frame at a periphery of the battery pack **10**. The structural support frame may comprise, for example, angle iron components secured around a periphery of the battery pack **10** and the battery module layers **12** that may be secured directly or indirectly to each structural support frame. In some instances, the thermal management device **20** of each battery module layer **12** may be secured directly to a respective one of the structural support frames to support the array of battery cells **16** thereon. The structural support frames may be spaced such that as each battery module layer **12** is stacked on a prior layer and secured to the structural support frame (e.g., via a bolted arrangement), the thermal management device **20** of the overlying battery module layer **12** is pressed into contact with the battery cells **16** of the underlying battery module layer **12**, or an intervening structure (e.g., a heat transfer pad), to maintain the battery module layers **12** of the multi-layer battery stack **14** in close thermal contact with each other.

[0083] With reference to FIG. **5**, each battery module layer **12** may further include one or more anchors **40** to assist in securing the array of battery cells **16** to the thermal management device **20** of the battery module layer **12**. According to the illustrated embodiment of FIG. **5**, for example, anchors **40** in the form of anchor castings are provided at each of the ends of the array of battery cells **16** and secured to the thermal management device **20** via bolted connections to hold the array of battery cells **16** in position on the thermal management device **20** and to assist in maintaining the battery cells **16** in contact with each other. For each battery module layer **12**, all of the battery cells **16** of the battery module layer **12** may be compressed together. For example, for each battery module layer **12**, all of the battery cells **16** of the battery module layer **12** may be compressed together with the aid of a compression band **46** encircling the array of battery cells **16**. In other instances, compression brackets may be secured to the battery cells **16** with tie rods or other devices for pressing the battery cells **16** together. Although the example embodiment of the battery module layer **12** shown in FIG. **5** is shown with all of the battery cells **16** compressed together, it is appreciated that in other embodiments that the battery cells **16** may be compressed together in sub-modules (e.g., sub-modules **18** of FIGS. **17** through **20**) to maintain contact between the battery cells **16** or intervening structures of each sub-module, with the sub-modules then fixedly secured together to form the array of battery cells **16**, as discussed in greater detail elsewhere.

[0084] With reference to FIG. **5**, each battery module layer **12** may further include one or more standoffs or structural supports **48** to interface with an adjacent battery module layer **12** including, for example, the thermal management device **20** of an overlying battery module layer **12**. Advantageously, the one or more standoffs or structural supports **48** may be provided on opposing sides of the battery module layer **12** in a respective intermediate position along a longitudinal length of the battery module layer **12** to assist in supporting the overlying thermal management device **20** and minimize or prevent undesirable deflection of the overlying thermal management device **20**. In addition, the standoffs or structural supports **48** may similarly serve as anchors (akin to anchors **40**) for the plurality of battery cells **16** to assist in locating and maintaining the battery cells **16** of the battery module layer **12** in place. As shown, the one or more standoffs or structural supports **48** may be shaped or include features to avoid obstructing components on the end faces **54** of the battery cells **16**, such as the electrode terminals **52**.

[0085] With reference now to FIG. **6**, the battery cells **16** of each the battery module layer **12** are shown in direct thermal engagement with the thermal management device **20** adjacent and overlying the battery cells **16** such that all of the battery cells **16** of the battery module layer **12** are positioned between two thermal management devices **20** above and below each respective battery module layer **12** to facilitate heat transfer on plural sides of the battery cells **16**. Advantageously, the linear array of battery cells **16** of each battery module layer **12** are held in compression between two thermal management devices **20** of the multi-layer battery stack **14** to ensure close thermal contact among all of the battery cells **16** and facilitate efficient cooling of the battery stack **14** during operation, or alternatively, heating of the battery stack **14** during, for example, cold starts of the battery system. Close thermal contact in this context includes contact of the thermal management devices **20** directly with the battery cells **16** or contact via intermediate thermally conductive substrates or materials, such as a thermal paste or a thermal pad.

[0086] According to the illustrated embodiment of the battery pack **10** of FIGS. **2** to **6**, the thermal management device **20** is provided in the form of an active heat exchanger having at least one liquid heat exchange medium passageway **24** for circulating a liquid heat exchange medium for cooling or heating purposes, and more specifically may be referred to as a battery cold plate **20** that is configured to provide cooling or heating of the battery cells in operation. The battery cold plate **20** of the illustrated embodiment comprises a generally planar manifold **22** and includes at least one heat transfer medium passageway **24** to facilitate the circulation of a heat transfer medium through the manifold **22** during operation to assist in drawing heat away from the battery cells **16** to cool the battery cells **16** or, alternatively, supplying heat to the battery cells **16** to heat the battery cells **16**. As shown in FIG. **5**, one or more fittings **26** may be provided on the battery cold plate **20** to enable conduits for the heat transfer medium to be attached to the cold plate **20** to enable fluid communication between the heat transfer medium passageway **24** of each cold plate **20** with each other and other components of a thermal management system, such as one or more chillers and one or more heaters to enable the battery cooling and heating functionality described herein.

[0087] Notably, according to the illustrated embodiment, each of the battery cells include one or more electrode terminals **52** on an end face **54** of the battery cell **16** which are oriented normal to a direction in which the battery cells **16** are aligned in the array and parallel to major surfaces **28** (FIG. **6**) of the battery cold plate **20** that are themselves oriented normal to the stacking direction D_1 of the multi-layer battery stack **14**. The major surfaces **28** of the battery cold plates **20** are also perpendicular to a plane of the electrodes in the battery cells **16**. In this configuration, electrical bus bar connections for the battery cell **16** may be maintained on a side of the battery stack **14** and enable upper and lower surfaces of the array of battery cells **16** to present uninterrupted mating surfaces for interfacing with the overlying and underlying cold plates **20**, respectively, and provide a form factor that is particularly well suited for cooling and heating of the battery cells **16**.

[0088] With reference back to FIGS. **2** and **3**, the battery pack **10** further includes a battery enclosure **60** that accommodates, and generally surrounds, the multi-layer battery stack **14** and the battery pack frame **30**. The battery enclosure **60** includes an enclosure base **62** and an enclosure cover **64** to fully enclose the multi-layer battery stack **14**. The enclosure base **62** and the enclosure cover **64** may be coupled together in a watertight seal to assist in protecting the battery stack **14** from hot debris in the case of a thermal runaway event. In some embodiments, the enclosure base **62** may be provided in the form of a shallow enclosure or tray upon which the battery stack **14** may be assembled and plumbed prior to installation of the enclosure cover **64**, as described in more detail elsewhere. As shown in FIGS. **2** and **3**, the frame members **32** of the battery pack frame **30** may be secured (e.g., bolted) directly to sidewalls of the battery enclosure **60** to provide a reinforced enclosure for the battery stack **14**. As can also be appreciated from FIGS. **2** and **3**, the enclosure **60** may be sized and shaped to closely surround the battery stack **14** such that only a relatively small proportion of the interior volume of the battery pack **10** is unoccupied. In this manner, a battery pack **10** with a particularly high energy density is provided.

[0089] The battery enclosure **60** may further include one or more interfaces **66** for routing electrical power or signals to and from the battery pack **10** and for routing heat transfer medium to and from the battery pack **10** for cooling or heating purposes. The interface **66** shown in FIG. **2** is shown simply as an aperture in the battery enclosure **60** and more particularly the enclosure base **62**, however, it is appreciated that the aperture may be fitted with one of more industrial connectors including electrical connectors for routing electrical power or signals to and from the battery pack **10** and fluid connectors for routing heat transfer medium to and from the battery pack **10**, or otherwise include pass-throughs for one or more electrical conduits or heat transfer conduits. All of the connections provided at the one or more interfaces **66** may be sealed or otherwise impenetrable to water ingress into the battery enclosure **60** to maintain a battery enclosure **60** that is watertight.

[0090] With reference now to FIG. **7**, an example embodiment of one battery cell **16** of the plurality of battery cells

16 of the battery packs **10** disclosed herein is shown in isolation. The battery cell **16** may be a prismatic style battery cell and may include uninterrupted surfaces around a body of the cell. The battery cell **16** includes electrode terminals **52** on its end faces **54** that enable a series of the battery cells **16** to be arranged in a tightly packed array as shown, for example, in FIGS. **5** and **6**. Vent valves **50** may also be provided on end faces **54** of the battery cell **16** to provide relief of gases to avoid rupturing or other damage to the battery cell **16** under certain conditions or scenarios. As shown in FIG. **7**, the battery cell **16** may be provided in a form factor having a generally rectangular prismatic shape with a cell length CL, a cell height CH, and a cell thickness CT. In some instances, the battery cell **16** may have a generally rectangular prismatic shape with a cell length of 520±50 mm, a cell height of 125±10 mm, a cell thickness of 20±5 mm. The battery cell **16** may have a generally high aspect ratio of cell length to cell height. For example, in some embodiments, the aspect ratio of cell length to cell height may be between and include 3:1 to 6:1.

[0091] Alternatively, with reference to FIG. **8**, another example embodiment of one battery cell **16'** of the battery packs disclosed herein is shown in isolation. The battery cell **16'** may be a prismatic style battery cell and may include uninterrupted surfaces around a body of the cell. The battery cell **16'** includes electrode terminals **52'** on its upper face **54'** that enable a series of the battery cells **16'** to be arranged in a tightly packed array. A vent valve **50'** may also be provided on the upper face **54'** of the battery cell **16'** to provide relief of gases to avoid rupturing or other damage to the battery cell under certain conditions or scenarios. As shown in FIG. **8**, the battery cell **16'** is provided in a form factor having a generally rectangular prismatic shape with a cell length CL_2, a cell height CH_2, and a cell thickness CT_2. In some instances, the battery cell **16'** may have a generally rectangular prismatic shape with a cell length of 175±50 mm, a cell height of 150±20 mm, a cell thickness of 45±5 mm. The battery cell **16'** may have a generally moderate aspect ratio of cell length to cell height. For example, in some embodiments, the aspect ratio of cell length to cell height may be between and include 1:1 to 2:1.

[0092] With reference now to FIGS. **9** through **11**, a battery pack **110** is shown according to another example embodiment that is particularly well suited to serve as a common battery pack **110** that may be combined in parallel together with other like battery packs **110** to optimize vehicle power and vehicle range, as well as to be arranged in different arrangements on a vehicle to optimize weight distribution. As shown in FIGS. **9** and **10**, the battery pack **110** may be provided in a form factor having a generally rectangular shape similar to that of the battery pack **10** of FIGS. **2** through **6**. In one particularly advantageous embodiment for long-haul tractors and other commercial vehicles, the battery pack **110** may be provided in a form factor having a generally rectangular shape with a pack length of 1100±150 mm, a pack height of 600±100 mm, a pack width of 600±100 mm.

[0093] As shown in FIGS. **9** and **10**, the battery pack **110** includes a plurality of battery module layers **112** stacked to form a multi-layer battery stack **114**, with each battery module layer **112** including a plurality of battery cells **116** arranged in an array and connected in series with each other and all other battery cells **116** of the battery pack **110**. Again, a sufficient number of the battery cells **116** may be connected together in series to provide a target battery pack voltage, for example, in a range of between and including 600V and 1200V that is common to each of the common battery packs **110**. The common battery packs **110** can then be connected in parallel with each other to increase vehicle power and vehicle range of a host commercial vehicle **1** as desired or required.

[0094] To increase energy density, it is advantageous to provide the battery cells **116** of the battery pack **110** in the plurality of module layers **112**. Again, unless the context and language clearly dictates otherwise, the term "energy density" should be construed broadly to include both volumetric energy density (i.e., Watt hours per Liter) and gravimetric energy density (i.e., Watt hours per kilogram). While the illustrated embodiment of FIGS. **9** and **10** shows four stacked battery module layers **112**, it is appreciated that the number of battery module layers **112** may vary and include two, three, four, five or more battery module layers **112**. Further, in some lower capacity applications, a single battery layer **112** may be provided. For a given vehicle, or for a fleet or a collection of vehicles, it is advantageous in some embodiments to provide a same number of battery module layers **112** in the battery packs **110** thereof such that the battery packs **112** have a common form factor for the particular vehicle, or for the fleet or the collection of vehicles.

[0095] With reference to FIGS. **9** through **11**, the plurality of battery module layers **112** may be stacked in a vertical direction D_2 to form a multi-layer battery stack **114** with each battery module layer **112** including a plurality of the battery cells **116** arranged in a linear array. Each battery module layer **112** may further include a thermal management device **120**, such as an active heat exchanger (also referred to as a cold plate), that is in direct thermal engagement with the array of battery cells **116** to provide cooling or heating of the battery cells **116** in operation.

[0096] The battery pack **110** may further include a battery pack frame **130** including a plurality of frame members **132**, wherein each battery module layer **112** is secured to a respective frame member **132** to support the battery module layers within the battery pack **110**. In some advantageous embodiments, the frame members **132** may be arranged to apply a compressive load L_2 (FIGS. **9** and **10**) on the battery module layers **112** to assist in maintaining the battery module layers **112** of the multi-layer battery stack **114** in thermal contact with each other. In this manner, cooling and heating of the battery cells **116** may be carried out more efficiently via the thermal management devices **120** of the battery pack **110**. As an example, each frame member **132** may be provided in the form of a structural support frame at a periphery of the battery pack **110**. The structural support frame may comprise, for example, angle iron components secured around a periphery of the battery pack **110** and the battery module layers **112** that may be secured directly or indirectly to each structural support frame. In some instances, the thermal management device **120** of each battery module layer **112** may be secured directly to a respective one of the structural support frames to support the array of battery cells **116** thereon. The structural support frames may be spaced such that as each battery module layer **112** is stacked on a prior layer and secured to the structural support frame (e.g., via a bolted arrangement), the thermal management device **120** of the overlying battery module layer **112** is pressed into contact with the battery cells **116** of the underlying battery module layer **112**, or an intervening structure (e.g., a heat transfer pad), to maintain the battery module layers **112** of the multi-layer battery stack **114** in close thermal contact with each other.

[0097] With continued reference to FIGS. **9** through **11**, each battery module layer **112** may further include one or more anchors **148** to assist in securing the array of battery cells **116** to the thermal management device **120** of the battery module layer **112**. According to the illustrated embodiment of FIGS. **9** through **11**, the anchors **148** are provided in the form of elongated bars or plates positioned adjacent to lower ends of the array of battery cells **116** and secured to the thermal management device **120** via bolted connections to hold the array of battery cells **116** in position on the thermal management device **120** and to assist in maintaining the battery cells **116** in contact with each other. For each battery module layer **112**, all of the battery cells **116** of the battery module layer **112** may be compressed together. For example, for each battery module layer **112**, all of the battery cells **16** of the battery module layer **112** may be compressed together with the aid of a compression band encircling the array of battery cells **116**, as shown in the example embodiment of FIGS. **2** through **6**. In other instances, compression brackets **140** may be secured to opposing ends of the battery cells **116** with selectively adjustable tie rods **146** (FIG. **9**) or other devices for pressing the battery cells **116** together. Although the example embodiment of the battery module layer **112** shown in FIGS. **9** through **11** is shown with all of the battery cells **116** compressed together, it is appreciated that in other embodiments that the battery cells **116** may be compressed together in sub-modules (e.g., sub-modules **18** of FIGS. **17** through **20**) to maintain contact between the battery cells **116** or intervening structures of each sub-module, with the sub-modules then fixedly secured together to form the array of battery cells **116**, as discussed in greater detail elsewhere.

[0098] With reference to FIGS. **9** and **10**, the battery cells **116** of each the battery module layer **112** are shown in direct thermal engagement with the thermal management device **120** adjacent and overlying the battery cells **116** such that all of the battery cells **116** of the battery module layer **112** are positioned between two thermal management devices **120** above and below each respective battery module layer **112** to facilitate heat transfer on plural sides of the battery cells **116**. Advantageously, the linear array of battery cells **116** of each battery module layer **112** are held in compression between two thermal management devices **120** of the multi-layer battery stack **114** to ensure close thermal contact among all of the battery cells **116** and facilitate efficient cooling of the battery stack **114** during operation, or alternatively, heating of the battery stack **114** during, for example, cold starts of the battery system. Close thermal contact in this context includes contact of the thermal management devices **120** directly with the battery cells **116** or contact via intermediate thermally conductive substrates or materials, such as a thermal paste or a thermal pad.

[0099] According to the illustrated embodiment of the battery pack **110** of FIGS. **9** through **11**, the thermal management device **120** is provided in the form of an active heat exchanger having at least one liquid heat exchange medium passageway **124** for circulating a liquid heat exchange medium for cooling or heating purposes, and more specifically may be referred to as a battery cold plate **120** that is configured to provide cooling or heating of the battery cells **116** in operation. The battery cold plate **120** of the illustrated embodiment comprises a generally planar manifold **122** and includes at least one heat transfer medium passageway **124** (FIG. **9**) to facilitate the circulation of a heat transfer medium through the manifold **122** during operation to assist in drawing heat away from the battery cells **116** to cool the battery cells **116** or, alternatively, supplying heat to the battery cells **116** to heat the battery cells **116**. As shown in FIG. **9**, one or more fittings **126** may be provided on the battery cold plate **120** to enable conduits **127** for the heat transfer medium to be attached to the cold plate **120** to enable fluid communication between the heat transfer medium passageway **124** of each cold plate **120** with each other and other components of a thermal management system, such as one or more chillers and one or more heaters to enable the battery cooling and heating functionality described herein.

[0100] According to the illustrated embodiment of FIG. **9**, the battery cold plate **120** may include a set of liquid heat exchange medium openings (concealed beneath and in fluid communication with the fittings **126**) on a same end of the battery pack **110**, which serve as an inlet and an outlet for the liquid heat exchange medium. As shown in FIG. **9**, the outlet of one of the battery cold plates **120** may be connected to the inlet of an adjacent one of the battery cold plates **120** to enable the liquid heat exchange medium to pass through each of the battery module layers **112** in a continuous path. As also described elsewhere herein, the battery pack may be configured such that the liquid heat exchange medium may flow in alternate directions along the continuous path to provide heating or cooling functionality to the multi-layer battery stack **114** in reversible directions. For example, with reference to FIG. **9**, in one configuration, the liquid heat exchange medium may move from a heater or chiller through a conduit to the battery cold plate **120** of a lower one of the battery module layers **112**, as indicated by arrows **129**, and then circulates through the battery cold plate **120** through one or more liquid heat exchange medium passageways **124** thereof, to be discharged and routed by another conduit **127** to the battery cold plate **120** of an adjacent battery module layer **112**, wherein the liquid heat exchange medium then circulates through one or more liquid heat exchange medium passageways **124** of that battery cold plate **120** to be discharged and routed by yet another conduit **127** to the battery cold plate **120** of an adjacent battery module layer **112**, and so on until exiting an upper most battery cold plate **120**, as indicated by arrows **131**. Conversely, as described elsewhere, flow may be reversed such that the liquid heat exchange medium enters the upper most battery module layer **112**, indicated by arrows **131**, and then circulates sequentially through each of the battery module layers **112** before being discharged from the multi-layer battery stack **114**, as indicated by arrows **129**. In this manner, all connections for the fittings **126** and conduits **127** for the liquid heat transfer medium may be provided on one end of the multi-layer battery stack **114**, and, advantageously separated from electronics, including one or more aspects, modules or components of a battery management system (BMS) **156**, which may be provided on an opposing end of the multi-layer battery stack **114**, as shown in FIG. **10**. According to such an embodiment, there may be provided an electronics side of the pack **110** and a heat transfer medium routing and interface side of the pack **110**. In other embodiments, connections and interfaces for electronics and connections and interfaces for the liquid heat transfer medium may be intermixed within the pack **110**. In addition, the heat transfer medium may be routed through the battery module layers **112** in a different order or manner than sequentially. For example, the heat transfer medium may be routed through one or more battery module layers **112** in parallel.

[0101] Notably, according to the illustrated embodiment of the battery pack **110** of FIGS. **9** through **11**, each of the battery cells **116** include one or more electrode terminals **152** on an end face **154** of the battery cell **116** which are oriented normal to a direction in which the battery cells **116** are aligned in the array and parallel to major surfaces **128** of the battery cold plate **120** that are themselves oriented normal to the stacking direction D_2 of the multi-layer battery stack **114**. The major surfaces **128** of the battery cold plates **120** are also perpendicular to a plane of the electrodes **152** in the battery cells **116**. In this configuration, electrical bus bar connections for the battery cell **116** may be maintained on a side of the battery stack **114** and enable upper and lower surfaces of the array of battery cells **116** to present uninterrupted mating surfaces for interfacing with the overlying and underlying cold plates **120**, respectively, and provide a form factor that is particularly well suited for cooling and heating of the battery cells **116**.

[0102] Alternatively, as shown and described elsewhere herein, each of the battery cells **116** may include one or more electrode terminals on an upper face of the battery cell **116** (similar to battery cell **16'** of FIG. **8**), which are oriented parallel to the stacking direction D_2 of the multi-layer battery stack **114**. In this regard, the major surfaces **128** of the battery cold plates **120** may be parallel to a plane of the electrodes **152** in the battery cells **116**. In this configuration, electrical bus bar connections for the battery cell **116** may be maintained along the upper surface of each battery module layer **112**. Also as described elsewhere herein, venting of materials from a venting event of the battery cells **116** may occur along the upper surface of each battery module layer **112**.

[0103] Although the embodiment shown in FIGS. **9** through **11** depicts the use of a plurality of conduits **127** and fittings **126** for routing heat transfer medium between layers of the battery pack **110**, it is appreciated that other means of routing the heat transfer medium throughout the battery pack may be provided. For example, according to one variant, the conduits **127** and fittings **126** shown in FIG. **9** may be replaced by a manifold with one or more internal passages that span between adjacent battery cold plates of the battery pack. An example of such an embodiment is shown and described with reference to FIGS. **12** and **13**.

[0104] As shown in FIG. **12**, there is provided a battery pack **110'** that includes a plurality of battery module layers **112'** stacked to form a multi-layer battery stack **114'**, with each battery module layer **112'** including a plurality of battery cells **116'** arranged in an array and connected in series with each other and all other battery cells **116'** of the battery pack **110'**. Again, a sufficient number of the battery cells **116'** may be connected together in series to provide a target battery pack voltage, for example, in a range of between and including 600V and 1200V that is common to each of a plurality of common battery packs **110'**. The common battery packs **110'** can then be connected in parallel with each other to increase vehicle power and vehicle range of a host commercial vehicle as desired or required.

[0105] Again, to increase energy density, it is advantageous to provide the battery cells **116'** of the battery pack **110'** in the plurality of module layers **112'**. While the illustrated embodiment of FIG. **12** shows only two stacked battery module layers **112'**, it is appreciated that the number of battery module layers **112'** may vary and include three, four, five or more battery module layers **112'**. Further, in some lower capacity applications, a single battery layer **112'** may be provided. For a given vehicle, or for a fleet or a collection of vehicles, it is advantageous in some embodiments to provide a same number of battery module layers **112'** in the battery packs **110'** thereof such that the battery packs **112'** have a common form factor for the particular vehicle, or for the fleet or the collection of vehicles.

[0106] With reference to FIGS. **12** and **13**, the plurality of battery module layers **112'** may be stacked in a vertical direction to form a multi-layer battery stack **114'** with each battery module layer **112'** including a plurality of the battery cells **116'** arranged in a linear array. Each battery module layer **112'** may further include a thermal management device **120'**, such as an active heat exchanger (also referred to as a cold plate), that is in direct thermal engagement with the array of battery cells **116'** to provide cooling or heating of the battery cells **116'** in operation. Advantageously, unlike the embodiment shown and described with respect to FIGS. **9** through **11**, the battery pack **110'** of FIG. **12** is provided with a connecting manifold **140'** that extends between a lower one of the thermal management devices **120'** and an upper one of the thermal management devices **120'** and replaces the conduits **127** and fittings **126** shown in the embodiment of FIGS. **9** through **11**. As can be appreciated in the partially cutaway view of FIG. **13**, the connecting manifold **140'** includes heat transfer medium passages **141'** arranged to provide fluid communication between the lower thermal management device **120'** and the upper thermal management device **120'** in order to facilitate distribution of a heat transfer medium through each of the lower thermal management device **120'** and the upper thermal management device **120'** during operation to provide heating or cooling functionality for the plurality of battery cells **116'** of the battery module layer(s) **112'**. Additionally, each of the lower and upper thermal management devices **120'** may comprise an active heat exchanger (e.g., battery cold plate) having a generally planar manifold **122'** that includes at least one heat transfer medium passageway **124'** (FIG. **13**) to facilitate the circulation of the heat transfer medium through the planar manifold **122'** during operation to assist in drawing heat away from the battery cells **116'** to cool the battery cells **116'** or, alternatively, supplying heat to the battery cells **116'** to heat the battery cells **116'**.

[0107] As shown in FIGS. **12** and **13**, the connecting manifold **140'** is positioned at an end of the battery pack **110'** and extends vertically between battery cold plates of the lower and upper thermal management devices **120'**. The connecting manifold **140'** is configured to assist in securing the plurality of battery cells **116'** in place within the battery pack **110'** between the lower and upper thermal management devices **120'**, and also serves as a structural support between the lower and upper thermal management devices **120'** to help maintain a rigid connection between adjacent thermal management devices **120'** and provide a particularly robust battery stack **114'**. The connecting manifold **140'** may also serve as one of opposing hold down members that assist in fixedly securing the battery cells **116'** together within the battery pack **110'** between said hold down members. Notably, connections (e.g., bolted connections) between the connecting manifold **140'** and the thermal management devices **120'** may be located such that the connecting manifold **140'** and an opposing hold down member may apply a compressive force to the battery cells **116'** of the battery module layer **112'**. Still further, although not illustrated in FIG. **12**, it is appreciated that a compression strap, tie rods or other devices may be provided between the connecting manifold **140'** and an opposing hold down member to assist in applying a compressive load to the battery cells **116'**.

[0108] With reference to FIG. **13**, which shows one of the thermal management devices **120'** and the connecting manifold **140'** with select cutaway sections to reveal internal passages, the connecting manifold **140'** of the illustrated embodiment includes a plurality of heat transfer medium passages **141'** for providing fluid communication between adjacent thermal management devices **120'**. As shown in FIG. **13**, representative arrows are provided to illustrate one example routing of heat transfer medium through the connecting manifold **140'** and the thermal management device **120'**. For instance, heat transfer medium may enter and pass through one passage **141'** of the connecting manifold **140'** after passing through an overlying thermal management device **120'** (not shown in FIG. **13**) and then enter an underlying thermal management device **120'** at an opening (e.g., inlet) provided in one region of the underlying thermal management device **120'** that communicates with the aforementioned passage **141'**. The heat transfer medium may then circulate through one or more passageways **124'** of the underlying thermal management device **120'** toward an opening (e.g., outlet) provided in another region of the underlying thermal management device **120'**, which in turn may be in fluid communication with a passage **141'** of another connecting manifold **140'** of an adjacent layer of the battery pack to provide sequential flow through the battery stack **114'**. In this manner, it will be appreciated that at least one of the passages **141'** of each connecting manifold **140'** may be blocked to assist in routing the heat transfer medium through the battery pack in a desired path when the blocked passage is not along the desired path. Moreover, it will be appreciated that the connecting manifolds **140'** of the battery stack **114'** may be configured in various embodiments to route the heat transfer medium through the thermal management devices **120'** of a battery pack **110'** in series, in parallel, or in a combination thereof. Still further, although the example embodiment shows routing of the heat transfer medium via a series of connecting manifolds **140'** on one side of the battery pack **110'**, it is appreciated that one or more similarly constructed manifolds may be provided at one or more other sides or locations of the battery pack **110'** to provide a variety of routing options. Other features and benefits of utilizing connection manifolds **140'** in connection with the battery packs described herein will be appreciated by a thorough review of the illustrated embodiments.

[0109] With reference now to FIG. **14**, it is emphasized here that embodiments of the battery packs **10**, **110**, **110'** and related battery technology described above and elsewhere throughout this disclosure may be utilized in a common form factor for a particular vehicle, or for a fleet or a collection of vehicles having different vehicle attributes, such as the long-haul tractors **1**A, **1**B, **1**C, **1**D depicted in plan view in FIG. **14**, that may each have a different wheelbase, other configuration difference, and/or a different performance capability. In addition, as discussed above, for such a fleet or collection of vehicles, the common battery packs **10**, **110**, **110'** can be arranged in a variety of different configurations or arrangements A_1, A_2, A_3, A_4. Such arrangements A_1, A_2, A_3, A_4 may feature, for example, a different number of battery packs **10**, **110**, **110'** battery packs **10**, **110**, **110'** oriented in different directions, and/or battery packs **10**, **110**, **110'** positioned at different locations or positions on the vehicles **1**A, **1**B, **1**C, **1**D. FIG. **14** illustrates in some non-limiting examples four different battery pack arrangements A_1, A_2, A_3, A_4 that are particularly well suited for a fleet of long-haul tractors.

[0110] Having a common battery pack **10**, **110**, **110'** for a particular vehicle, or for a fleet or a collection of vehicles, can be particularly advantageous for a variety of reasons. For example, battery pack **10**, **110**, **110'** at different locations is exposed to different ambient conditions, the capacity of battery cells **16**, **116**, **116'** in some battery packs **10**, **110**, **110'** may drop faster than others. The embodiments described herein may provide common battery packs **10**, **110**, **110'** with an identical form factor that enable each of the common battery packs **10**, **110**, **110'** to be exchanged with the others to facilitate periodic rearranging of the common battery packs **10**, **110**, **110'** on the host vehicle **1**A, **1**B, **1**C, **1**D. Or, as another example, common battery packs **10**, **110**, **110'** having an identical form factor enable any one of the common battery packs **10**, **110**, **110'** to be replaced with a new battery pack **10**, **110**, **101'** of the same form factor. This has significant service benefits.

[0111] Although embodiments of the battery packs **10**, **110**, **110'** have been shown and described herein as having a generally rectangular form factor, it is appreciated that battery packs may be provided in a variety of other form factors. For instance, battery packs may be provided in a T-shape, L-shape, boot-shape or stairstep-shape configuration, as shown, for example, in FIGS. **15** and **16**.

[0112] With reference to FIG. **15**, at least one of the battery packs may be provided in a L-shape, boot-shape or stairstep-shape configuration C_1, and may have in one non-limiting example an overall pack length PL_2 of 1100±150 mm, an overall pack height PH_2 of 600=100 mm, an overall pack width PW_2 of 600±100 mm, a lower step height SH of 425±75 mm, and an upper landing length LL of 600±100 mm. Such a L-shape, boot-shape or stairstep-shape configuration C_1 may be particularly advantageous in nesting the battery packs with one or more components of a host vehicle **1**, such as the rails **4** of a chassis **2** of a tractor. In particular, a battery pack may be positioned with a lower step portion of the L-shape, boot-shape or stairstep-shape configuration C_1 beneath a rail **4** of the chassis **2**. For this purpose, an enclosure of the battery pack may be provided with one or more features, such as rail channels or cavities, to assist in nesting the battery pack with the rails **2**.

[0113] With reference to FIG. **16**, at least one of the battery packs **10**, **110** may be provided in a T-shape configuration C**2**, and may have in one non-limiting example an overall pack length PL_3 of 1250±150 mm, an overall pack height PH_3 of 600±100 mm, an overall pack width PW_3 of 2200±100 mm, a stem width SW of 600±100 mm, and a stem height SH of 200±75 mm. Such a T-shape configuration C**2** may also be particularly advantageous in nesting the battery packs with one or more components of a host vehicle **1**, such as the rails **4** of a chassis **2** of a tractor. In particular, a battery pack may be positioned with a stem portion of the

T-shape configuration C**2** nested between rails **4** of the chassis **2**. For this purpose, the enclosure of the battery pack may be provided with one or more features, such as rail channels **68**, to assist in nesting the battery pack with the rails **4**.

[0114] Again, the shapes shown in FIGS. **15** and **16** are non-limiting examples and other shapes that are built-up from stacks of linear arrays of battery cells beyond those illustrated are also contemplated.

[0115] The battery packs **10**, **110**, **110'** described herein can further be utilized in connection with a battery pack system having a thermal management system that is centralized or distributed, or a hybrid thereof. For example, the thermal management system may include a centralized chiller for all of the common battery packs **10**, **110**, **110'** for distributing a heat transfer medium to the common battery packs **10**, **110**, **110'** for cooling purposes. As another example, the thermal management system may include a plurality of chillers associated with the common battery packs **10**, **110**, **110'** for distributing a heat transfer medium to the common battery packs **10**, **110**, **110'** for cooling purposes. As yet another example, the thermal management system may include a respective chiller associated with each of the common battery packs **10**, **110**, **110'** for routing a heat transfer medium to the common battery pack **10**, **110**, **110'** for cooling purposes. Similarly, the thermal management system may include a centralized heater for all of the common battery packs **10**, **110**, **110'** for distributing a heat transfer medium to the common battery packs **10**, **110**, **110'** for heating purposes. Or, the thermal management system may include a plurality of heaters associated with the common battery packs **10**, **110**, **110'** for distributing a heat transfer medium to the common battery packs **10**, **110**, **110'** for heating purposes. For example, the thermal management system may include a respective heater associated with each of the common battery packs **10**, **110**, **110'** for routing a heat transfer medium to the common battery pack **10**, **110**, **110'** for heating purposes. Notably, any of the chiller arrangements outlined above can be combined with any of the heater arrangements outlined above. For instance, in some implementations, the thermal management system may include a centralized chiller for all of the common battery packs for distributing a heat transfer medium to the common battery packs for cooling purposes (i.e., a centralized chiller system), and a respective heater associated with each of the common battery packs for routing a heat transfer medium to the common battery packs in a distributed manner for heating purposes (i.e., a distributed heater system).

[0116] The battery packs **10**, **110**, **110'** described herein can further be utilized in connection with a battery pack system having a centralized battery management system (BMS) for providing centralized monitoring and control functionality for the common battery packs; or a master-slave battery management system (BMS) for providing distributed monitoring and control functionality for the common battery packs.

[0117] The battery packs **10**, **110**, **110'** described herein can further be utilized in connection with a battery pack system having a centralized charging system comprising a single charger for charging the common battery packs; or a distributed charging system comprising a plurality of chargers for charging the common battery packs.

[0118] In view of the above disclosure, it will be appreciated that vehicles, in particular commercial vehicles, may be provided that include a battery pack system having a plurality of common battery packs in accordance with embodiments of the battery packs described above and elsewhere in this disclosure. The vehicles may include a chassis and the common battery packs may be positionable along the chassis to optimize a weight distribution of the vehicles. For instance, the vehicles may be long-haul tractors having different wheelbases and the battery packs may be arranged differently to distribute weight differently in each vehicle to account for various differences in the tractors. The chassis, which may be a chassis of a long-haul tractor, may include chassis rails and the battery packs may be positioned under the chassis rails or alongside the chassis rails. The battery packs may be arranged in a common plane or may be arranged at one or more different elevations, and may be arranged in a common pack orientation or different pack orientations. Further, a fleet of the vehicles may have a drive system that is common among the vehicles regardless of a number of the common battery packs that are connected in parallel for each vehicle.

Battery Packs with Sub-Modular Construction

[0119] Although the embodiment of the battery pack **10** illustrated in FIGS. **2** to **6** and the embodiment of the battery pack **110** illustrated in FIGS. **9** through **11** discussed above each depicts all of the battery cells **16**, **116** of the battery module layer **12**, **112** as being arranged together as a single compressed array of battery cells **16**, **116** it is appreciated that embodiments of the battery packs **10**, **110** disclosed herein may feature battery module layers **12**, **112** that are formed from a plurality of sub-modules **18**. For example, as shown in FIG. **17**, discrete subsets of the plurality of battery cells **16** of a given battery module layer **12** may be held together in sub-modules **18** with each sub-module **18** being configured to be fixedly secured to the thermal management device **20** (e.g., active heat exchanger or battery cold plate) and/or an adjacent sub-module **18**. In the illustrated embodiment, for example, subsets of six individual battery cells **16** are held together in sub-modules **18** by opposing sub-module brackets **70** secured to each of opposing ends of the battery cells **16**. Alternatively, the discrete subsets of the battery cells **16** may be held together in the sub-modules **18** via one or more straps, clamps or other coupling arrangements. The straps, brackets **70**, clamps or other coupling arrangements may be configured to hold the battery cells **16** of each sub-module **18** together in a rigid manner to enable each sub-module **18** to be independently manipulated in space during assembly of the sub-modules **18** into one or more battery module layers **12** of a multi-layer battery stack. Further, the straps, brackets **70**, clamps or other coupling arrangements enable the battery cells **16** to be held together absent structural adhesive in some embodiments. The omission of structural adhesive may provide manufacturing and other benefits, such as the recycling of battery cells **16** after the battery pack **10** is removed from the vehicles. In other embodiments, a structural adhesive and/or a thermal adhesive or paste may be provided between the battery cells **16**.

[0120] As shown in FIG. **17**, the sub-modules **18** are connectable together in at least a longitudinal direction D_L which is aligned with a direction De in which the battery cells **16** of the battery module layer **12** extend in the array. The sub-modules **18** may be connected together, for example, by fasteners, latches, interlocks **72** or other connecting devices or means. Additionally, the sub-modules **18** may be connectable together in a vertical direction D_V which is normal to the direction Dc in which the battery cells **16** of the battery module layer **12** extend in the array. The connections may be made, for example, at the straps, brackets **70** or clamp arrangements that hold the battery cells **16** of the sub-modules **18** together.

[0121] In the example embodiment of the battery pack stack of FIG. **17**, the sub-modules **18** are fixedly connected together by interlocks **72** provided on the sub-module brackets **70**, and fixedly secured to the underlying thermal management device **20** by fasteners (e.g., bolts). The fasteners may be aligned with, or recessed with respect to, an outer peripheral edge of the thermal management device **20**. The straps, brackets **70**, clamps or other coupling arrangements may be configured to fix each sub-module **18** to the underlying thermal management device **20** in a manner that urges the battery cells **16** into contact with the thermal management device **20** or an intervening thermally conductive material (e.g., thermal paste or thermal pad). This may be accomplished by drawing the battery cells **16** into close thermal contact with the thermal management device **20** or an intervening thermally conductive material as bolts are tightened into the thermal management device **20**, and more particularly a perimeter portion of the thermal management device **20**.

[0122] While only a portion of a single battery module layer **12** comprising two sub-modules **18** is shown in FIG. **17**, it is appreciated that numerous sub-modules **18** may be provided, such as, for example, three, four, five, six, seven, eight, nine, ten or more sub-modules **18** for any given battery module layer **12**. In addition, it is appreciated that the sub-modules **18** may be built up in a multi-directional array to form two or more battery module layers **12**, including three, four, five, six, or more battery module layers **12** stacked in the vertical direction D_V. In an embodiment, the sub-modules in a given battery module layer **12** are connectable together in the longitudinal direction D_L via the interlocks **72** to form the given layer **12**, while the assembled battery module layers **12** are stacked and coupled to other layers with fasteners (e.g., bolts). Alternatively, the connection between each layer **12** in the stacked arrangement may be accomplished via interlocks **72** or other coupling arrangements to eliminate bolted connections in the battery stack.

[0123] With continued reference to FIG. **17**, each sub-module **18** may comprise one or more end plates **74** that provide thermal insulation and/or a protective shield between the sub-module **18** and one or more adjacent sub-modules **18**. Additionally, fire retardant material (not illustrated) may be provided between adjacent sub-modules **18**. The fire retardant material may be secured to or integrated with each sub-module **18**, or may be provided as a separate element between adjacent sub-modules **18** for fire protection purposes. In addition, or alternatively, each sub-module **18** may comprise fire retardant material between each of at least some of the battery cells **16** of the sub-module **18**. Furthermore, in some embodiments, each sub-module **18** may comprise thermal resistant material (e.g., a thermal insulator) between each of at least some of the battery cells **16** of the sub-module **18** to prevent or delay the propagation of thermal runaway.

[0124] FIG. **18** illustrates a variant in which the sub-modules **18** are connected together and to adjacent thermal management devices **20** by fasteners. As shown, the sub-modules **18** may be built up in a multi-directional array to form a plurality of battery module layers **12**. Notably, in the vertical direction D_V, the sub-modules **18** are connected together via the intermediary of an intervening thermal management device **20** (e.g., battery cold plate). In this arrangement, the fasteners may pass through each of the upper and lower sub-modules **18**, and more particularly the sub-module brackets **70**, as well as the thermal management device **20** to secure all of the components together. In addition, as shown in the leftmost illustrations of FIG. **18**, the sub-module brackets **70** (or straps, clamps or other coupling arrangements) may extend beyond end faces of the battery cells **16** and include clearance for an elongated bus bar to span across the end faces of the battery cells **16**.

[0125] FIG. **19** illustrates a further variant in which a plurality of structural supports **80** are positioned to extend between a lower thermal management device $\mathbf{20}_L$ of one battery module layer **12** and an upper thermal management device $\mathbf{20}_U$ of an overlaying battery module layer **12** to support the upper thermal management device $\mathbf{20}_U$ in position above the lower thermal management device $\mathbf{20}_L$ and to assist in eliminating or reducing appreciable deflection of the upper thermal management device $\mathbf{20}_L$. The structural supports **80** may be removably attached to the lower and upper thermal management devices **20**, or formed integrally therewith. Each structural support **80** may comprise an elongate form factor that extends an entirety or substantially an entirety of a longitudinal length of the battery cells **16**, or beyond. The structural supports **16** may comprise at least two structural supports that are spaced apart along a longitudinal length of the battery module layer **12** with at least some of the battery cells **16** positioned therebetween. The structural supports **80** may comprise at least three structural supports that are spaced apart along a longitudinal length of the battery module layer **12** in equidistant intervals with at least some of the battery cells **16** positioned between adjacent structural supports **80**. Each of the structural supports **80** may be positioned immediately next to one of the sub-modules **18**. The structural supports **80** may be provided at ends of the battery module layer **12** to serve as a shield to protect the battery cells **16** therebetween. The structural supports **80** may interface with the one or more of the straps, brackets **70**, clamps or other coupling arrangements that hold each of the sub-modules **18** together, or otherwise cover at least a portion of the straps, brackets **70**, clamps or other coupling arrangements. The structural supports **80** may provide thermal insulation between some of the battery cells **16** in the battery module layer **12** and others of the battery cells **16** in the battery module layer **12**. The structural supports **80** may be covered at least in part with a thermal insulation material and/or a fire retardant material.

[0126] FIG. **20** shows a sequence of assembling a sub-module **18** of battery cells **16** together using a variant of a sub-module bracket **70**. The sub-module bracket **70** is configured to be fastened to an underlying structure, such as, for example, the thermal management device **20**. The sub-module bracket **70** includes sidewalls **76** that are spaced to hold a select number of individual battery cells **16** (in this case five battery cells **16**) together in close contact. The sub-module bracket **70** may further include a window **78** or clearance aligned with the end faces **54** of the battery cells **16** such that the electrode terminals **52**, for example, can be accessed and connected together by a bus bar arrangement and to an electrical system of the host vehicle. The sub-module bracket **70** (or alternatively, straps, clamps or other coupling arrangements) may be configured to hold the battery cells **16** of each sub-module **18** together in compression. This may be accomplished by compression of a pad in between cells **16**, elastic deformation of the sidewalls **76** of the sub-module bracket **70**, or by other devices or means, such as, for example, tie rods or clamping mechanisms. The sub-module bracket **70** further includes end structures **77** extending between and integrally formed with the sidewalls **76** and arranged normal to the sidewalls **76**. The end structures **77** are structured to interface with the end faces **54** of the battery cells and assist in preventing lateral movement of the cells **16** in the stack while also providing structural support to the sub-module **18**. The end structures **77** and the sidewalls **76** cooperate to maintain close contact of the cells **16** with the thermal management device **20** in multiple directions. An upper end structure may have a generally thinner form factor while a lower end structure may extend away from the end faces **54** of the cells **16** to provide means for the connection of the bracket **70** to the underlying structure, such as a fastener apertures **79**.

Cold Plate with Integral Fins

[0127] With reference now to FIG. **21**, a battery pack according to a further embodiment is provided, which includes a thermal management device in the form of a heat exchanger **220** having a plurality of integral fin members **222**. In some advantageous instances, the heat exchanger **220** is an active heat exchanger, which includes one or more internal passageways through which a heat exchange medium is actively circulated during operation, and may also be referred to herein as a battery cold plate (despite that it may provide both cooling and heating functionality). As shown in FIG. **21**, the heat exchanger **220** has a main body **224**, through which a heat exchange medium may flow. The main body **224** of the heat exchanger **220** has a first major surface **226** that faces upward as illustrated in FIG. **21**. The first major surface **226** may be planar or substantially planar. In some alternative embodiments, a heat exchange medium does not flow through the main body **224**, and the main body is coupled to another component which provides the heat exchange functionality of the system, such as a separate heat exchanger component interfaced with the main body **224**. In such alternatives, the main body **224** may be in direct contact with the heat exchanger component, with no non-metallic materials, including adhesives, between a base of the main body **224** and the heat exchanger.

[0128] As illustrated in FIG. **21**, the heat exchanger **220** includes the fin members **222**, each of which includes a relatively thin sheet or plate of material that extends directly outward from (e.g., perpendicular to) the first major surface **226** of the heat exchanger **220**, as well as directly across the first major surface **226** of the heat exchanger **220**. A thickness of each of the fin members **222** is substantially smaller than a thickness of the main body **224** of the heat exchanger **220**. Each of the fin members **222** extends parallel to or substantially parallel to each of the other fin members **222**. Each of the fin members **222** is integrally or monolithically formed with the main body **224** of the heat exchanger **220** at the first major surface **226** thereof. For example, the fin members **222** and the main body **224** can be formed of metallic materials and the fin members **222** can be welded to the main body **224**. Alternatively, the fin members **222** and the main body **224** can be formed together from a single piece of larger material, such as by machining or by casting the fin members **222** and the main body **224** as a single piece of material.

[0129] FIG. **21** also illustrates a plurality of battery cells **216** being installed on the heat exchanger **220**. As illustrated in FIG. **21**, the battery cells **216** can be installed on the heat exchanger **220** in pairs, where each pair of battery cells **216** includes a fire retardant material and/or a compression pad **230** positioned between the pair of battery cells **216**. Thus, the first retardant material and/or the compression pad **230** can be sandwiched between the pair of battery cells **216** to form a battery cell unit **232**, where the entire battery cell unit **232**, but only a single battery cell unit **232**, can be installed between an adjacent pair of the fin members **222** of the heat exchanger **220**, such as by moving the battery cell unit **232** vertically downward as illustrated in FIG. **21**, and toward the first major surface **226** of the main body **224** of the heat exchanger in a direction perpendicular to the first major surface **226**. In some embodiments, outer surfaces of the battery cell unit **232**, that is, a first major surface of a first one of the battery cells **216** and a first major surface of a second one of the battery cells **216** opposite to the first one of the battery cells **216**, can be bonded to the adjacent fin members **222**, such as by chemical bonding, such as by an adhesive, glue, epoxy, etc., which may include a thermal paste and/or thermal adhesive. In other instances, each battery cell unit **232** may be installed between opposing fins **222** without chemical bonding, and, in some instances, may be held by compression fit or the like.

[0130] FIG. **22** illustrates a plurality of battery cell units **232** installed on the heat exchanger **220** as described for the battery cell unit **232** including the battery cells **216**. As illustrated in FIG. **22**, each of the battery cells **216** and each of the fin members **222** have the same height, or substantially the same height, in a direction extending away from the first major surface **226** of the main body **224** of the heat exchanger **220**. Furthermore, the battery cells **216** and the fin members **222** each have a respective first major surface and a respective second major surface opposite to the first major surface, where each of these major surfaces of each of the battery cells **216** and the fin members **222** have the same, or substantially the same, surface area. As illustrated in FIG. **22**, the plurality of battery cell units **232** installed on the heat exchanger **220** form a battery module layer **212** composed of a plurality of individual battery cells **216**. In such a system, the fin members **222** provide structural support for the individual battery cells **216** and the battery module layer **212**, that is, they can act as anchors for the cells **216**. The fin members **222** also increase the heat exchange capacity of the heat exchanger **220** (enhancing its heating and/or cooling performance) and improve heat transfer between the cells **216** and the heat exchanger **220**, by increasing a degree of contact between the heat exchanger **220** and the individual battery cells **216**.

[0131] As illustrated in FIG. **22**, the system includes two individual battery cells **216** for every one of the fin members **222**, and one set of the fire retardant material and/or compression pad **230** for every two of the individual battery cells **216**. In alternative embodiments, however, different arrangements can be provided. For example, the system may include one individual battery cell **216** for every one of the fin members **222**, and one fire retardant material and/or one compression pad **230** for every one of the individual battery cells **216**, or three individual battery cells **216** for every one of the fin members **222**, and one fire retardant material and/or compression pad **230** for every three of the individual battery cells **216**, or four individual battery cells **216** for every one of the fin members **222**, and one fire retardant material and/or compression pad **230** for every four of the individual battery cells **216**, etc.

[0132] As illustrated in FIGS. **21** and **22**, the heat exchanger **220** includes a plurality of fin members **222** that extend outward from the first major surface **226** of the main body **224** of the heat exchanger **220**. In some embodiments, a multi-layer battery stack may be provided similar to, for example, the multi-layer battery stacks **14**, **114** described above with respect to FIGS. **2** through **6** and **9** through **11**. Accordingly, the multi-layer battery stack can include a plurality of heat exchangers **220** stacked together with a plurality of battery module layers **212** in an alternating manner. In such embodiments, every one of the heat exchangers **220** and every one of the battery module layers **212** can be configured as illustrated in FIGS. **21** and **22**. In some alternative embodiments, however, some of the heat exchangers **220** (e.g., every other one of the heat exchangers **220**) can have a first plurality of fin members **222** that extend outward from the first major surface **226** of the main body **224** of the heat exchanger **220** and a second plurality of fin members **222** that extend outward from a second major surface of the main body **224** of the heat exchanger **220**, where the second major surface is opposite to the first major surface. In such embodiments, some of the heat exchangers **220** (e.g., every other one of the heat exchangers **220**) can be provided without the fin members **222**. These two different types of heat exchangers **220** can alternate with one another in the multi-layer battery stack such that each of the battery module layers **212** is coupled to fins extending either from an upper major surface or a lower major surface of a heat exchanger **220**.

[0133] In either of these embodiments, each of the battery module layers **212** can be in physical and thermal contact with two distinct heat exchangers **220**, one on each of opposite sides thereof, to increase or otherwise improve the heat exchange capacity of the system. Furthermore, the battery module layers **212** and heat exchangers **220** may be held in compression when they are stacked in a multi-layer battery stack, such as in a stacking direction thereof, to, among other things, increase or otherwise improve the heat exchange capacity of the system.

[0134] With reference now to FIG. **23**, a battery pack according to yet a further embodiment is provided, which is similar in many aspects to the embodiment of FIGS. **21** and **22** but wherein a plurality of battery cells **216'** having a different form factor (such as, for example, the form factor of the battery cell **16'** disclosed above with reference to FIG. **8**) are aligned end-to-end transversely across a width of the heat exchanger **220'**. As illustrated in FIG. **23**, and similar to the above described embodiment, a heat exchanger **220'** is shown to include fin members **222'**, each of which comprises a relatively thin sheet or plate of material that extends directly outward from (e.g., perpendicular to) a first major surface **226'** of the heat exchanger **220'**, as well as directly across the first major surface **226'** of the heat exchanger **220'**. A thickness of each of the fin members **222'** is substantially smaller than a thickness of a main body **224'** of the heat exchanger **220'**. Each of the fin members **222'** extends parallel to or substantially parallel to each of the other fin members **222'**. Each of the fin members **222'** is integrally or monolithically formed with the main body **224'** of the heat exchanger **220'** at the first major surface **226'** thereof.

[0135] FIG. **24** illustrates a plurality of battery cells **216'** being installed on the heat exchanger **220'**. As illustrated in FIG. **24**, the battery cells **216'** can be installed on the heat exchanger **220'** in a pair of rows, where each pair of rows of battery cells **216'** includes a fire retardant material and/or a compression pad **230'** positioned between the pair of rows of battery cells **216'**. Thus, the first retardant material and/or the compression pad **230'** can be sandwiched between the pair of rows of battery cells **216'** to form a battery cell unit **232'**, where the entire battery cell unit **232'**, but only a single battery cell unit **232'**, can be installed between an adjacent pair of the fin members **222'** of the heat exchanger **220'**, such as by moving the battery cell unit **232'** vertically downward as illustrated in FIG. **23**, and toward the first major surface **226'** of the main body **224'** of the heat exchanger in a direction perpendicular to the first major surface **226'**. In some embodiments, outer surfaces of the battery cell unit **232'**, that is, a first collective surface of a first row of the battery cells **216'** and a first collective surface of a second row of the battery cells **216'** adjacent to the first row of the battery cells **216'**, can be bonded to the adjacent fin members **222'**, such as by chemical bonding, such as by an adhesive, glue, epoxy, etc., which may include a thermal paste and/or thermal adhesive. In other instances, each battery cell unit **232'** may be installed between opposing fins **222'** without chemical bonding, and, in some instances, may be held by compression fit or the like.

[0136] FIG. **24** illustrates a plurality of battery cell units **232'** installed on the heat exchanger **220'** as described for the battery cell unit **232'** including the battery cells **216'**. As illustrated in FIG. **24**, each of the battery cells **216'** and each of the fin members **222'** have the same height, or substantially the same height, in a direction extending away from the first major surface **226'** of the main body **224'** of the heat exchanger **220'**. Furthermore, each row of battery cells **216'** and the fin members **222'** each have a respective first major surface and a respective second major surface opposite to the first major surface, where each of these major surfaces of each of the rows of battery cells **216'** and the fin members **222'** have the same, or substantially the same, surface area. As illustrated in FIG. **24**, the plurality of battery cell units **232'** installed on the heat exchanger **220'** form a battery module layer **212'** composed of rows and columns of a plurality of individual battery cells **216'**. In such a system, the fin members **222'** provide structural support for the individual battery cells **216'** and the battery module layer **212'**, that is, they can act as anchors for the cells **216'**. The fin members **222'** also increase the heat exchange capacity of the heat exchanger **220'** (enhancing its heating and/or cooling performance) and improve heat transfer between the cells **216'** and the heat exchanger **220'**, by increasing a degree of contact between the heat exchanger **220'** and the individual battery cells **216'**.

[0137] As illustrated in FIG. **24**, the system includes two rows of three individual battery cells **216'** each for every one of the fin members **222'**, and one fire retardant material and/or compression pad **230'** for every two rows of the three individual battery cells **216'**. In alternative embodiments, however, different arrangements can be provided. For example, the system may include a single row of individual battery cells **216'** for every one of the fin members **222'**, and one fire retardant material and/or one compression pad **230'** for each single row of the individual battery cells **216'**, or three rows of individual battery cells **216'** for every one of the fin members **222'**, and one fire retardant material and/or compression pad **230'** for every three rows of the individual battery cells **216'**, or four rows of individual battery cells **216'** for every one of the fin members **222'**, and one fire retardant material and/or compression pad **230'** for every four rows of the individual battery cells **216'**, etc.

[0138] In some embodiments, a multi-layer battery stack may be provided similar to, for example, the multi-layer battery stacks **14** described above with respect to FIGS. **2** through **6** of the multi-layer battery stacks **114** described above with respect to FIGS. **9** through **11**. Accordingly, the multi-layer battery stack can include a plurality of heat exchangers **220'** stacked together with a plurality of battery module layers **212'** in an alternating manner. In such embodiments, every one of the heat exchangers **220'** and every one of the battery module layers **212'** can be configured as illustrated in FIGS. **23** and **24** to form a battery stack that is particularly robust and particularly efficient in heating and cooling of the resulting battery stack.

Bi-Directional Coolant Flow

[0139] Battery packs for electric vehicles can contain hundreds of battery cells. The cells can be cooled by the flow of thermal or heat exchange media (such as a liquid or gaseous heat exchange media, e.g., coolant, air, or a refrigerant). During cooling, charging, and other processes, such as when a battery system is operating, battery cells located on an upstream side of the flow of the heat exchange media can have a lower temperature than other battery cells in the battery pack, while batteries on the downstream side of the flow can have a higher temperature than other battery cells in the battery pack. Such a temperature difference between upstream and downstream cells can be higher than 10° C., especially during a fast charge of the battery cells or extended operation of the battery. This type of temperature difference has a significant impact on battery cell capacity fade and impedance growth over time. The battery cells located on the downstream side are exposed to higher temperature and therefore the capacity fades more quickly. This creates a challenge for battery balancing and shortens battery life.

[0140] When battery cells are exposed to relatively high temperatures, the capacity of the battery cells fades more quickly, and the impedance of the battery cells increases more quickly, than if they were not exposed to such temperatures. Elevated cell impedances further increase cell temperatures, increasing these imbalances. FIG. **25** shows an effect of temperature cycles on battery cell capacity fade, and FIG. **26** shows an effect of temperature on battery cell impedance growth. FIGS. **25** and **26** illustrate one example of these effects based on a specific battery system, and exact numbers in different battery systems may differ. FIG. **27** illustrates a plurality of battery cells arranged adjacent one another across the width of the page (as shown in FIG. **27**), and a coolant flowing from left to right (as shown in FIG. **27**) through a thermal management device in the form of an active heat exchanger and, more specifically, a battery cold plate, adjacent the plurality of battery cells. As illustrated in FIG. **27**, battery cells at the left (as shown in FIG. **27**), and adjacent an upstream portion of the flow of the coolant, are cooled to a relatively low temperature, and battery cells at the right (as shown in FIG. **27**), and adjacent a downstream portion of the flow of the coolant, are cooled to a relatively high temperature, as a result of their locations with respect to the flow of the coolant. Concepts of the disclosure alleviate these concerns and provide additional advantages that overcome these and other deficiencies, as described further below.

[0141] With reference to FIGS. **28**A and **28**B, a thermal management system **250** for cooling (or alternatively heating) a battery pack **210** according to a further embodiment is provided. The thermal management system **250** includes a thermal management device in the form of an active heat exchanger **220** (or more specifically a cold plate) that is coupled to, or located adjacent to or in close proximity to, battery cells of the battery pack **210**. In some instances, the active heat exchanger **220** may be constructed or configured in accordance with the thermal management devices **20**, **120**, **120'** described and shown with reference to at least FIGS. **2** through **6** and **9** through **13**. In other instances, the heat exchanger **220** may also be a different type of heat exchanger than the thermal management device **20**, **120**, **120'** of the earlier described embodiments. As shown in FIGS. **28**A and **28**B, the thermal management system **250** includes, in addition to the active heat exchanger **220**, a pump **256**, a first valve **258**, and a second valve **260**. The following description provides non-limiting examples where the first and second valves **258**, **260** are multi-way valves (e.g., a first three-way valve **258** and a second three-way valve **260**), but it is to be appreciated that the disclosure contemplates use of other types of valves. As shown in FIGS. **28**A and **28**B, the first multi-way valve **258** carries a fluid flowing out of the pump **256**, in the sense that fluid flowing through the thermal management system **250** encounters the first multi-way valve first after leaving the pump **256** along its flow path through the thermal management system **250**. As shown in FIGS. **28**A and **28**B, the second multi-way valve **260** carries a fluid flowing into the pump **256**, in the sense that fluid flowing through the thermal management system **250** encounters the second multi-way valve last before entering the pump **256** along its flow path through the thermal management system **250**.

[0142] As illustrated in FIGS. **28**A and **28**B, the thermal management system **250** includes a first conduit **262** that couples an outlet of the pump **256** to an inlet of the first multi-way valve **258**, a second conduit **264** that couples a first outlet of the first multi-way valve **258** to a first end of a heat exchange medium passageway extending through the heat exchanger **220**, a third conduit **266** that couples a second end of the heat exchange medium passageway extending through the heat exchanger **220** to a first inlet of the second multi-way valve **260**, and a fourth conduit **268** that couples an outlet of the second multi-way valve **260** to an inlet of the pump **256**. When the thermal management system **250** is in operation, the first multi-way valve **258** can be switched to allow a heat exchange medium to flow through the first multi-way valve **258** from the first conduit **262** to the second conduit **264**, and the second multi-way valve **260** can be switched to allow a heat exchange medium to flow through the second multi-way valve **260** from the third conduit **266** to the fourth conduit **268**. In such a configuration, the pump **256** can be operated to pump the heat exchange medium through the system **250** from the outlet of the pump **256**, through the first conduit **262**, through the first multi-way valve **258**, through the second conduit **264**, through the heat exchange medium passageway extending through the heat exchanger **220**, and thus through the heat exchanger **220** itself, from the first end thereof to the second end thereof, through the third conduit **266**, through the second multi-way valve **260**, and then through the fourth conduit **268** to the inlet of the pump **256**. This flow path can be referred to as a first flow path and is indicated by arrows **270** in FIG. **28**A.

[0143] As also illustrated in FIGS. **28**A and **28**B, the thermal management system **250** further includes a fifth conduit **272** that couples a second outlet of the first multi-way valve **258** to the third conduit **266**, and a sixth conduit **274** that couples the second conduit **264** to a second inlet of the second multi-way valve **260**. When the thermal management system **250** is in operation, the first multi-way valve **258** can be switched to allow a heat exchange medium to flow through the first multi-way valve **258** from the first conduit **262** to the fifth conduit **272**, and the second multi-way valve **260** can be switched to allow a heat exchange medium to flow through the second multi-way valve **260** from the sixth conduit **274** to the fourth conduit **268**. In such a configuration, the pump **256** can be operated to pump the heat exchange medium through the system **250** from the outlet of the pump **256**, through the first conduit **262**, through the first multi-way valve **258**, through the fifth conduit **272**, through a portion of the third conduit **266**, through the heat exchange medium passageway extending through the heat exchanger **220**, and thus through the heat exchanger **220** itself, from the second end thereof to the first end thereof, through a portion of the second conduit **264**, through the sixth conduit **274**, through the second multi-way valve **260**, and then through the fourth conduit **268** to the inlet of the pump **256**. This flow path can be referred to as a second flow path and is indicated by arrows **276** in FIG. **28**B.

[0144] Thus, as noted in the foregoing, in some cases, depending on the arrangements of the valves **258** and **260**, the heat exchange medium can be pumped and flow from the first end of the heat exchange medium passageway extending through the heat exchanger **220** to the second end thereof, or from the second end of the heat exchange medium passageway extending through the heat exchanger **220** to the first end thereof. Thus, by switching the valves **258** and **260** at regular intervals, the thermal management system **250** can alternate the direction of the flow of the heat exchange medium through the heat exchanger **220**. The valves **258** and **260** can be actuated and switched to alternate the flow path of the heat exchange medium through the system **250** from time to time. As examples, the valves **258** can be switched to change the flow path of the heat exchange medium from the first flow path to the second flow path once per week, once every two days, once every day, or twice a day. As further examples, the valves **258** and **260** can be switched to change the flow path of the heat exchange medium from the first flow path to the second flow path once every time a vehicle carrying the system **250** is turned off, or once every time the vehicle carrying the system **250** comes to a stop. In some cases, the frequency of the alternation can be greater to increase uniformity of temperature effects on the battery cells in the battery pack **210**, and the frequency of the alternation can be decreased if greater uniformity of temperature effects on the battery cells in the battery pack **210** is not needed. In some embodiments, the switching of the valves **258** and **260** can be controlled by a driver of the vehicle carrying the system **250**, while in other embodiments, the switching of the valves **258** and **260** cannot be controlled by a driver of the vehicle carrying the system **250**. In some embodiments, the switching of the valves **258** and **260** can be controlled by a computer system of the vehicle carrying the system **250**, such as at least controller (e.g., controller **455**) and/or BMS system described herein, while in other embodiments, the switching of the valves **258** and **260** cannot be controlled by a computer system of the vehicle carrying the system **250**.

[0145] In some embodiments, the system **250** includes a plurality of temperature sensors, such as a first temperature sensor coupled to one or more battery cells proximate a downstream side of a flow of the heat exchange medium, and configured to measure a temperature of such battery cells, and a second temperature sensor coupled to one or more battery cells proximate an upstream side of the flow of the heat exchange medium, and configured to measure a temperature of such battery cells. In some embodiments, a computer system or controller associated with the system **250**, such as at least controller **455** described herein, can be configured to receive signals from such temperature sensors and to operate the system **250**, including switching of the first and second valves **258**, **260**, based on temperatures measured by the sensors. For example, the computer system and/or controller can be configured to switch the valves **258** and **260** if a difference between the temperatures measured by the temperature sensors exceeds a threshold value, such as 5° C., 10° C., 15° C., or 20° C.

[0146] As described herein, the system **250** of the illustrated embodiment includes two multi-way valves **258** and **260**. In some embodiments, the valves **258** and **260** can be referred to as synchronized dual valves. In alternative embodiments, the system **250** can include a single valve. In other embodiments, the system **250** may not have any valves and may use other devices or techniques to achieve the switching of the flow paths of the heat exchange medium through the heat exchanger **220** as described herein. The heat exchanger **220** can be considered an active heat exchanger in the sense that a heat transfer medium is actively utilized by the heat exchanger for heating or cooling purposes. The heat exchanger **220** may be used to cool the battery pack **210**, or the heat exchanger **220** may be used to heat the battery pack **210**, in which case the heat exchanger **220** may be referred to as a hot plate. In some embodiments, the heat exchanger **220** can include a heat sink.

[0147] As described herein, the system **250** may include a single pump **256**. In alternative embodiments, however, two or more pumps may supply the heat exchange medium in opposite directions and the pumps may be operated alternately to supply the heat exchange medium to the at least one heat exchanger **220**. In further embodiments, the single pump **256** may be a bi-directional pump configured to supply the heat exchange medium in two different directions (i.e., forward operation to conduit **262** or reverse operation to conduit **268** with a single pump **256**) to perform at least some of the techniques described above. In such embodiments, the valves **258** and **260** may be omitted from the system **250**. In some embodiments, the battery pack **210** includes a plurality of battery module layers that are stacked, such as in a vertical direction, where each battery module layer includes a respective plurality of battery cells arranged in a planar array and a respective active heat exchanger, and the heat exchange passageway extends through each of the heat exchangers of the battery module layers (similar to the embodiments described above with respect to at least FIGS. **2** through **6** and **9** through **13**). In still further embodiments, the system **250** may be associated with a single battery pack **210** in a distributed heating and cooling system, or the system **250** may be associated with a plurality of common battery packs, similar to the systems and arrangements of such systems described at least with reference to FIGS. **1** through **16**.

[0148] With reference to FIGS. **29**A and **29**B, a thermal management system **280** for cooling (or alternatively heating) a battery pack **282** according to a further embodiment is provided. The thermal management system **280** includes a thermal management device in the form of an active heat exchanger (or more specifically a cold plate) **284** that is coupled to, or located adjacent to or in close proximity to, battery cells of the battery pack **282**. In some instances, the active heat exchanger **284** may be constructed or configured in accordance with the thermal management devices **20** described and shown with reference to at least FIGS. **2** through **6** and **9** through **13**. In other instances, the heat exchanger **284** may also be a different type of heat exchanger **284** than the thermal management device **20** of the earlier described embodiments. As shown in FIGS. **29**A and **29**B, the thermal management system **280** includes, in addition to the active heat exchanger **284**, a pump **286** and a valve **288**. As illustrated in FIGS. **29**A and **29**B, the thermal management system **280** includes exactly one path-switching valve **288**, or a single path-switching valve **288**, and does not include any valves that switch flow paths other than the valve **288**.

[0149] The following description provides non-limiting examples where the valve **288** is a multi-way valve (e.g., a four-way valve), but it is to be appreciated that the disclosure contemplates use of other types of valves. As shown in FIGS. **29**A and **29**B, the valve **288** carries a relatively cool or cold fluid flowing out of the pump **286** (cool or cold fluid indicated by solid lines), in the sense that fluid flowing through the thermal management system **280** encounters the valve **288** first after leaving the pump **286** along its flow path through the thermal management system **280**. As shown in FIGS. **29**A and **29**B, the valve **288** also carries a relatively warm or hot fluid flowing into the pump **286** (warm or hot fluid indicated by broken lines), in the sense that fluid flowing through the thermal management system **280** encounters the valve **288** last before entering the pump **286** along its flow path through the thermal management system **280**. Such an arrangement may be used, in particular, to cool the battery pack **282**. In some alternative embodiments, to heat the battery pack **282**, the valve **288** carries a relatively warm or hot fluid flowing out of the pump **286** and a relatively cool or cold fluid flowing into the pump **286**.

[0150] As illustrated in FIGS. **29**A and **29**B, the thermal management system **280** includes a first conduit **290** that couples an outlet of the pump **286** to a first inlet/outlet or port of the multi-way valve **288**, a second conduit **292** that couples a second inlet/outlet or port of the multi-way valve **288** to a first end of a heat exchange medium passageway extending through the heat exchanger **284**, a third conduit **294** that couples a second end of the heat exchange medium passageway extending through the heat exchanger **284** to a third inlet/outlet or port of the multi-way valve **288**, and a fourth conduit **296** that couples a fourth inlet/outlet or port of the multi-way valve **288** to an inlet of the pump **286**.

[0151] When the thermal management system **280** is in operation, the multi-way valve **288** can be switched to allow a heat exchange medium to flow through the first multi-way valve **288** from the first conduit **290** to the second conduit **292**, and to allow a heat exchange medium to flow through the multi-way valve **288** from the third conduit **294** to the fourth conduit **296**. In such a configuration, the pump **286** can be operated to pump the heat exchange medium through the system **280** from the outlet of the pump **286**, through the first conduit **290**, through the multi-way valve **288** a first time, through the second conduit **292**, through the heat exchange medium passageway extending through the heat exchanger **284**, and thus through the heat exchanger **284** itself, from the first end thereof to the second end thereof, through the third conduit **294**, through the multi-way valve **288** a second time, and then through the fourth conduit **296** to the inlet of the pump **286**. This flow path can be referred to as a first flow path and is indicated by arrows **298***a* in FIG. **29**A.

[0152] When the thermal management system **280** is in operation, the multi-way valve **288** can be switched to allow a heat exchange medium to flow through the first multi-way valve **288** from the first conduit **290** to the third conduit **294**, and through the multi-way valve **288** from the second conduit **292** to the fourth conduit **296**. In such a configuration, the pump **286** can be operated to pump the heat exchange medium through the system **280** from the outlet of the pump **286**, through the first conduit **290**, through the multi-way valve **288** a first time, through the third conduit **294**, through the heat exchange medium passageway extending through the heat exchanger **284**, and thus through the heat exchanger **284** itself, from the second end thereof to the first end thereof, through the second conduit **292**, through the multi-way valve **288** a second time, and then through the fourth conduit **296** to the inlet of the pump **286**. This flow path can be referred to as a second flow path and is indicated by arrows **298***b* in FIG. **29**B.

[0153] Thus, as noted in the foregoing, in some cases, depending on the arrangement of the valve **288**, the heat exchange medium can be pumped and flow from the first end of the heat exchange medium passageway extending through the heat exchanger **284** to the second end thereof, or from the second end of the heat exchange medium passageway extending through the heat exchanger **284** to the first end thereof. Thus, by switching the valve **288** at regular intervals, the thermal management system **280** can alternate the direction of the flow of the heat exchange medium through the heat exchanger **284**. The valve **288** can be actuated and switched to alternate the flow path of the heat exchange medium through the system **280** from time to time. As examples, the valve **288** can be switched to change the flow path of the heat exchange medium from the first flow path to the second flow path once per week, once every two days, once every day, or twice a day. As further examples, the valve **288** can be switched to change the flow path of the heat exchange medium from the first flow path to the second flow path once every time a vehicle carrying the system **280** is turned off, or once every time the vehicle carrying the system **280** comes to a stop. In some cases, the frequency of the alternation can be greater to increase uniformity of temperature effects on the battery cells in the battery pack **282**, and the frequency of the alternation can be decreased if greater uniformity of temperature effects on the battery cells in the battery pack **282** is not needed. In some embodiments, the switching of the valve **288** can be controlled by a driver of the vehicle carrying the system **280**, while in other embodiments, the switching of the valve **288** cannot be controlled by a driver of the vehicle carrying the system **280**. In some embodiments, the switching of the valve **288** can be controlled by a computer system of the vehicle carrying the system **280**, such as at least controller (e.g., controller **455**) and/or BMS system described herein, while in other embodiments, the switching of the valve **288** cannot be controlled by a computer system of the vehicle carrying the system **280**.

[0154] In some embodiments, the system **280** includes a plurality of temperature sensors, such as a first temperature sensor coupled to one or more battery cells proximate a downstream side of a flow of the heat exchange medium, and configured to measure a temperature of such battery cells, and a second temperature sensor coupled to one or more battery cells proximate an upstream side of the flow of the heat exchange medium, and configured to measure a temperature of such battery cells. In some embodiments, a computer system or controller associated with the system **280**, such as at least controller **455** described herein, can be configured to receive signals from such temperature sensors and to operate the system **280**, including switching of the valve **288**, based on temperatures measured by the sensors. For example, the computer system and/or controller can be configured to switch the valve **288** if a difference between the temperatures measured by the temperature sensors exceeds a threshold value, such as 5° C., 10° C., 15° C., or 20° C.

[0155] The heat exchanger **284** can be considered an active heat exchanger **284** in the sense that a heat transfer medium is actively utilized by the heat exchanger **284** for heating or cooling purposes. The heat exchanger **284** may be used to cool the battery pack **282**, or the heat exchanger **284** may be used to heat the battery pack **282**, in which case the heat exchanger **284** may be referred to as a hot plate. In some embodiments, the heat exchanger **284** can include a heat sink.

[0156] In some embodiments, the battery pack **282** includes a plurality of battery module layers that are stacked, such as in a vertical direction, where each battery module layer includes a respective plurality of battery cells arranged in a planar array and a respective active heat exchanger **284**, and the heat exchange passageway extends through each of the heat exchangers **284** of the battery module layers (similar to the embodiments described above with respect to at least FIGS. **2** through **6** and **9** through **13**). In still further embodiments, the system **280** may be associated with a single battery pack **282** in a distributed heating and cooling system, or the system **280** may be associated with a plurality of common battery packs, similar to the systems and arrangements of such systems described at least with reference to FIGS. **1** through **16**.

[0157] In view of the above, the present disclosure advantageously provides for controlling the flow of a heat exchange medium to achieve increased uniformity of temperatures or effects of temperature differences within a battery pack. Such features can alleviate issues discussed herein related to temperatures of battery cells on a downstream side of a flow of the heat exchange medium being higher than temperatures of battery cells on an upstream side of the flow of the heat exchange medium, for example, while the battery cells are being cooled by the heat exchange medium. Such features can also alleviate issues discussed herein related to temperatures of battery cells on a downstream side of a flow of the heat exchange medium being lower than temperatures of battery cells on an upstream side of the flow of the heat exchange medium, for example, while the battery cells are being heated by the heat exchange medium. Thus, the features described herein can reduce, minimize, or eliminate effects on battery pack performance resulting from non-uniform temperatures across a battery pack over extended periods of time. For example, the features described herein provide improvements in that battery cell capacity fade and impedance growth are well balanced across the battery pack over time.

Battery Pack Enclosure

[0158] With reference to FIG. **30**, a battery pack **310** according to a further embodiment is provided. Similar to the battery packs **10** described above, the battery pack **310** includes a plurality of battery module layers **312***a*-**312***d* (collectively referred to as a plurality of battery module layers **312**), each layer **312** including a plurality of individual battery cells, and the layers **312** being stacked in an alternating fashion with a plurality of thermal management devices **320**, which may be, for example, an active heat exchanger provided in the form of a battery cold plate. As a result, each battery module layer **312** is stacked between two thermal management devices **320**, such that each of the thermal management devices **320** is stacked adjacent to at least one of the battery module layers **312**. The battery module layers **312** and the thermal management devices **320** are stacked in a vertical direction D_V (as illustrated in FIG. **30**) to form a multi-layer battery stack **314**. Each of the battery module layers **312***a*-**312***d* may be constructed or configured in accordance with the battery module layers **12**, **112**, **112'** described at least with reference to FIGS. **2** through **6** and **9** through **13**.

[0159] As illustrated in FIG. **30**, the battery pack **310**, and its multi-layer battery stack **314**, includes four battery module layers **312** and five thermal management devices **320**. Specifically, the battery pack **310**, and its multi-layer battery stack **314**, includes a stack of layers including a first thermal management device **320***a* at a first end of the stack **314**, which is a bottom end of the stack **314** as illustrated in FIG. **30**, a first battery module layer **312***a* adjacent to a surface of the first thermal management device **320***a*, a second thermal management device **320***b* adjacent to a surface of the first battery module layer **312***a* opposite to the first thermal management device **320***a*, a second battery module layer **312***b* adjacent to a surface of the second thermal management device **320***b* opposite to the first battery module layer **312***a*, a third thermal management device **320***c* adjacent to a surface of the second battery module layer **312***b* opposite to the second thermal management device **320***b*, a third battery module layer **312***c* adjacent to a surface of the third thermal management device **320***c* opposite to the second battery module layer **312***b*, a fourth thermal management device **320***d* adjacent to a surface of the third battery module layer **312***c* opposite to the third thermal management device **320***c*, a fourth battery module layer **312***d* adjacent to a surface of the fourth thermal management device **320***d* opposite to the third battery module layer **312***c*, and a fifth thermal management device **320***e* adjacent to a surface of the fourth battery module layer **312***d* opposite to the fourth thermal management device **320***d*, and at a second end of the stack **314** opposite to the first end of the stack, which is a top end of the stack **314** as illustrated in FIG. **30**.

[0160] In other embodiments, the battery pack **310**, and its multi-layer battery stack **314**, may include a different number of battery module layers **312** and a different number of thermal management devices **320** than illustrated in FIG. **30**. For example, the battery pack **310**, and its multi-layer battery stack **314**, may include one battery module layer **312** and two thermal management devices **320**, or two battery module layers **312** and three thermal management devices **320**, or three battery module layers **312** and four thermal management devices **320**, or five battery module layers **312** and six thermal management devices **320**, or six battery module layers **312** and seven thermal management devices **320**, or eight battery module layers **312** and nine thermal management devices **320**, etc.

[0161] As further illustrated in FIG. **30**, the battery pack **310** also includes a housing or an enclosure **360** (also referred to as a battery enclosure **360** or a battery pack enclosure **360**), including a first portion **362** thereof, which is a bottom portion thereof as illustrated in FIG. **30**, and which may be referred to herein as a “tray” **362** or an “enclosure tray” **362**, and a second portion **364** thereof, which is a top portion thereof as illustrated in FIG. **30**, and which may be referred to herein as a “lid,” “cover,” or “enclosure cover” **364**. The enclosure tray **362** includes a tray floor **376** and tray sidewalls **378** extending upwardly from the tray floor **376** to define an internal tray cavity **384**. The enclosure cover **364** includes a cover ceiling **380** at a top thereof and cover sidewalls **382** extending downwardly from the cover ceiling **380** to define an internal cover cavity **386**. In some embodiments, a volume of the internal cover cavity **386** is larger than a volume of the internal tray cavity **384** such that the internal cover cavity **386** can accommodate a majority of the battery pack **310**. This is particularly the case when the multi-layer battery stack **314** includes a significant number (e.g., three, four, or five) of battery module layers **312**.

[0162] In some embodiments, the tray **362** may include some or all of the ports or other connectors or interfaces of the enclosure **360** through which electrical, thermal, and any other connections can be made between the battery pack **310** and other components outside of the enclosure **360**, and the cover **364** may include none of the ports or other connectors or interfaces of the enclosure **360** through which electrical, thermal, and any other connections can be made between the battery pack **310** and other components outside of the enclosure **360**. When the battery pack **310** is assembled, the components of the multi-layer battery stack **314** may be stacked on top of one another on top of the tray **362**, and the multi-layer battery stack **314** may be fixedly mounted to the tray **362**. Once these components have been assembled and plumbed to the enclosure interface with appropriate electrical cables and fluid conduits, then the cover **364** can be positioned over the multi-layer battery stack **314** to surround, house, and enclose the multi-layer battery stack **314**, and the cover **364** can then be securely coupled to the tray **362**. Such secure coupling can be achieved mechanically, such as with a plurality of bolts or other mechanical fasteners, and/or chemically, such as with an adhesive, glue, epoxy, etc. In some instances, the cover **364** is removably coupled to the tray **362** to facilitate servicing of the battery pack **310**.

[0163] Regardless of the manner in which the cover **364** is securely coupled to the tray **362**, it may be advantageous that each of the tray **362** and the cover **364** has a respective flat surface (e.g., a flat tray sealing surface **366** and a flat cover sealing surface **368**) so that these flat surfaces **366**, **368** can be flush against one another when the enclosure **360** is assembled, to improve a seal and/or other properties of the enclosure **360**. In some embodiments, one or both of the sealing surfaces **366**, **368** may include a groove extending a full distance around a peripheral portion of the enclosure **360**. In cases where a respective groove is provided in each of the sealing surfaces **366**, **368**, the grooves may follow identical paths such that a first portion of a gasket can be positioned within the groove formed in the sealing surface **366** and, when the cover **364** is positioned over the tray **362**, a second portion of the gasket can be positioned within the groove formed in the sealing surface **368**, such that the gasket forms a seal between the tray **362** and the cover **364** and such that the grooves limit or restrict the deformation of the seal.

[0164] It can be advantageous to make the tray **362** and/or the cover **364** from relatively lightweight materials, such as to reduce material costs and reduce overall weight of the enclosure **360**. Nevertheless, it can also be advantageous to make the tray **362** and/or the cover **364** from relatively heavy materials, such as to improve strength, rigidity, and durability of the enclosure **360**. Rigidity can be of particular importance in at least some portions of the enclosure **360** at least because it can facilitate the formation of the grooves (when provided) in the sealing surfaces **366** and **368**, and because it can facilitate formation of an adequate seal between the tray **362** and the cover **364**. In particular, as the tray **362** and cover **364** become more flexible, it becomes more difficult to maintain the sealing surface **366** flush against the sealing surface **368**, or an intermediate seal or gasket material.

[0165] Thus, in some embodiments, the cover **364** can be formed from at least two different sections or portions having a different degree of rigidity or other properties, such as for example, a first, more rigid lower portion **370** of the cover **362**, as illustrated in FIG. **30**, which is configured to directly physically engage with the tray **362**, and a second, less rigid upper portion **372** of the cover **364**, as illustrated in FIG. **30**, which is configured to extend over and around at least a portion of the multi-layer battery stack **314**, and which does not directly physically engage with the tray **362**. In some embodiments, the lower portion **370** can be more rigid than the upper portion **372** as a result of different material properties and/or different thicknesses, or gauges, of the two portions (that is, a material of the lower portion **370** can be thicker than a material of the upper portion **372**). In some embodiments, both of the first and second portions **370**, **372** can be metallic, and they can be coupled to one another by welding, such as at a welding seam **374** that extends a full distance around a peripheral portion of the enclosure **360**. This allows the lower portion **370** to be made from a relatively rigid cover component that is particularly stout and unsusceptible to elastic and/or plastic deformation under expected loading conditions to improve sealing between the tray **362** and the cover **364**, without unduly increasing the overall rigidity and/or weight of the enclosure **360**.

[0166] This also allows the lower portion **370** of the cover **364** to have a common configuration regardless of the height of the multi-layer battery stack **314** which varies with a number of the battery module layers **312** that are provided within a particular enclosure **360**. For example, the lower portion **370** can be coupled to a first upper portion **372** having a first height (in the direction D_V) or the lower portion **370** can be coupled to a second upper portion **372** having a second height (in the direction D_V), where the first height is different than the second height. This can simplify manufacturing by allowing a common lower portion **370** to be used to cover multi-layer battery stacks **314** of different sizes (e.g., different heights in the direction D_V). In some embodiments, the height of the upper portion **372** of the cover **364** in the direction D_V, and thus the overall height of the cover **364**, can be dependent upon the height of the multi-layer battery stack **314** it is intended to cover, and thus dependent at least in part on the number of battery module layers **312** and thermal management devices **320** in the multi-layer battery stack **314**. In some embodiments, each battery module layer **312** has a common footprint (i.e., a common width and common length in a horizontal plane) with only a height the multi-layer battery stack **314** being variable to advantageously enable use of the common lower portion **370** in battery packs **310** of different sizes, as described above.

[0167] In some embodiments, welding the upper portion **372** of the cover **364** to the lower portion **370** of the cover **364** can cause the material of the lower and/or upper portions **370**, **372** to warp or otherwise be deformed from their original shapes, e.g., such that they may have less planar profiles after the welding than before, particularly if the materials being welded are relatively thin or lightweight. Thus, to reduce the degree to which the at least the sealing surface **368** may be warped or otherwise deformed during the welding, the weld seam **374** can be located at least a threshold or minimum distance X_W from the portion of the cover **360** that includes the sealing surface **368**. In some embodiments, the threshold distance X_W may be at least 50 mm. In some embodiments, the weld seam **374** can be located closer to the tray **362** than to the cover ceiling **380** of the cover **364**.

[0168] In some embodiments, the entirety of the cover **364** can be made of a relatively lighter weight, more flexible material, rather than the cover **364** being formed from at least two different portions having disparate degrees of rigidity as described elsewhere herein, and may, as a result, lack a perfectly planar sealing interface. In such embodiments, the welding described herein need not be performed. In such embodiments, the tray sealing surface **366** can be coupled to the cover sealing surface **368**, such as chemically, by a sealant or adhesive, such as a gel and/or a glue, which can accommodate the relatively flexible nature of the entirety of the cover **364** and the larger tolerances associated with the sealing interface therewith. Such a sealant can be referred to as a liquid sealant. The liquid sealant may beneficially set to fill an irregularly shaped or contoured gap a sealing interface between the cover **364** and the tray **362**.

Structural Battery Pack Enclosure

[0169] The phrase "thermal runaway" should be construed broadly as a process that is accelerated by increasing temperature that in turn releases energy that further increases temperature, and in the context of electric vehicle batteries, may refer to at least one battery cell venting hot gas or hot gas entrained with debris that leads to breakdown and similar vent of other cells in the battery pack. In addition, vehicle crashes are known to be potentially deadly events that can also cause significant structural damage to the vehicles involved. When an electric vehicle is involved in a crash, the sudden impact to the battery of the electric vehicle can likewise lead to thermal runaway that increases the likelihood of a battery fire or other serious outcomes as a result of the crash. As a result, certain aspects of the present disclosure include battery pack enclosures that provide a structural support as well as a crumple zone. Such aspects of the present disclosure can include features that provide side impact protection and a greater capacity to absorb impact energy within a battery pack enclosure. The redundant sealing protects the battery pack from water intrusion.

[0170] With reference to FIG. **31**, an embodiment of a battery pack **310** includes a plurality of battery module layers **312** stacked together in an alternating fashion with a plurality of thermal management devices **320** to form a multi-layer battery stack **314**. Each battery module layer **312** includes a plurality of battery cells **316** arranged in an array as best shown in FIG. **32**. The thermal management devices **320** will be described in greater detail with reference to FIG. **32**. Each of the battery module layers **312** may be constructed or configured in accordance with the battery module layers **12**, **112**, **112'** described and shown at least with reference to FIGS. **2** through **6** and **9** through **13**. A battery pack enclosure **360** (also referred to as a battery enclosure **360** or enclosure **360**) surrounds the multi-layer battery stack **314**. As will be described in greater detail below, the battery enclosure **360** includes one or more crumple zones **301** (or crush zones) that are configured to deform in response to an impact event, such as from a vehicle crash, to absorb energy from the impact and assist in protecting the multi-layer battery stack **314** from damage, and, as a result, reduce the likelihood of thermal runaway.

[0171] The multi-layer battery stack **314** may be arranged with major sides **303** of the stack **314** extending in a longitudinal direction D_L such that the major sides **303** may also be referred to as major longitudinal sides **303** or as longitudinal sides **303** of the multi-layer battery stack **314**. The major sides **303** are best shown in FIG. **32**, as the major sides **303** of the multi-layer battery stack **314** are covered by the enclosure **360** in FIG. **31**. Continuing with reference to FIG. **31**, the enclosure **360** includes, for example, a respective crumple zone **301** (or crush zone) adjacent to at least two major sides **303** of the multi-layer battery stack **314**. In the embodiment shown in FIG. **31**, the enclosure **360** includes respective crumple zones **301** adjacent each of the four major sides (i.e., left, right, top, and bottom sides in the orientation of FIG. **31**) of the multi-layer battery stack **314**. In other words, the battery pack enclosure **360** includes a respective crumple zone adjacent each of longitudinal left and right sides **303**, and each of top and bottom longitudinal sides **303** of the multi-layer battery stack **314**.

[0172] The battery pack **310** may further include a battery pack rack **330** with a plurality of rack members **332**. Each battery module layer **312** may be secured to a respective rack member **332** with the rack members **332** coupled directly to the battery pack enclosure **360**, as shown in FIG. **31**. The rack members **332** may also be formed integrally with the battery enclosure **360** with each battery module layer **312** secured to a respective pair of rack members **332** on opposing sides of each layer **312**, such as on left and right longitudinal sides **303** of each layer **312** in a non-limiting example. In some embodiments, the battery pack rack **330** and the plurality of rack members **332** are a separate structure coupled between the battery enclosure **360** and the multi-layer battery stack **314**. In some instances, the rack members **332** may be arranged and spaced to apply a compressive load CL on the battery module layers **312** and the thermal management devices **320** to assist in maintaining the battery module layers **312** in thermal contact with each other and with the thermal management devices **320**. The battery pack rack **330** and the plurality of rack members **332** may also be constructed or configured, in whole or in part, in accordance with the battery pack frame **30**, **130** and plurality of frame members **32**, **132** described and shown at least with reference to FIGS. **2** through **6** and **9** through **11**.

[0173] The battery enclosure **360** may be provided in a number of different form factors. For example, with reference to FIG. **31**, the battery enclosure **360** may be provided in the form of a shell with two spaced apart layers **360**A, **360**B that are joined together at least by a plurality of structural supports **305**. In an embodiment, there are more than two layers **360**A, **360**B, such as at least three, four, five, or more layers. The spaced apart layers **360**A, **360**B of the shell enclosure **360** and the plurality of structural supports **305** define one or more air gaps **313** between such layers **360**A, **360**B and supports **305** that generally correspond to, or assist in forming, the one or more crumple zones **301**. The shell structure of the enclosure **360** may be formed by a plurality of separate and distinct side components **307** (also referred to as distinct shell portions **307**) that are joined together mechanically (i.e., with bolts or other mechanical fasteners) or chemically (i.e., with adhesive, glue, epoxy, etc.) to form the enclosure **360**. Each of the side components **307** may include a respective shell arrangement with respective layers **360**A, **360**B and supports **305** formed as a structural extrusion having a constant cross-sectional profile over a length of each component **307** in the longitudinal direction D_L. The enclosure **360** may also include two or more, or all, of the side components **307** integrally formed as a single structural extrusion.

[0174] For example, the bottom side component **307** may be a separate and distinct structure in a manner similar to the tray **362** described elsewhere herein, while the left, right, and top side components **307** are integrally formed as a single device akin to the cover **364** that can be coupled to the bottom side component **307** to improve assembly efficiency. In further embodiments, each of the components **307** may be separate, but with standard dimensions that generally correspond to different sizes of common battery packs, such as at least common battery pack **10** described with reference to FIGS. **1** through **16**, to enable efficient assembly of battery enclosures **360** of different sizes. To improve manufacturing efficiency, and as described in more detail with reference to FIG. **32**, the top and bottom side components **307** may be first side components **307**A with an identical size, shape, and/or arrangement, while the left and right side components **307** may be second side components **307**B that have an identical size, shape, and/or arrangement that is different from that of the first components **307**A to reduce the number of unique parts of the enclosure **360**.

[0175] FIG. **32** is a detail view of area A in FIG. **31**. The battery pack **310** includes the plurality of cells **316** arranged in an array extending in the longitudinal direction D_L to form each battery module layer **312** of the multi-layer battery stack **314** (FIG. **31**). The array of cells **316** in each layer **312** also collectively define the major sides **303** of the multi-layer battery stack **314** that likewise extend in the longitudinal direction D_L. The thermal management devices **320** may each be active heat exchangers (or more particularly battery cold plates), that are in direct thermal engagement with the array of battery cells **16** to provide cooling or heating of the battery cells **16** in operation. More specifically, the thermal management devices **320** may be provided in the form of a generally planar manifold that includes a heat transfer medium passageway to facilitate the circulation of a heat transfer medium through the manifold during operation to assist in drawing heat away from the battery cells **316** to cool the battery cells **316** or, alternatively, supplying heat to the battery cells **316** to heat the battery cells **316**.

[0176] As shown in FIG. **32**, one or more fittings **326** may be provided on each thermal management device **320** to enable conduits **325** for the heat transfer medium to be attached to the thermal management device **320** to enable fluid communication between one or more heat transfer medium passageways (not shown) of each thermal management device **320** with each other and other components of a thermal management system, such as one or more chillers and one or more heaters to enable the battery cooling and heating functionality described herein. Each of the thermal management devices **320** may be constructed or configured in accordance with the thermal management devices **20**, **120**, **120'** described and shown at least with reference to FIGS. **2** through **6** and **9** through **13**. Further, the multi-layer battery stack **314** is disposed in direct contact with a surface **309** of the battery pack enclosure **360** underlying the multi-layer battery stack **314**, which may be a heat transfer surface or thermal management device **320'** that is integrated with the pack enclosure **360** and includes internal heat transfer medium passageway **324'**.

[0177] At least one major side surface **311** of the battery pack enclosure **360** is spaced from the multi-layer battery stack **314**. The at least one major side surface **311** of the battery pack enclosure **360** may be an interior surface of the battery enclosure **360**, or more specifically, an interior surface of a respective at least one of the side components **307** that extends in the longitudinal direction D_L and faces a corresponding at least one major side **303** of the multi-layer battery stack **314**. In an embodiment, the space between the at least one major side surface **311** of the battery enclosure **360** and the multi-layer battery pack is an air gap and/or a debris collection space **403** of the type described elsewhere herein. In an embodiment, the at least one major side surface **311** includes major side surfaces **311** of the enclosure **360** on at least each of the left, right, and top sides of the enclosure **360** such that there is a space around at least three (i.e., left, right, and top) major sides of the multi-layer battery stack **314**.

[0178] As mentioned above, each of the side components **307**, as well as the enclosure **360** generally, may include one or more crumple zones **301** that are configured to deform in response to an impact event to assist in absorbing energy of the impact protecting the multi-layer battery stack **314** from damage. One such crumple zone **301** is indicated with a dashed oval in FIG. **32**. The crumple zones **301** are generally defined by an air gap **313** between the layers **360**A, **360**B (FIG. **31**) and the supports **305** of each side component **307** and/or the enclosure **360**. In an embodiment, the plurality of structural supports **305** (e.g., structural webs, partitions, or gussets) are arranged generally normal to the layers **360**A, **360**B of the shell structure of the enclosure **360** and/or the side components **307**. The first layer **360**A of the enclosure

360 and/or each side component **307** may be an outer layer that defines an outer surface **315** of the enclosure **360** and/or each respective side component **307**, while the second layer **360**B is an inner layer that defines the at least one major side surface **311** of the enclosure **360** that faces the multi-layer battery stack **314**. The first layer **360**A may be curved or angled to provide the outer surface **315** with a similar curved or angled shape. The second layer **360**B may be generally flat and planar to assist in accommodating the multi-layer battery stack **314**, which may be generally shaped as a rectangular prism.

[0179] In an embodiment, each of the plurality of side components **307** include a respective plurality of structural supports **305** that are spaced equidistant from each other, or with some other select spacing, across the respective side component **307**. Further, the curved shape of the first layer **360**A and the flat and planar shape of the second layer **360**B of each side component **307** interface at peripheral edges **317** of each side component **307**. As a result of the selected arrangement (i.e., equidistant spacing in some embodiments) of the structural supports **305**, the structural supports **305** proximate the peripheral edges **317** of each side component **307** may be positioned closer to each other than to the structural supports **305** proximate a center region **319** of each side component **307** to increase a structural strength of the shell proximate the peripheral edges **317** of each side component **307** and assist with defining the one or more crumple zones **301** proximate the center region **319** of each side component **307**. In an embodiment, the crumple zones **301** are the air gap **313** between a support **305** proximate the center region **319** of each side component and the next successive structural support **305** toward the peripheral edges **317**.

[0180] In addition, the curved or tapered outer surface **315** of the enclosure **360** and/or the side components **307** provide each of the side components **307** with a width or thickness **321** that changes over a height of the respective side components **307**. As a result, each of the side components **307** may have a tapered structure where the thickness **321** is smallest proximate one of the peripheral edges **317** and largest proximate the center region **319** of each side component **307** before returning to the smallest thickness **321** proximate the opposite peripheral edge **317**. The changing thickness **321** across each side component **307** provides a larger volume in the air gap **313** proximate the center region **319** and/or a vertex of each side component **307** and the corresponding major side **303** of the multi-layer battery stack **314**. In addition, the supports **305** of each side component **307** will have a height that varies with the thickness **321** of the side components **307**, meaning that supports **305** proximate the center region **319** will generally be taller than the supports **305** proximate the peripheral edges **317**, but may have a thickness that is similar to the supports at the peripheral edges **317** in some embodiments. The central supports **305** (i.e., supports **305** positioned proximate the center region **319** of the side components **307**) may provide structural support that serves to deflect impacts proximate the center region **319** of the side components **307** toward the crumple zones **301**.

[0181] In an embodiment, the crumple zone **301** may correspond to a majority of the side component **307**, including the structural support **305** positioned proximate the center region **319** of each side component **307**. The increased length or height of the central supports **305** reduces rigidity and increases flexibility in the central supports **305** such that during an impact event, a central portion of each side component **307** that generally corresponds to the major sides **303** of the multi-layer battery stack **314** will crumple before portions of the each side component **307** that are proximate the peripheral edges **317**. In addition, forces from the impact event are directed toward the more rigid portions of the side components **307** proximate the peripheral edges **317**. The peripheral edges **317** may in some instances be mounted on a chassis of a vehicle, such as the chassis **2** shown and described at least with reference to FIG. **1**, such that the forces from the impact event are directed from the crumple zone **301** or crumple zones **301** to the peripheral edges **317** and further to the vehicle chassis.

[0182] In some embodiments, the peripheral edges **317** of the side components **307** may be different from each other to assist in forming the enclosure **360**. For example, the peripheral edge **317** of the first side components **307**A (i.e., top and bottom side components **307**) may be provided in the form of a structural support **305**, meaning a wall that is normal to at least the second layer **360**B. The peripheral edge **317** of the second side components **307**B (i.e., the left and right side components **307**) may be an interface or meeting point between the curved and flat surfaces of the first and second layers **360**A, **360**B, respectively, that does not necessarily terminate in a support **305** or wall, but rather, extends to cover the support **305** or wall at the peripheral edge **317** of the corresponding first component **307**A and provide space for a connection between the first and second components **307**A, **307**B to form the enclosure **360**. Thus, aspects of at least the supports **305** and/or the overall shell structure of each side component **307** cooperate to define the crumple zones **301** and protect the multi-layer battery stack **314** from damage from an impact event.

[0183] As described elsewhere herein, at least a portion of each of the thermal management devices **320** may extend beyond an end face of the battery cells **316** to enable a mechanical connection between the thermal management devices **320** and the frame members **332** of the frame **330** to support the thermal management devices **320** and apply a compressive load on the multi-layer battery stack **314**. Such features are further illustrated in FIG. **33**. As illustrated in FIGS. **34**A and **34**B, such features provide additional benefits. In particular, FIG. **34**A illustrates a schematic view of the system in an ordinary working configuration, and FIG. **34**B illustrates a schematic view of the system when a collision or side impact has occurred and deformed the battery enclosure surrounding the multi-layer battery stack. As illustrated in FIG. **34**B in particular, in the event of a collision or side impact, the thermal management devices **320** extending laterally beyond end face(s) of the battery cells **316** results in the thermal management devices **320** being impacted before the battery cells **316**, thus providing an additional buffer or layer of protection for the battery cells **316** in the event of a collision. In other words, the thermal management devices **320** may provide intermittent stops or obstructions along a height of the enclosure to prevent a deformation of the enclosure from directly impacting the battery cells supported therein. Thus, the thermal management devices **320** can provide additional structure to protect the battery cells **316** in the event of a side impact or other impact event that may deform the enclosure.

[0184] The battery pack **310** of FIG. **31** and FIG. **32** is illustrated without end parts or end covers to facilitate understanding of the disclosure and in particular, of internal aspects of the battery pack **310**, and the advantages of certain aspects of the battery pack **310**. FIG. **35** is an exploded view of end parts **327** that are coupleable to the side components **307** to form the battery enclosure **360**. FIG. **36** shows the assembled battery enclosure **360**.

[0185] With reference to FIG. **35** and FIG. **36**, the battery enclosure **360** includes the plurality of side components **307** coupled together and/or integrally formed to generally surround the left, right, top, and bottom sides of the multi-layer battery stack **314**. The battery enclosure **360** further includes end parts **327** that are coupleable to opposing end sides **329** (i.e., front and rear sides in some embodiments) of the side components **307** to complete the battery enclosure **360**. Only a single end part **327** is shown in FIG. **35**, although an identical end part **327** may be attached to the opposing end side **329** of the side components **327** that is not visible in the orientation of FIG. **35** and FIG. **36** according to the techniques described herein. Each of the side components **307** and the end parts **327** may also be referred to as enclosure parts accordingly. The end parts **327** may be provided in a number of form factors, such as at least in a form similar to the side components **307** (but with a different shape in some embodiments) including at least two spaced apart layers **360**A, **360**B and supports **305** therebetween, or the end parts **327** may be provided as a generally flat and planar plate that may be a single layer of metal or other suitable material. In some embodiments, the end parts **327** may be removably coupleable to the shell or tubular structure formed by the side components **307** to enclose the multi-layer battery stack **314**. Such coupling may be accomplished mechanically (i.e., with bolts or other fasteners or connectors) as well as chemically (i.e., with adhesive, glue, epoxy, etc.).

[0186] The end parts **327** may be structured to seal against a respective one of the layers **360**A, **360**B of each side component **307** at opposing longitudinal ends **329** of the shell or tubular structure formed by the side components **307** to seal the multi-layer battery stack **314** within the enclosure **360**. More specifically, the end faces of the layers **360**A, **360**B of the side components **307** may define a respective sealing interface at opposing ends **329** of the structure formed by the side components **307**. The end parts **327** are attached in sealing engagement to the side components **307** at such sealing interfaces at the opposing ends **329** to prevent ingress of water, oil, debris, and other contaminants into the battery enclosure **360**. In an embodiment, such sealing arrangement at both opposite ends **329** includes two redundant layers of sealing generally indicated in FIGS. **35** and **36** by a dark line **331** representing an outer seal **331** and a light line **333** representing an inner seal **333**.

[0187] The outer seal **331** is positioned along, or proximate to, an outer peripheral edge or boundary of the end parts **327** and generally corresponds to a seal between the end plates **327** and the first layer **360**A of the side components **307**. The inner seal **333** is positioned inside the outer seal **331** (i.e., closer to a center of the end parts **327** than the outer seal **331**) and generally corresponds to a seal between the end plates **327** and the second layer **360**B of the side components **307**. Such redundant seals **331**, **333** may also be referred to as dual seals, wherein the end parts **327** interface with dual sealing surfaces (i.e., surfaces of layers **360**A, **360**B at the opposing ends **329**) to provide the redundant sealing. The layers **360**A, **360**B of each side component **307** as well as potentially of the end parts **327** in some embodiments, may also provide a redundant sealing structure because if the first or outer layer **360**A is compromised (i.e., punctured, cracked, damaged, etc.), then the second or inner layer **360**B may still prevent ingress of contaminants into the battery enclosure **360**. In addition, each of the side components **307** as well as each of the end parts **327** may be associated with fire retardant material (i.e., a fire retardant coating or all or at least a portion of these components or a separate layer of fire retardant material, etc.). Further, one or more fillings or porous materials may be provided in the air gap **313** in the side components **307** to soak up any materials that breaches a seal and/or the layers **360**A, **360**B and provide yet further redundancy against contaminants entering the enclosure **360**.

[0188] FIGS. **37** and **38** illustrate an additional embodiment of an end part **327*a*** that can be used in place of the end part **327**, and which may be referred to as an "end cap." The end part **327*a*** may be fabricated by casting, such as casting of a metallic material, and may include cast-in (i.e., not machined) features, including holes or apertures **327*b***. In use, conduits, wires, or other lines or devices (e.g., vents) can extend through such apertures **327*b***, such as to carry electricity (e.g., high-voltage and/or low-voltage electricity), communications, coolant, vent gases, and/or other materials, from one side of the end part **327*a*** to an opposite side of the end part **327*a*** (i.e., from inside an enclosure to outside the enclosure or from outside the enclosure to inside the enclosure). For this purpose, the end part **327*a*** may be provided with a variety of fittings, connectors and/or interfaces (not illustrated), such as, for example, one or more battery vents, electrical connectors, hydraulic fittings, to provide a generally sealed battery pack which can be connected and plumbed to other system components to provide various aspects of the battery pack functionality described herein.

[0189] FIG. **39** is a schematic cross-sectional view of a further embodiment of a battery pack **310** and battery pack enclosure **360**. The battery pack enclosure **360** may include a plurality of enclosure parts **335** that are coupled together to form the enclosure **360** as a tubular structure that circumferentially surrounds the multi-layer battery stack **314**. In other words, the enclosure parts **335** may have a hollow construction bounded by at least two layers **360**A, **360**B similar to side components **307** to provide the enclosure **360** with an overall tubular structure. Each enclosure part **335** may include a respective plurality of internal structural partitions **337** that, along with layers **360**A, **360**B, define a plurality of internal cavities **313** (also referred to as air gaps **313**) in the enclosure parts **335**.

[0190] The internal structural partitions **337** may be similar to the structural supports **305** described above, except that at least some of the partitions **337** are arranged in a lattice or wireframe structure and/or are otherwise positioned in the enclosure parts **335** with an arrangement that is different than the partitions **337** being normal to the layers **360**A, **360**B of the enclosure parts **335** as in FIGS. **31** through **34**. More specifically, at least some, most, or all of the partitions **337** may be positioned at an angle (i.e., a selected angle relative to horizontal between and including 15 degrees and 75 degrees) to the enclosure parts **335**, as shown in FIG. **35**. Certain ones of the partitions **337** may be positioned normal to the layers **360**A, **360**B (also referred to as normal partitions **337**N) at selected intervals along each enclosure part **335** with one or more angled partitions **337**A therebetween to define respective crumple zones **301**

between the normal partitions **337**N. As shown in FIG. **35**, a distance D_N between normal partitions **337**N proximate a center region **319** of each enclosure part **335** may be greater than, and in some cases, at least two times, three times, or four times or more, greater than a distance DE between normal partitions **337**N proximate peripheral edges **317** of the enclosure parts **335**.

[0191] FIG. **40** illustrates an additional embodiment of a battery pack enclosure **360***c* having features that can be combined with other battery pack enclosures described herein. The battery pack enclosure **360***c* may include a plurality of enclosure parts **335***a* that are coupled together to form the enclosure **360***c* as a tubular structure that circumferentially surrounds a multi-layer battery stack. The enclosures parts **335***a* may be in some instances extruded parts having a constant cross-sectional profile over a length thereof. The enclosures parts **335***a* may have a lattice-like structure with a plurality of internal cavities, which collectively provide structural rigidity and protection of the battery cells supported therein. In some instances, one or more heat exchange medium passages may be integrally formed in the battery enclosure parts **335***a* to assist in cooling or heating functionality described elsewhere herein. In such instances, heat exchange medium may be delivered to the battery pack and move through at least a portion of the battery pack enclosure **360***c* itself.

[0192] In view of the above, the battery packs of the present disclosure include battery pack enclosures with redundant sealing to prevent contaminant ingress. In addition, the present disclosure includes battery pack enclosures that can mitigate the effects of a crash or other impact event reducing the likelihood or otherwise mitigating the effects of, a thermal runaway condition as a result of such impact event by providing enhanced structural protection. The battery pack enclosures also can provide a robust package suitable for use in a variety of applications, including in connection with various electric vehicles including long-haul tractors.

Venting Gas Protection

[0193] When battery cells are overcharged, exposed to extreme temperature, or mechanically damaged, a thermal runaway may happen. During a thermal runaway event, high temperature gasses, and sometimes debris with a high temperature are discharged from the vent of the battery cells. Thermal runaway conditions can result in failure of the enclosure, as well as potentially more serious and dangerous outcomes such as a battery fire.

[0194] Turning to FIG. **41**, illustrated therein is a schematic representation of a thermal runaway condition. When pressure in the cells and/or enclosure represented by arrows **402** exceeds a threshold level of a membrane **404** or some other aspect of the vent(s) described herein, the membrane **404** will burst to allow discharged matter **401** to exit the battery cells and/or enclosure. The discharged matter **401** may be a hot gas, debris, or any combination thereof, such as a hot gas with entrained debris. The discharged matter **401** from one cell may flow to other battery cells and lead to decomposition of the surrounding battery cells to create a thermal runaway condition of the type described above. Thermal runaway can lead to destruction of the battery, damage to the enclosure, and/or substantial risk to occupants of the vehicle including the battery, such as with a battery fire.

[0195] With reference to FIG. **42**, a battery pack **410** (which may also be referred to herein as a battery pack system **410** or a system **410**) includes a multi-layer battery stack **414** as well as thermal management devices **420** above and/or below each of a plurality of battery module layers **412** that form the stack **414**, which may be, for example, provided in the form of active heat exchangers or more specifically battery cold plates, as described further elsewhere herein. More specifically, the battery pack **410** includes the plurality of battery module layers **412** stacked in a vertical direction to form the multi-layer battery stack **414** with each battery module layer **412** including a respective plurality of battery cells **416** arranged in a linear array. In the schematic cross-sectional view of FIG. **42**, only a single battery cell **416** of each layer **412** is shown. The battery pack **410** may also include a battery pack frame **430** including a plurality of frame members **432**, wherein each battery module layer **412** is secured to a respective frame member **432** to compress the thermal management devices **420** against the battery cells of each battery module layer **412** and hold the battery module layers **412** in compression in the stacked arrangement in the multi-layer stack **414**. As will be readily appreciated, the battery pack **410** described here may be built-up or configured according to the any of the aspects and features of the battery packs **10**, **110**, **110'** described above at least with respect to FIGS. **1** through **16**.

[0196] Each of the plurality of battery cells **416** include an end face **454** arranged normal to a direction in which the battery cells **416** are aligned in the linear array (namely, normal to a direction extending into and out of the page of FIG. **42**). At least a portion of each of the thermal management devices **420** may extend beyond the end face **454** of the battery cells **416** to enable a mechanical connection between the thermal management devices **420** and the frame members **432** of the frame **430** to support the thermal management devices **420** and apply a compressive load on the multi-layer battery stack **414**, as described herein. Each of the plurality of battery cells **416** further includes a vent **450** (also referred to as a vent valve **450**) located on the end face **454**. The vents **450** of the battery cells are in communication with an environment inside a battery enclosure **460** surrounding the multi-layer battery stack **414**, the thermal management devices **420**, and the battery pack frame **430**. In some embodiments, the multi-layer battery stack **414**, the thermal management devices **420**, and the battery pack frame **430** are spaced from the battery enclosure **460** by at least a debris collection space **403** that may be provided in the form of an air gap between the enclosure **460** and the battery pack frame **430**, or between the enclosure **460** and other internal aspects of the battery pack **410**. The vents **450** may be provided in a number of different form factors that are capable of allowing gases to enter and escape the battery cells.

[0197] The battery pack **410** may further include vent protection functionality to decrease the likelihood of thermal runaway conditions and improve safety and operational lifespan of the battery pack **410**, among other benefits. More specifically, the plurality of frame members **432** of the battery pack frame **430** may have vent protection functionality by being integrally formed with, or as, vent isolators. In such an embodiment, the frame members **432** serve as vent isolators and have the structural features and functionality of the frame members **432** described herein, but are also configured to assist in isolating discharged matter from the vent **450** of any one of the battery cells of each battery module layer **412** from the vents **450** of adjacent battery cells of the battery module layer **412** and to assist in directing the discharged matter away from the end face **454** of the battery cell during a thermal runaway event. The following description is directed to embodiments where the frame members **432** include such integrated vent isolation features and functionality, although it is to be appreciated that the vent isolators may also be a separate structure with similar features that is coupled to a respective frame member **432**, bracket, or other fastening device of any of the battery pack frames **430** and/or battery packs **410** described herein in further embodiments. To assist in understanding the benefits and advantages of the disclosure, the frame members **432** will be referred to as vent isolators **432** in the following description of FIGS. **42** through **45** only.

[0198] The battery pack frame **430** may include a single vent isolator **432** for each battery module layer **412** in the multi-layer battery stack **414** with the vent isolator **432** provided in a form factor of an angle iron with a respective vent aperture **405** facing and aligned with the vent **450** of each battery cell **416** in each battery module layer **412**, as further described below. In an embodiment, the vent isolators **432** may be a "U"-shaped frame member that defines an interior hollow channel **407** that is open on one side via a vent slot **409** extending along a longitudinal length of the respective vent isolator **432**. In FIG. **42**, the channel **407** is generally positioned with the vent slot **409** facing downward and opening into the space **403** according to the ordinary meaning of "down" as gravity pulls objects down. As a result, the vent slot **409** may be at a bottom of each vent isolator **432**, while the vent apertures **405** are positioned normal to the vent slot **409** and on a face of the respective vent isolator that interfaces with the end face **454** of the battery cells of each layer **412**.

[0199] According to the illustrated embodiment of FIG. **42**, each vent isolator **432** includes a first vertical sidewall **411** and a second vertical sidewall **413** opposite the first vertical sidewall **411** connected by a transverse sidewall **415** with the transverse sidewall **415** defining a width or thickness of the vent isolator **432**. The first vertical sidewall **411** includes the series of vent apertures **405** and interfaces with the end face **454** of each battery cell **416** in each battery module layer **412**. Further, the sidewalls **411**, **413**, **415** cooperate to define the hollow channel **407**. Each of the second vertical sidewall **413** and the transverse sidewall **415** may be a solid piece of metal or some other suitable material, with "solid" meaning that these sidewalls **413**, **415** do not include openings, apertures, or other like structures and that gas and liquid are not capable of flowing through these sidewalls **413**, **415**. Further, each of the vent isolators **432** may be bare metal, or may include a fire retardant coating on at least a portion of, or all of, the vent isolators **432**. In an embodiment, each of the plurality of battery cells **416** may likewise be coated with a fire retardant material.

[0200] In yet further embodiments, only certain aspects of the battery pack **410** are associated with fire retardant material, which may be a fire retardant coating, a layer of fire retardant material, or others. For example, only a surface area of, or at least a portion of a surface area of, the end face **454** of each battery cell and/or only select vent isolators **432** may be associated with fire retardant material based on design factors, such as likely locations of occurrence of thermal runaway conditions and the risks associated therewith in different locations in the battery pack **410**. Thus, in some embodiments, a fire retardant material may be associated with at least some of the plurality of vent isolators **432** or at least some of the plurality of battery cells **416**, or both. As shown in FIG. **42**, the battery pack **410** may also include a layer of fire retardant material **417** in direct contact with, or in close contact with, the battery enclosure **460** in a vicinity of the vents **450** of the battery cells **416** of the multi-layer battery stack **414**. In an embodiment, the layer of fire retardant material **417** is on an entire internal surface of the battery enclosure **460**. The battery pack **410** may further include a plurality of debris dams **419** that assist with holding each cell **416** in the battery module layers **412** in place while also protecting at least a portion of the end face **454** of each cell **416**, as further described below.

[0201] During a thermal runaway event, each vent aperture **405** defines at least a portion of a guide, conduit or passageway that assists in routing discharged matter from an associated one of the battery cells away from the vent **450** associated with the respective vent aperture **405** and away from the end face **454** of the battery cells. More specifically, the structure of the first vertical sidewall **411** surrounding each vent aperture **405** may be described as defining at least a portion of a guide, conduit, or passageway that assists in collecting and routing discharged matter from one of the battery cells away from the end faces **454** of the cells and toward the debris collection space **403**, as generally indicated by dashed arrow **421**. Likewise, the second vertical sidewall **413**, the transverse sidewall **415** and/or the slot **409** may further define at least a portion of a guide, conduit, or passageway that assists in collecting and routing discharged matter from one of the battery cells away from the end faces **454** of the cells and toward the debris collection space **403**, as generally indicated by dashed arrow **421**. The debris collection space **403** may be positioned along a periphery of the battery pack **410**, and more specifically, along a periphery of the multi-layer battery stack **414** that is spaced from the end faces **454** of the battery cells **416**. At the same time, the debris dams **419** protect at least a portion of the end faces **454** of the cells at the bottom of each battery module layer **412** where discharged matter may otherwise be prone to collect as it travels to the debris collection space **403** during a thermal runaway event. In an embodiment, the debris dams **419** are shaped to direct debris away from each end face **454** and toward the debris collection space **403**, for example, by having a shape that curves away from, or is positioned at angle away from, the end faces **454** of the battery cells **416**. Such an arrangement may assist in preventing high temperature venting gas from directly impinging on the end faces **454** of the battery cells or some other portion of the battery cell surface, while also redirecting any discharged matter that impinges on the debris dams **419** toward the debris collection space **403**. In some embodiments, the debris collection space **403** is elongated and spans an entirety or substantially an entirety of a longitudinal length of the linear array of the battery cells **416** of each battery module layer **412** and thus is capable of collecting and holding a substantial amount of discharged matter without such matter contacting the other cells **416**.

[0202] FIG. **43** is an isometric view of one battery module layer **412** of the battery pack **410**. Each battery module layer **412** includes a plurality of battery cells **416** of the type described herein that are arranged in a series or array, and in direct contact with the thermal management device **420**

underlying the cells **416**. The debris dam **419** may be in direct contact with the thermal management device **420** and positioned adjacent a bottom portion of each end face **454** of the cells **416** to protect the bottom portion of each end face **454**. The vent isolator **432** is spaced from the debris dam **419** across at least a select portion of a height of the battery cells **416** in the layer **412** and may be positioned proximate a top surface of the cells **416** in some embodiments. In an embodiment, the vent isolator **432** may also have a different location corresponding to the location of the vents **450**. Further, the vent isolator **432** spans a series of the battery cells **416** of the battery module layer **412**, meaning that the vent isolator **432** extends across multiple end faces **454** of multiple respective battery cells **416** in a direction that is parallel to a direction Dc in which the battery cells **416** are generally arranged in the series or array.

[0203] FIG. **44** shows the vent isolator **432** in more detail. The vent isolator **432** includes a linear array of vent apertures **405** in the direction Dc. Each vent aperture **405** is aligned with a respective one of the vents **450** of the series or array of the battery cells **416** of the battery module layer shown in FIG. **43**. FIG. **44** also provides more detail regarding the features or aspects of at least some embodiments of the vent isolator **432** described with reference to FIG. **42**, such as for, example, the channel **407**, the vent slot **409**, and the sidewalls **411**, **413**, **415**, as well as the overall shape and structure of the vent isolator **432**. As shown in FIG. **44**, the channel **407** and vent slot **409** may extend along an entirety of the vent isolator **432** in the direction Dc, or a direction that is parallel to the direction De to facilitate alignment of the vent apertures **405** with the vents **450** of the cells **416**.

[0204] Turning to FIG. **45**, each vent isolator **432** may include a plurality of separators **423** (which may also be referred to herein as walls **423** or partitions **423**) that may be internal to the isolator **432** and positioned between adjacent vent apertures **405** in the linear array of apertures **405**. The separators **423** may be a solid material according to the above definition of "solid" that assists in preventing discharged matter from one vent **450** or cell **416** from impacting, directly or indirectly, the other vents **450** and cells **416**. Further, the separators **423** may nearly completely seal and/or isolate an internal space of the vent isolators **423** between respective adjacent vent apertures **405** such that discharged matter from one vent **450** of one cell **416** cannot reasonably contact the vents **450** of other adjacent cells **416**. More specifically, "nearly completely seal and/or isolate" means that each separator **423** may be extend between, and be coupled to and in sealing contact with the sidewalls **411**, **413**, **415** to create a generally isolated or sealed space around each vent aperture **405** that is only open at the bottom through the vent slot **409**. As a result, the only path out of the vent isolator **432** for discharged matter from one vent **450** of one cell **416** is through the vent slot **409** (FIG. **42**) at the bottom of each respective isolated or sealed space around each vent aperture **405**. In this way, the separators, as well as the vent isolator **432** generally, assist with preventing discharged matter from one cell **416** during a thermal runaway event from contacting other cells **416**, and in particular the vents **450** of other cells **416**, to significantly reduce the likelihood of a thermal runaway condition and the risks and potential damage associated with the same. The separators **423** may be the same material as the vent isolators **432**, or may be a different suitable material, and may be formed integrally with the vent isolator **432** or separately fastened thereto. In an embodiment, at least a portion of, or all of, each of the separators **423** are associated with fire retardant material.

[0205] The above features may also be recited as one or more steps in a method, such as during a thermal runaway event, isolating discharged matter from the vent **450** of one battery cell **416** from vents **450** of adjacent battery cells **416** of the battery pack **410** with the vent isolator **423** the above-described structure. The method further includes collecting the discharged matter in the debris collection space **403** provided around the periphery of the battery pack **410**. Additional steps in the method are contemplated herein based on the above description of FIGS. **41** to **45**.

[0206] In view of the above, the vent isolators **432** and debris collection space **403** assist with preventing direct impingement of high temperature discharged matter from one cell **416** during a thermal runaway event from contacting other cells **416** to significantly reduce the likelihood of a thermal runaway condition with other cells **316** and the risks and potential damage associated with the same.

[0207] FIG. **46** illustrates a battery pack **410'** that may be an embodiment or implementation of the battery pack **410** represented schematically in FIG. **42**. The battery pack **410'** includes a plurality of battery module layers **412'** stacked in a vertical direction to form a multi-layer battery stack **414'** with each battery module layer **412'** including a respective plurality of battery cells **416'** arranged in a linear array. The battery pack **410'** may also include a battery pack frame **430'** including a plurality of frame members **432'**, wherein each battery module layer **412'** is secured to a respective frame member **432'** to compress thermal management devices described elsewhere against the battery cells **416'** of each battery module layer **412'** and hold the battery module layers **412'** in compression in the stacked arrangement in the multi-layer stack **414'**. The battery pack frame **430'** may be similar, or identical, to battery pack frame **130'** described with reference to FIGS. **9** and **10**. Each battery cell **416'** includes an end face **454'** with a vent **450'** (or vent valve **450'**) located on the end face **454'**, as best shown in the detail view of FIG. **46**. Except as otherwise noted, the remaining features of the battery pack **410'** may be similar or identical to battery pack **10** and/or battery pack **110**, **110'** described elsewhere.

[0208] The frame members **432'** provide the vent protection functionality described above in FIG. **42**, which is explained herein with reference to FIG. **47** based on the embodiment or implementation of the battery pack **410'**. Specifically, FIG. **47** is a cross-sectional view of the battery pack **410'** along line A-A in FIG. **46**. FIG. **47** illustrates a cross section of specific battery cells **416'** in each battery module layer **412'**. In an embodiment, the frame members **432'** may be right angle or 90-degree angle frame members **432'**. As shown in FIG. **46**, the frame members **432'** are spaced from each other over a height of the battery pack **410'**, with each frame member **432'** generally having a height that is less than a majority of a height of a respective end face **454'** of the battery cells **416'**. Thus, there is a space or gap **403'** between the frame members **432'** that may be similar to debris vent space **403** described above. Although not shown, the battery pack **410'** may also include an enclosure of the types described herein coupled to the battery pack frame **430'** and generally enclosing the multi-layer battery stack **414'** (FIG. **46**). Thus, the space **403'** may be between the end faces **454'** of the battery cells **416'** and the battery enclosure that is limited in part by the frame members **432'**.

[0209] If a venting event occurs during operation, debris is vented from the vents **450'** on the end face **454'** of one or more battery cells **416'** in a layer of the multi-layer stack **414'**. The vented matter is guided by the frame members **432'** through the space **403'**. The frame members **432'** of other layers act as a shield that protects the vents **450'** and the end faces **454'** generally of the cells **416'** in the other layers by preventing the vented debris from contacting the vents **450'** and/or end faces **454'** of the other layers. Thus, the vented debris is prevented from contacting additional cells **416'** to reduce the likelihood of a thermal runaway event, battery fire, or other adverse impacts. The path of the vented debris is illustrated in FIG. **47** by arrow **421'**. In sum, the vented debris is directed outward and downward in the orientation of FIG. **46** by at least the frame members **432'**, through the space **403'**, and toward a bottom of the battery pack **410'** for collection without contacting the cells **416'** in other layers **412'** of the battery pack **410'**. In this way, the battery pack frame **430'** may be implemented with frame members **432'** that assist with preventing discharged matter from one cell **416'** during a thermal runaway event from contacting other cells **416'**, and in particular the vents **450'** and/or end faces **454'** of other cells **416'**, to significantly reduce the likelihood of a thermal runaway condition and the risks and potential damage associated with the same.

[0210] FIG. **48** is an isometric view of a further battery pack **410"** with vent protection functionality. As noted herein, the battery packs described in the disclosure may include a variety of different types of battery cells, including but not limited to prismatic battery cells. The further battery pack **410"** is an example embodiment of a battery pack **410"** that includes such prismatic cells **416"** arranged in layers **412"** in a multi-layer battery stack **414"**. Each layer **412"** may include a plurality of cells **416"** in several rows and columns with the rows and columns adjacent to each other or spaced from each other according to the size of the layer **412"** and/or battery pack **410"**, which may be selected. For example, the battery pack **410"** of FIG. **48** may include layers **412"** with three rows of battery cells **416"** in a length or longest dimension of the battery pack **410"** and a selected number of columns in a width dimension, such as at least 10, 20, or more columns. Although not shown, the battery pack **410"** may be associated with a battery pack enclosure of the types described herein. The battery pack **410"** may also include a battery pack frame **430"**, albeit the frame members **432"** are omitted in favor of the vent isolators described below.

[0211] The prismatic cells **416"** have an end face **454"** that may be at the top of the cells **416"** such that the end face **454"** is a top outermost surface of the cells **416"** according to the orientation of FIG. **48**. The cells **416"** may also be arranged with the end face **454"** being a bottom outermost surface, or a side outermost surface depending on the selected orientation of the cells **416"**. A vent **450"** of the cells **416"** is located on the end face **454"**, or at the top of the cells **416"** in the illustrated embodiment. As shown in FIG. **48**, the vents **450"** of the cells **416"** in each row of cells **416"** in the lengthwise direction of each layer **412"** may generally be aligned with each other. A vent isolator **432"** is associated with each row of vents **450"**, such as the three vent isolators **432"** for the three rows of vents **450"** in the battery pack **410"**. The vent isolator **432"** may be a structural frame member that enables stacking of the layers **412"**. Further, the vent isolators **432"** may be provided in only one layer **412"** and for each of the rows of vents **450"**, or may be provided in each layer **412"** or selected layers **412"**. While the vent isolators **432"** are preferably associated with each row of vents **450"**, the disclosure contemplates vent isolators **432"** being associated with less than each row of vents **450"**, such as only selected rows of vents **450"**.

[0212] The vent isolators **432"** have a frame construction with rails **433"** engaging and coupled to a top plate **435"**. The rails **433"** are spaced from each other across the vents **450"** and the top plate **435"** is a continuous sheet such that the combination of the rails **433"** and top plate **435"** defines a channel or space **403"** for distribution of vented debris that may generally be similar to the debris vent spaces **403**, **403'** described above. The vent isolators **432"** further include a bottom plate **437"** with a plurality of apertures **439"** that are generally provided in a number and arrangement that corresponds with the vents **450"** in each row of cells **416"**. The bottom plate **437"** bounds the debris vent space **403"** at the bottom, except for apertures **439"**. The plurality of apertures **439"** may be separated from each other by portions of the bottom plate **437"**. Thus, during a venting event, ejected debris and other matters from the vents **450"** is provided to the channel or debris vent space **403"** between the rails **433"** and the top plate **435"** with the rails **433"** and top plate **435"** functioning to guide the ejected debris and other matters away from other cells **416"** in other rows and from other layers **412"** in the battery pack **410"**, as further described below.

[0213] FIG. **49** is a cross-sectional view of an array or row of battery cells **416"** of the further battery pack **410"** along line B-B in FIG. **48** illustrating operation of the vent isolators **432"**. During a venting event, debris is ejected from vents **450"** on the end face **454"** and passes through apertures **439"** in the bottom plate **437"** of the vent isolators **432"** to be collected in the channel or debris vent space **403"**. The rails **433"**, top plate **435"**, and bottom plate **437"** guide the vented debris along the debris vent space **403"** under pressure from the venting event until it is ejected at outer end faces or sides **441"** of the respective array or row of battery cells **416"**, as indicated by arrows **421"**. Because the prismatic cells **416"** are generally smaller in size, and in some embodiments, much smaller than the other battery cells, such as battery cells **416** and **416'** (and other like battery cells described herein), the vents **450"** of successive cells **416"** in each row can be in communication with each other via apertures **439"** without causing a significant thermal runaway event. In other words, venting of the cells **416"** associated with each vent isolator **432"** may not be significant enough to cause the serious impacts and risks described herein with larger scale thermal runaway events, such as for an entire layer of cells **416"** or entire battery pack **410"**. In this way, the battery pack **410"** may be implemented with vent isolators **432"** that assist with preventing discharged matter from one row of cells **416"** during a thermal runaway event from contacting other rows of cells **416"** and other layers **412"** of cells **416"**. The vent isolators **432"** may also be arranged at the top end face of prismatic cells **416"**, among other variations discussed herein.

Venting Gas Detection

[0214] The battery packs of the present disclosure may further include venting detection and warning functionality, meaning, the battery packs include aspects and/or techniques for detecting whether a thermal runaway event (or venting event) has occurred with at least one battery cell and providing a suitable warning indication to a driver and/or occupant of a vehicle including the battery pack. Such a warning indication may provide time for the driver and/or occupant(s) to safely exit the vehicle to mitigate the risk of harm to the driver and/or occupant(s) in the event of battery thermal runaway of the type described herein.

[0215] With reference to FIG. **50**, one or more embodiments of the battery pack **410** include the multi-layer battery stack **414** surrounded by the battery enclosure **460** (which may also be referred to herein as a battery pack enclosure **460**). The multi-layer battery stack **414** includes a plurality of battery module layers **412** stacked to form the multi-layer battery **414** with each battery module layer **412** including a respective plurality of battery cells arranged in an array. FIG. **50** is a schematic cross-sectional view such that only one battery cell in the array forming each layer **412** is shown. Each battery cell includes the vent **450** that is configured to discharge matter upon a fault condition of the battery cell, as described herein. The multi-layer battery stack **414** may be separated from the battery enclosure **460** by an air gap **451**. In some embodiments, the air gap **451** surrounds the multi-layer battery stack **414**. It is appreciated that the battery pack **410** and multi-layer battery stack **414** may be built-up or constructed in accordance with any other the battery packs disclosed herein, including, for example, the battery packs **10**, **110**, **110'** and battery pack stacks **14**, **114**, **114'** described with reference to FIGS. **2** through **6** and **9** through **13**.

[0216] The battery pack **410** further includes at least one sensor **453**. The at least one sensor **453** may be disposed on the battery enclosure **460**, on the multi-layer battery stack **414**, or in some other location. Further, the at least one sensor **453** may be positioned in a selected location relative to the battery enclosure **460** and/or the multi-layer battery stack **414**, such as in upper corners or any upper portion of the battery enclosure **460** and/or multi-layer battery stack **414** in some non-limiting examples. The at least one sensor **453** is in communication with the air gap **451** around the multi-layer battery stack **414**. As will be described in more detail below, the at least one sensor **453** is configured to detect a change in at least one characteristic of the battery enclosure **460** over time, or more particularly, at least one characteristic of the air gap **451** internal to the battery enclosure **460** over time. The at least one characteristic may be associated with vented matter from the vent **450** of at least one of the battery cells during a thermal runaway event of the type described herein. The battery pack **410** may include only a single sensor **453**, or may include more than one sensor **453**. In some non-limiting examples, the at least one sensor **453** may be only a pressure sensor operable to detect pressure over time (e.g., 1000 Pa above ambient) and/or a rate of pressure change in the air gap **451**, only a gas sensor operable to detect a change in gas concentration over time, or a combination of such a pressure sensor and a gas sensor.

[0217] In an embodiment where the at least one sensors **453** is a pressure sensor **453**, the pressure sensor **453** may be a transducer operable to detect pressure of the air gap **451**, and the controller **455** described further below may detect or determine pressure over time or the rate of pressure change over a detection period based on the raw pressure measurements from the pressure sensor **453**. In further embodiments, the pressure sensor **453** may be associated with a clock or timer that is part of the pressure sensor **453** or is onboard the controller **455** to facilitate such pressure rate calculations at the pressure sensor **453**. Where the at least one sensor **453** is a gas sensor **453**, the gas sensor **453** may likewise be a sensor operable to detect or determine gas concentration of the air gap **451** over time, with the controller **455** further configured to interpret the raw gas concentration measurements. The present disclosure also contemplates use of additional and/or different types of sensors, which may include, but are not limited to, vibration sensors, temperature sensors, and others.

[0218] The following description includes certain non-limiting examples of techniques for detecting or determining pressure over time, but it is to be appreciated that such detection or determination of pressure over time may also be used to calculate a rate of pressure change over an observed period of time, such as at least with assistance from the controller **455**. The at least one sensor **453** is in communication, either wired or wirelessly, with a controller **455** (which may also be referred to herein as a computing system **455**) that may be carried by the battery pack **410** or may be located external to the battery pack **410**. The controller **455** will be described in more detail with reference to FIG. **53**, but briefly, the controller **455** receives instructions, signals, and/or data from the at least one sensor **453** regarding the detected conditions in the battery enclosure **460** (i.e., the detected conditions of the air gap **451**) and may transmit instructions, signals, and/or data to a status indicator **457**. The status indicator **457** is therefore in communication, either wired or wirelessly, with the at least one sensor **453**. The status indicator **457** is operable to provide at least one warning indication to a driver and/or occupant of a vehicle including the battery pack **410** in response to the detected change in the at least one characteristic over time in the battery pack enclosure associated with discharged matter from the vent valve **450** of at least one of the battery cells **412** via the at least one sensor **453**.

[0219] The status indicator **457** may be positioned in the vehicle, such as on a dashboard, in or proximate to an instrument cluster, or some other location that is preferably proximate to, or in a line of sight of, the driver of the vehicle. Further, the status indicator **457** may be one or more light-emitting diodes (LEDs), a speaker, a buzzer, or any combination thereof. As a result, the at least one warning indication provided by the status indicator **457** may be a haptic signal, a visual alert, an auditory alert, or any combination thereof in some embodiments. The controller **455** may also be in communication with a mobile device of the driver and may provide instructions, signals, and/or data to the mobile device to provide additional warning indications of the type described herein via onboard hardware of the mobile device.

[0220] The battery enclosure **460** may include a relief valve **459** located anywhere along the battery enclosure **460**, such as at a top or a side of the battery enclosure **460** in some non-limiting examples. The relief valve **459** may be provided in a form factor that is similar to the vents **450** of the battery cells described herein and illustrated in FIG. **41**, or some other type. The relief valve **459** is configured to allow air and other gases to enter and escape the battery enclosure

460 while preventing ingress of water, oil, other liquids, and dust and debris into the battery enclosure **460**. In particular, the relief valve **459** is operable to expel pressure and/or gas accumulated in the battery enclosure **460** that exceeds a threshold pressure and/or that is actuated in response to the change in at least one characteristic of the battery enclosure **460** over time, such as, for example, a gas concentration exceeding a threshold limit as described herein to prevent failure of the battery enclosure **460** or a thermal runaway condition. The relief valve **459** may operate automatically, meaning that the relief valve **459** includes aspects for venting the pressure and/or gas at the threshold pressure and/or threshold gas concentration. Alternatively, the relief valve **459** may be in wired or wireless communication with the controller **455** and the controller **455** sends instructions, signals, and/or data to the relief valve **459** to expel pressure and/or gas upon detection of a thermal runaway event via the at least one sensor **453**.

[0221] FIG. **51** is a graphical representation of pressure in the battery enclosure **460** over time. In particular, FIG. **51** is provided to illustrate one or more embodiments where the at least one sensor **453** is a pressure sensor **453**, and the associated detection of a thermal runaway event of at least one battery cell in the battery enclosure **460** by measuring pressure in the air gap **451** in the battery enclosure **460** with the pressure sensor **453**. In FIG. **51**, pressure is on the vertical or y-axis and time is on the horizontal or x-axis. The units for the pressure may be Pascals (Pa), and the units for time may be seconds(s).

[0222] Under normal operating conditions, the battery pack **410** may experience comparatively small variations in pressure over time in the air gap **451** inside the battery enclosure **460** that may be attributable to vibrations from driving the vehicle, and/or temperature fluctuations in the battery enclosure **460** as a result of environmental conditions around the battery pack **410**, operation of the cooling systems described herein, operation of the battery cells, or any combination thereof. These comparatively small variations are represented in FIG. **51** by a first portion **461** of the graph line that includes small peaks and valleys. When a thermal runaway event occurs in one or more of the battery cells, the one or more battery cells vent matter in the nature of hot gas or hot gas entrained with debris. The vented matter results in a relatively sudden increase in pressure that continues to increase as the matter is discharged to provide a pressure profile similar to that illustrated by a second portion **463** of the graph line. As shown with the dashed arrow in FIG. **51** labeled **464**, an initial portion of the second portion **463** of the graph line associated with the thermal runaway event has a sustained positive slope that is noticeably discernable from the pressure fluctuations of the first portion **461**. The dashed arrow **464** in FIG. **51** is a visual representation of the rate of pressure change in the air gap **451** that is associated with a thermal runaway event and lasts for a duration that is considerably longer in duration than variations in pressure over time in the air gap **451** associated with vibration and/or temperature variations during normal operating conditions shown in the first portion **461** of the depicted pressure profile, which notably include increasing and varying rates of pressure change, and decreasing and varying rates of pressure change that fluctuate over relatively shorter durations. Notably, the sustained period of time in which the rate of pressure change exceeds a particular threshold value reflected in the second portion **463** of the illustrated pressure profile may be used to identify a thermal runaway event.

[0223] Again, in some embodiments, a sustained rate of pressure change (DP/DT) that exceeds a threshold value for an extended threshold duration may be used to identify a thermal runaway event. In some instances, the threshold value of the sustained rate of pressure change (DP/DT) may be a rate of pressure change of at least 50 Pa/s, and the threshold duration may be at least three seconds. In some instances, the threshold value of the sustained rate of pressure change (DP/DT) may be between and including 50 Pa/s and 150 Pa/s, and the threshold duration may between and including 3 seconds and 5 seconds. In an advantageous embodiment, the graphical representation generally corresponds to the at least one sensor **453** being a pressure sensor **453** operable to detect or determine pressure over time, and in turn a rate of pressure change (DP/DT). The pressure sensor **453** may send information, signals, and/or data to the controller **455** and/or status indicator **457** to provide the at least one warning indication once the detected or determined pressure and/or rate of pressure change by the pressure sensor **453** in the air gap **451** is greater than established thresholds for a particular threshold duration or time, such as the thresholds described immediately above. In this way, small variations in pressure, such as those that correspond to the first portion **461** of FIG. **51** do not result in the status indicator **457** providing the at least one warning indication.

[0224] In a non-limiting example, if the air gap **451** has a volume of approximately 130 liters (L) and the thermal runaway event releases 0.1 L/s of hot gas or hot gas entrained with debris, then the pressure inside the battery enclosure **460** will increase by approximately 75 Pa/s, which is a considerably larger rate of pressure change than is expected to occur during normal operating conditions. Other variations are possible based on a number of factors such as the size, type, and/or number of battery cells as well as characteristics of the battery enclosure **460** such that the above ranges may be higher or lower than the stated amounts in some embodiments.

[0225] Upon occurrence of a thermal runaway event that results in a pressure profile that exceeds pre-established thresholds, the pressure in the battery enclosure **460** may be vented by the relief valve **459** of the battery enclosure **460** (FIG. **50**). In this way, the relief valve **459** of the battery enclosure **460** may assist with regulating pressure inside the battery enclosure **460** and preventing damage to the battery enclosure **460** and mitigating the likelihood of other more serious outcomes, following a thermal runaway event.

[0226] FIG. **52** is a graphical representation of detected gas concentration in the battery enclosure **460** over time. In particular, FIG. **52** is provided to illustrate one or more embodiments where the at least one sensor **453** is a gas sensor **453**, and the associated detection of a thermal runaway event of at least one battery cell in the battery enclosure **460** by measuring changes in gas concentration in the air gap **451** in the battery enclosure **460** with the gas sensor **453**. In FIG. **52**, gas concentration (GC) is on the vertical or y-axis and time is on the horizontal or x-axis. The units for the gas concentration may be parts per million (ppm) and the units for time may be seconds(s).

[0227] Under normal operating conditions, the battery pack **410** may experience comparatively small variations in gas concentration over time in the air gap **451** inside the battery enclosure **460** that may be attributable to operation of the battery cells, or other factors. These comparatively small variations are represented in FIG. **51** by a first portion **467** of the graph line that includes small peaks and valleys. In practice, such peak and valleys in the first portion **467** may instead be a steadily increasing gas concentration, but with a sustained rate of increase that is significantly lower than that associated with a thermal runaway (or venting) event, as described further below. When a thermal runaway event occurs in one or more of the battery cells, the one or more battery cells vent matter in the nature of hot gas or hot gas entrained with debris. The gas may include carbon monoxide (CO), carbon dioxide (CO2), a lithium complex (LiX) including lithium in combination with other elements, or any combination thereof. The vented matter corresponds to a relatively sudden significant increase in gas concentration over a short time that is generally illustrated by a second portion **469** of the graph line. As shown with the dashed arrow in FIG. **52** labeled **471**, at least a portion of the second portion **469** of the graph line has a sustained positive slope that may be steeper and readily discernable from the first portion **467** of the graph line. The dashed arrow in FIG. **52** labeled **471** is a visual representation of the rate of change in gas concentration in the air gap **451** that is associated with a thermal runaway event being considerably higher for a considerably longer in duration than changes in gas concentration, if any, in the air gap **451** associated with normal operating conditions shown by the first portion **467** of the graph line.

[0228] In some embodiments, a sudden increase in gas concentration DGC which results in a gas concentration level that exceeds a threshold gas concentration may be used to identify a thermal runaway event. In some instances, the threshold gas concentration may be at least 50 ppm, or between and including 20 ppm and 80 ppm. Further, the change in gas concentration may be for a change in concentration of a single gas detected by the gas sensor **453**, such as CO, or may be a change in total gas concentration for several selected gases detected by the gas sensor **453** in the air space **451** in the battery enclosure **460**. Other variations are possible based on a number of factors such as the size, type, and/or number of battery cells as well as characteristics of the battery enclosure **460** such that the above ranges may be higher or lower than the stated amounts in some embodiments.

[0229] Upon occurrence of a thermal runaway event that results in a gas concentration profile that exceeds one or more pre-determined thresholds, the gas in the battery enclosure **460** may be vented by the relief valve **459** of the battery enclosure **460** (FIG. **50**). In this way, the relief valve **459** of the battery enclosure **460** may assist with regulating gas concentration inside the battery enclosure **460** to prevent damage to the battery enclosure **460** while also mitigating the likelihood of other more serious outcomes following a thermal runaway event. Further, the measurement of gas concentration inside the battery enclosure **460** may be particularly advantageous because it is not susceptible to variations that are a result of vibrations in the vehicle and/or small gradients of signal noise that may be associated with the aforementioned pressure detection.

[0230] FIG. **53** is a block diagram of the controller **455**. As further described below, the controller **455** is suitable for executing or otherwise performing at least some embodiments or techniques of the battery packs described herein, including but not limited to battery pack **410**. The physical or hardware aspects of the controller **455** may be provided in the battery enclosure **460**, in a separate housing carried by the battery enclosure **460**, and/or at an external location to the battery enclosure and communicatively coupled to at least the one or more sensors **453** in the battery enclosure **460**, among other devices. In an embodiment, the controller **455** is a centralized battery management system (BMS), or is one aspect of a BMS for providing centralized monitoring and control functionality for the common battery packs. The controller **455** may also be, or may be part of, a master-slave battery management system (BMS) for providing distributed monitoring and control functionality.

[0231] The controller **455** includes a processor **473**, for example a microprocessor, digital signal processor, programmable gate array (PGA) or application specific integrated circuit (ASIC). The controller **455** includes one or more non-transitory storage mediums **475**, for example read only memory (ROM), random access memory (RAM), Flash memory, or other physical computer- or processor-readable storage media in communication with the processor **473**. The non-transitory storage mediums **475** may store instructions and/or data used by the processor **473** and the controller **455** generally, for example an operating system (OS) and/or applications. The instructions as executed by the processor **473** may execute logic to perform the functionality of the various implementations or techniques of the devices and systems described herein, including, but not limited to, receiving signals from the one or more sensors **453**, and determining, based on the signals, whether to instruct the status indicator **457** to provide the at least one warning indication, among others.

[0232] The controller **455** may include, or be in communication with, the one or more sensors **453**, such as the pressure sensor and/or gas sensor. As described herein, the sensors **453** send signals, instructions, and/or data to the processor **473** based on detected conditions, such as pressure, a rate of pressure change, and/or gas concentration in the air gap **451** of the battery enclosure **460**. The controller **455** may include, or be in communication with, the status indicator **457**. As noted above, the status indicator **457** may be one or more LEDs or some other lighting element, a speaker, and/or a buzzer, among others. In at least some embodiments, each individual lighting element may be position- and hue-addressable, such as to control the color and state of each element independently of or in conjunction with the other lighting elements. The speaker may be a buzzer configured to emit sound as well as haptic signals or vibrations. In some embodiments, the controller **455** may include a separate speaker for emitting sound and a haptic device for emitting vibration, such as to change the strength, volume, or other characteristics of either of these signals relative to a buzzer.

[0233] The control unit **455** may include a user interface (UI) **477** to allow a user to operate or otherwise provide input to the controller **455**, the battery packs, and/or systems described herein, such as with respect to the operational state or condition of the battery pack **410**. In some embodiments, the user interface **477** is configured to display information to the user, such as a driver and/or occupant of a vehicle regarding the operational state or other characteristics of the battery pack **410**. Additionally, the user interface **477** may include a number of user actuatable controls, such as, for example, a number of switches or keys operable to turn certain aspects ON and OFF and/or to set various operating parameters of the battery pack **410**, the one or more sensors **453**, and the status indicator **457**, such as sensor sensitivity and operation and control of test and/or maintenance modes, among others. The switches and keys or the user interface **477** may include, for example, toggle switches, a keypad or keyboard, rocker switches or other physical actuators.

[0234] In some embodiments, the user interface **477** may include a display, for instance a touch panel display. The touch panel display (e.g., LCD or LED with touch sensitive overlay) may provide both an input and an output interface for the user. The touch panel display may present a graphical user interface, with various user selectable icons, menus, check boxes, dialog boxes, and other components and elements selectable by the end user to set operational states or conditions of the battery pack **410**. The user interface **477** may also include one or more auditory transducers, for example one or more speakers and/or microphones. Such may allow audible alert notifications or signals to be provided to the user as a result of manual interaction with the user interface **477**. Such may additionally, or alternatively, allow the user to provide audible commands or instructions. The user interface **477** may include additional components and/or different components than those illustrated or described, and/or may omit some components.

[0235] The controller **455** includes a communications subsystem **479** that may include one or more communications modules or components which facilitate communications with the one or more sensors **453**, the status indicator **457**, and/or other external devices **481**, such as a personal computing device, mobile device, server, or a remote computing system associated with the controller **455** that monitors the operational characteristics of the battery pack **410**. The communications sub-system **479** may provide wireless or wired communications to one or more such devices and may include wireless receivers, wireless transmitters and/or wireless transceivers to provide wireless signal paths to the various aspects, remote components, and/or systems of the one or more paired devices. The communications subsystem **479** may, for example, include components enabling short range (e.g., via Bluetooth®, BLE ("Bluetooth® low energy"), near field communication (NFC), or radio frequency identification (RFID) components and protocols) or longer range wireless communications (e.g., over a wireless LAN, Low-Power-Wide-Area Network (LPWAN), satellite, or cellular network) and may include one or more modems or one or more Ethernet or other types of communications cards or components for doing so. The communications sub-system **479** may also include one or more bridges or routers suitable to handle network traffic including switched packet type communications protocols (TCP/IP), Ethernet or other networking protocols.

[0236] The controller **455** further includes a power interface manager **483** that manages supply of power from a power source **485** to the various components of the controller **455**, such as at least the one or more sensors **453** and the status indicator **457**. The power interface manager **483** is coupled to the processor **473** and the power source **485**. Alternatively, in some implementations, the power interface manager **483** can be integrated in the processor **473**. The power source **485** may include an external power supply, or a rechargeable or replaceable battery power supply, as well as the battery pack **410** itself, among others. The power interface manager **483** may include power converters, rectifiers, buses, gates, circuitry, etc. in some embodiments. In particular, the power interface manager **483** can control, limit, and/or restrict the supply of power from the power source **485** based on the various operational states of the battery pack **410**, as described in more detail below.

[0237] In some embodiments or implementations, the instructions and/or data stored on the non-transitory storage mediums **475** that may be used by the processor **473** and the controller **455** generally, such as, for example, ROM, RAM and/or Flash memory, includes or provides an application program interface ("API") that provides programmatic access to one or more functions of the controller **322**. For example, such an API may provide a programmatic interface to control one or more operational characteristics of the battery pack **410**. Such control may be invoked by one of the other programs, other remote device or system, or some other module. In this manner, the API may facilitate the development of third-party software, such as various different user interfaces and control systems for other devices, plug-ins, and adapters, and the like to facilitate interactivity and customization of the operation and devices within the battery pack **410**.

[0238] In an embodiment, components or modules of the controller **455** and other devices within the battery packs described herein are implemented using standard programming techniques. For example, the logic to perform the functionality of the various embodiments or techniques described herein may be implemented as a "native" executable running on the controller **455**, e.g., microprocessor **473**, along with one or more static or dynamic libraries. In other embodiments, various functions of the controller **455** may be implemented as instructions processed by a virtual machine that executes as one or more programs whose instructions are stored on non-transitory storage mediums **475**. In general, a range of programming languages known in the art may be employed for implementing such example embodiments, including representative implementations of various programming language paradigms, including but not limited to, object-oriented (e.g., Java, C++, C#, Visual Basic.NET, Smalltalk, and the like), functional (e.g., ML, Lisp, Scheme, and the like), procedural (e.g., C, Pascal, Ada, Modula, and the like), scripting (e.g., Perl, Ruby, Python, JavaScript, VBScript, and the like), or declarative (e.g., SQL, Prolog, and the like).

[0239] In a software or firmware implementation, instructions stored in a memory configure, when executed, one or more processors of the controller **455**, such as microprocessor **473**, to perform the functions of the controller **455**. The instructions cause the microprocessor **473** or some other processor, such as an I/O controller/processor, to process and act on information received from the one or more sensors **453**, the status indicator **457**, and/or or other external devices **481** to provide the functionality and techniques described herein.

[0240] The embodiments or implementations described above may also use well-known or other synchronous or asynchronous client-server computing techniques. However, the various components may be implemented using more monolithic programming techniques as well, for example, as an executable running on a single microprocessor, or alternatively decomposed using a variety of structuring techniques known in the art, including but not limited to, multiprogramming, multithreading, client-server, or peer-to-peer (e.g., Bluetooth®, NFC or RFID wireless technology, mesh networks, etc.), running on one or more computer systems each having one or more central processing units (CPUs) or other processors. Some embodiments may execute concurrently and asynchronously, and communicate using message passing techniques.

[0241] In addition, programming interfaces to the data stored on and functionality provided by the controller **455**, can be available by standard mechanisms such as through C, C++, C#, and Java APIs; libraries for accessing files, databases, or other data repositories; scripting languages; or Web servers, FTP servers, or other types of servers providing access to stored data. The data stored and utilized by the controller **455** and overall battery packs may be implemented as one or more database systems, file systems, or any other technique for storing such information, or any combination of the above, including implementations using distributed computing techniques.

[0242] Different configurations and locations of programs and data are contemplated for use with techniques described herein. A variety of distributed computing techniques are appropriate for implementing the components of the illustrated embodiments in a distributed manner including but not limited to TCP/IP sockets, RPC, RMI, HTTP, and Web Services (XML-RPC, JAX-RPC, SOAP, and the like). Other variations are possible. Other functionality could also be provided by each component/module, or existing functionality could be distributed amongst the components/modules within the battery pack **410** in different ways, yet still achieve the functions of the controller **455**.

[0243] Furthermore, in some embodiments or implementations, some or all of the components of the controller **455** may be implemented or provided in other manners, such as at least partially in firmware and/or hardware, including, but not limited to, one or more application-specific integrated circuits ("ASICs"), standard integrated circuits, controllers (e.g., by executing appropriate instructions, and including microcontrollers and/or embedded controllers), field-programmable gate arrays ("FPGAs"), complex programmable logic devices ("CPLDs"), and the like. Some or all of the system components and/or data structures may also be stored as contents (e.g., as executable or other machine-readable software instructions or structured data) on a computer-readable medium (e.g., as a hard disk; a memory; a computer network, cellular wireless network or other data transmission medium; or a portable media article to be read by an appropriate drive or via an appropriate connection, such as a DVD or flash memory device) so as to enable or configure the computer-readable medium and/or one or more associated computing systems or devices to execute or otherwise use, or provide the contents to perform, at least some of the described techniques.

[0244] In some embodiments, the non-transitory storage mediums **475** store instructions that are executed by the at least one processor **473** during operation of the battery pack **410** to provide the at least one warning indication with the status indicator **457** in response to the rate of change in pressure (DP/DT) in the battery pack enclosure exceeding a threshold rate for at least a threshold duration. The threshold rate may be at least 50 Pascals per second, or between and including 50 Pascals per second and 150 Pascals per second. The threshold duration may be at least 3 seconds, or between and including 3 seconds and 5 seconds.

[0245] In embodiments where the one or more sensors **453** are a pressure sensor **453**, the non-transitory storage mediums **475** may also store instructions associated with smoothing, filtering, or otherwise interpreting the data from the pressure sensor **453** to filter out fluctuations in pressure associated with vibration and/or temperature during normal operating conditions. In some embodiments, the non-transitory storage mediums **475** store instructions that are executed by the at least one processor **473** during operation of the battery pack **410** to not provide the at least one warning indication with the status indicator **457** in response to the rate of change in pressure in the battery enclosure **460** less than the threshold rate, or greater than the threshold rate, but for less than the threshold duration. The non-transitory storage mediums **475** may also store instructions that are executed by the at least one processor **473** during operation of the battery pack **410** to not provide the at least one warning indication with the status indicator **457** in response to variations in pressure over time associated with vibration or operational temperature of the multi-layer battery stack, or both, such as by using filtering or smoothing techniques. As a result, the pressure sensor may be operable to distinguish between changes in pressure in the battery cell enclosure **460** associated with vibration, temperature of the multi-layer battery stack **414**, or both, and changes in pressure associated with the vented matter from the vent valve of the at least one of the battery cells as shown at least in FIG. **51**.

[0246] In some embodiments where the one or more sensors **453** are a gas sensor **453**, the non-transitory storage mediums **475** store instructions that are executed by the at least one processor **473** during operation of the battery pack **410** to detect, with the gas sensor **453**, the gas concentration of the air gap **451** and provide the at least one warning indication with the status indicator **457** in response to changes in gas concentration in the battery pack enclosure exceeding a threshold concentration. As above, the threshold concentration may be at least 50 ppm of a single gas, or a total concentration from multiple selected gases. The non-transitory storage mediums **475** may also store further instructions that are executed by the at least one processor **473** during operation of the battery pack **410** to not provide the at least one warning indication with the status indicator **457** in response to the change in gas concentration in the battery enclosure **460** being less than the threshold concentration above.

[0247] The present disclosure also contemplates methods associated with the above aspects and techniques described with reference to FIGS. **50** through **53**. For example, one or more embodiments of a method may include detecting a change in at least one characteristic over time in the space **451** between the battery pack enclosure **460** and the multi-layer battery stack **414** in the battery pack enclosure **460** with at least one sensor **453**. The at least one characteristic over time may be indicative of vented matter from the vent valve **450** of at least one battery cell in the multi-layer battery stack **414** during a thermal runaway event. The method further includes providing at least one warning indication with the status indicator **457** in response to the detected change in the at least one characteristic of the space **451** over time via the at least one sensor **453**. The method may include additional features of the type described herein, including but not limited to those in the appended claims.

[0248] In view of the above, the battery packs of the present disclosure may include venting detection and/or warning functionality for detecting whether a thermal runaway event has occurred and providing a suitable warning indication to a driver and/or occupant of a vehicle including the battery pack. Such a warning indication may provide time for the driver and/or occupant to safely exit the vehicle to mitigate the risk of harm to the driver and/or occupant in the event of battery damage following the thermal runaway event.

Additional Aspects

[0249] In a first aspect, a battery pack is provided comprising a plurality of battery module layers stacked in a vertical direction to form a multi-layer battery stack, each battery module layer including a plurality of battery cells arranged in a linear array and a thermal management device; and a battery pack frame including a plurality of frame members, wherein each battery module layer is secured to a respective frame member, and wherein the frame members are arranged to apply a compressive load on the battery module layers to assist in maintaining the battery module layers of the multi-layer battery stack in thermal contact with each other.

[0250] In a second aspect, the battery pack of aspect 1, wherein each frame member is provided in the form of a structural support frame at a periphery of the battery pack.

[0251] In a third aspect, the battery pack of aspect 2, wherein, for each battery module layer, the thermal management device is secured directly to a respective one of the structural support frames and supports the linear array of battery cells thereon.

[0252] In a fourth aspect, the battery pack of aspect 3, wherein each battery module layer further includes one or more anchors to assist in securing the linear array of battery cells to the thermal management device of the battery module layer.

[0253] In a fifth aspect, the battery pack of aspect 4, wherein each anchor is provided in the form of an elongated bar or plate positioned at a lower end of the battery cells and extending along a longitudinal direction of the battery pack.

[0254] In a sixth aspect, the battery pack of aspect 1, wherein, for each battery module layer, the battery cells are compressed together in sub-modules to maintain contact between the battery cells or intervening structures of each sub-module.

[0255] In a seventh aspect, the battery pack of aspect 1, wherein, for each battery module layer, all of the battery cells of the battery module layer are compressed together.

[0256] In an eighth aspect, the battery pack of aspect 7, wherein for each battery module layer, all of the battery cells of the battery module layer are compressed together with the aid of a compression band encircling the linear array of battery cells or compression brackets or plates secured to the battery cells.

[0257] In a ninth aspect, the battery pack of aspect 7, wherein for each battery module layer, all of the battery cells of the battery module layer are compressed together with the aid of opposing compression plates that are coupled together with adjustable tie rods to selectively adjust a compression force on the battery cells.

[0258] In a tenth aspect, the battery pack of aspect 1, wherein, for each battery module layer, discrete subsets of the battery cells of the battery module layer are compressed together in sub-modules.

[0259] In an 11th aspect, the battery pack of aspect 10, wherein, for each battery module layer, the discrete subsets of the battery cells of the battery module layer are compressed together in sub-modules with the aid of a compression band encircling the discrete subsets of the battery cells or compression brackets secured to the discrete subsets of the battery cells.

[0260] In a 12th aspect, the battery pack of aspect 10, wherein the sub-modules are fixedly secured to each other to form the linear array.

[0261] In a 13th aspect, the battery pack of aspect 1, wherein the battery cells of one of the battery module layers are in direct thermal engagement with the thermal management device of an adjacent battery module layer such that all of the battery cells of the battery module layer are positioned between two thermal management devices to facilitate heat transfer on plural sides of the battery cells.

[0262] In a 14th aspect, the battery pack of aspect 1, wherein all battery cells of the battery pack are positioned between two thermal management devices to facilitate heat transfer on plural sides of the battery cells.

[0263] In a 15th aspect, the battery pack of aspect 1, wherein the linear array of battery cells of each battery module layer are held in compression between two thermal management devices of the multi-layer battery stack.

[0264] In a 16th aspect, the battery pack of aspect 1, wherein the thermal management device is an active heat exchanger having at least one liquid heat exchange medium passageway for circulating a liquid heat exchange medium for cooling or heating purposes.

[0265] In a 17th aspect, the battery pack of aspect 16, wherein the active heat exchanger is a battery cold plate that is configured to provide cooling or heating of the battery cells in operation.

[0266] In a 18th aspect, the battery pack of aspect 1, wherein the thermal management device of each battery module layer is a battery cold plate that comprises a generally planar manifold and includes at least one heat transfer medium passageway to facilitate the circulation of a heat transfer medium through the manifold during operation to assist in drawing heat away from the battery cells to cool the battery cells or, alternatively, supplying heat to the battery cells to heat the battery cells.

[0267] In a 19th aspect, the battery pack of aspect 18, wherein, for each battery module layer, each battery cell includes a vent and one or more electrode terminals provided on an end face of the battery cell that is oriented normal to a major surface of the battery cold plate.

[0268] In a 20th aspect, the battery pack of aspect 18, wherein, for each battery module layer, each battery cell includes a vent and one or more electrode terminals provided on an upper face of the battery cell that is oriented parallel to a major surface of the battery cold plate.

[0269] In a 21st aspect, the battery pack of aspect 18, wherein a major surface of each battery cold plate is perpendicular to a plane of the electrodes in the battery cells.

[0270] In a 22nd aspect, the battery pack of aspect 18, wherein a major surface of each battery cold plate is parallel to a plane of the electrodes in the battery cells.

[0271] In a 23rd aspect, the battery pack of aspect 18, further comprising a battery enclosure that accommodates the multi-layer battery stack, and wherein each battery cold plate extends laterally beyond the battery cells on each of opposing sides of the battery pack to present a stack of battery cold plates that terminate adjacent a side wall of the enclosure and assist in protecting the battery cells from potential damage arising from a side impact event to the battery enclosure.

[0272] In a 24th aspect, the battery pack of aspect 16, wherein each active heat exchanger includes a set of liquid heat exchange medium openings on a same end of the battery pack, which serve as an inlet and an outlet for the liquid heat exchange medium.

[0273] In a 25th aspect, the battery pack of aspect 24, wherein the outlet of one of the active heat exchangers is connected to the inlet of an adjacent one of the active heat exchangers to enable the liquid heat exchange medium to pass through each of the battery module layers in a continuous path.

[0274] In a 26th aspect, the battery pack of aspect 25, wherein the battery pack is configured such that the liquid heat exchange medium may flow in alternate directions along the continuous path to provide heating or cooling functionality to the multi-layer battery stack in reversible directions.

[0275] In a 27th aspect, the battery pack of aspect 24, wherein electronics of the battery pack are provided on an opposing end of the battery pack opposite of the end of the battery pack having the liquid heat exchange medium openings to separate the electronics from connections for the liquid heat exchange medium made at the liquid heat exchange medium openings.

[0276] In a 28th aspect, the battery pack of aspect 1, further comprising: a battery enclosure that accommodates the multi-layer battery stack and battery pack frame, and wherein each of the frame members of the battery pack frame is secured to the battery enclosure.

[0277] In a 29th aspect, the battery pack of aspect 28, wherein the battery enclosure includes a tray and a cover, each of the tray and the cover including a flat sealing surface to facilitate a watertight seal between the tray and the cover.

[0278] In a 30th aspect, the battery pack of aspect 1, wherein the plurality of frame members are arranged and spaced relative to each other in order to apply the compressive load in response to the battery module layers being secured to the respective frame member.

[0279] In a 31 st aspect, the battery pack of aspect 1, wherein, for each battery module layer, the battery cells are arranged in a plurality of rows, with each row having a plurality of battery cells arranged in a linear array.

[0280] In a 32nd aspect, the battery pack of aspect 1, wherein each battery cell is provided in a form factor having a generally rectangular prismatic shape.

[0281] In a 33rd aspect, the battery pack of aspect 1, wherein each battery cell has an aspect ratio of cell length to cell height of between 3:1 to 6:1.

[0282] In a 34th aspect, the battery pack of aspect 1, wherein each battery cell has an aspect ratio of cell length to cell width of between 1:1 to 2:1.

[0283] In a 35th aspect, the battery pack of aspect 1, wherein each battery cell is provided in a form factor having a generally rectangular prismatic shape with a cell length of 520±50 mm, a cell height of 125±10 mm, a cell thickness of 20±5 mm.

[0284] In a 36th aspect, the battery pack of aspect 1, wherein each battery cell is provided in a form factor having a generally rectangular prismatic shape with a cell length of 175±50 mm, a cell height of 150±20 mm, a cell thickness of 45±5 mm.

[0285] In a 37th aspect, the battery pack of aspect 1, further comprising, for each battery module layer, one or more vented material collectors positioned to collect and route vented material discharged from one or more of the battery cells during a venting event away from the multi-layer battery stack.

[0286] In a 38th aspect, a battery pack system for commercial vehicles having different vehicle attributes is provided, the battery pack system comprising: a plurality of common battery packs arrangeable in commercial vehicles in a plurality of different configurations to optimize vehicle power and vehicle range, wherein each of the common battery packs includes a plurality of battery module layers stacked to form a multi-layer battery stack, with each battery module layer including a plurality of battery cells arranged in an array and connected in series with each other and the battery cells of each other battery module layer to provide a battery pack voltage in a range of between 600V and 1200V that is common to each of the common battery packs, and wherein each of the common battery packs is connectable in parallel with each other to increase vehicle power and vehicle range of a host commercial vehicle.

[0287] In a 39th aspect, the battery pack system of aspect 38, wherein a number of the common battery packs in the plurality of different configurations ranges from between 2 and 10.

[0288] In a 40th aspect, the battery pack system of aspect 38, wherein the plurality of different configurations includes at least one configuration in which a number of the common battery packs is different than a number of the common battery packs in another one of the configurations.

[0289] In a 41st aspect, the battery pack system of aspect 38, wherein each common battery pack includes a same number of battery module layers that is two, three, four or five battery module layers.

[0290] In a 42nd aspect, the battery pack system of aspect 38, wherein, for each common battery pack, each battery module layer further includes a thermal management device associated with and in thermal engagement with the array of battery cells of the battery module layer.

[0291] In a 43rd aspect, the battery pack system of aspect 42, wherein the thermal management device is an active heat exchanger having a liquid heat exchange medium passageway for circulating a liquid heat exchange medium for cooling or heating purposes.

[0292] In a 44th aspect, the battery pack system of aspect 43, wherein the active heat exchanger is a battery cold plate that is configured to provide cooling or heating of the battery cells in operation.

[0293] In a 45th aspect, the battery pack system of aspect 38, further comprising: a thermal management system that is centralized or distributed, or a hybrid thereof.

[0294] In a 46th aspect, the battery pack system of aspect 45, wherein the thermal management system includes a centralized chiller for all of the common battery packs for distributing a heat transfer medium to the common battery packs for cooling purposes.

[0295] In a 47th aspect, the battery pack system of aspect 45, wherein the thermal management system includes a plurality of chillers associated with the common battery packs for distributing a heat transfer medium to the common battery packs for cooling purposes.

[0296] In a 48th aspect, the battery pack system of aspect 45, wherein the thermal management system includes a respective chiller associated with each of the common battery packs for routing a heat transfer medium to the common battery pack for cooling purposes.

[0297] In a 49th aspect, the battery pack system of aspect 45, wherein the thermal management system includes a centralized heater for all of the common battery packs for distributing a heat transfer medium to the common battery packs for heating purposes.

[0298] In a 50th aspect, the battery pack system of aspect 45, wherein the thermal management system includes a plurality of heaters associated with the common battery packs for distributing a heat transfer medium to the common battery packs for heating purposes.

[0299] In a 51st aspect, the battery pack system of aspect 45, wherein the thermal management system includes a respective heater associated with each of the common battery packs for routing a heat transfer medium to the common battery pack for heating purposes.

[0300] In a 52nd aspect, the battery pack system of aspect 45, wherein the thermal management system includes a centralized chiller for all of the common battery packs for distributing a heat transfer medium to the common battery packs for cooling purposes, and further includes a respective heater associated with each of the common battery packs for routing a heat transfer medium to the common battery pack for heating purposes.

[0301] In a 53rd aspect, the battery pack system of aspect 38, further comprising: a centralized battery management system (BMS) for providing centralized monitoring and control functionality for the common battery packs; or a master-slave battery management system (BMS) for providing distributed monitoring and control functionality for the common battery packs.

[0302] In a 54th aspect, the battery pack system of aspect 38, further comprising: a centralized charging system comprising a single charger for charging the common battery packs; or a distributed charging system comprising a plurality of chargers for charging the common battery packs.

[0303] In a 55th aspect, the battery pack system of aspect 38, wherein the common battery packs have an identical form factor to enable each of the common battery packs to be exchanged with the others to facilitate periodic rearranging of the common battery packs on the host vehicle.

[0304] In a 56th aspect, the battery pack system of aspect 38, wherein the common battery packs have an identical form factor to enable any one of the common battery packs to be replaced with a new battery pack of the same form factor.

[0305] In a 57th aspect, the battery pack system of aspect 42, wherein each common battery pack further includes a battery pack frame including a plurality of frame members, wherein each battery module layer is secured to a respective frame member, and wherein the frame members are arranged to apply a compressive load on the battery module layers to assist in maintaining the battery module layers of the multi-layer battery stack in thermal contact with each other.

[0306] In a 58th aspect, the battery pack system of aspect 57, wherein each frame member is provided in the form of a structural support frame at a periphery of the common battery pack.

[0307] In a 59th aspect, the battery pack system of aspect 58, wherein, for each battery module layer, the thermal management device is secured directly to a respective one of the structural support frames and supports the array of battery cells thereon.

[0308] In a 60th aspect, the battery pack system of aspect 42, wherein each battery module layer further includes one or more anchors to assist in securing the array of battery cells to the thermal management device of the battery module layer.

[0309] In a 61st aspect, the battery pack system of aspect 42, wherein the battery cells of one of the battery module layers are in direct thermal engagement with the thermal management device of an adjacent battery module layer such that all of the battery cells of the battery module layer are positioned between two thermal management devices to facilitate heat transfer on plural sides of the battery cells.

[0310] In a 62nd aspect, the battery pack system of aspect 42, wherein all battery cells of each common battery pack are positioned between two thermal management devices to facilitate heat transfer on plural sides of the battery cells.

[0311] In a 63rd aspect, the battery pack system of aspect 42, wherein the array of battery cells of each battery module layer are held in compression between two thermal management devices of the multi-layer battery stack.

[0312] In a 64th aspect, the battery pack system of aspect 42, wherein the thermal management device of each battery module layer is a cold plate that comprises a generally planar manifold and includes at least one heat transfer medium passageway to facilitate the circulation of a heat transfer medium through the manifold during operation to assist in drawing heat away from the battery cells to cool the battery cells or, alternatively, supplying heat to the battery cells to heat the battery cells.

[0313] In a 65th aspect, the battery pack system of aspect 64, wherein, for each battery module layer, each battery cell includes a vent and one or more electrode terminals provided on an end face of the battery cell that is oriented normal to a major surface of the cold plate.

[0314] In a 66th aspect, the battery pack system of aspect 64, wherein a major surface of each cold plate is perpendicular to a plane of the electrodes in the battery cells.

[0315] In a 67th aspect, the battery pack system of aspect 64, wherein, for each battery module layer, each battery cell includes a vent and one or more electrode terminals provided on an upper face of the battery cell that is oriented parallel to a major surface of the cold plate.

[0316] In a 68th aspect, the battery pack system of aspect 64, wherein a major surface of each cold plate is parallel to a plane of the electrodes in the battery cells.

[0317] In a 69th aspect, the battery pack system of aspect 57, further comprising: for each common battery pack, a battery enclosure that accommodates the multi-layer battery stack and battery pack frame, and wherein each of the frame members of the battery pack frame is secured to the battery enclosure.

[0318] In a 70th aspect, the battery pack system of aspect 38, wherein, for each battery module layer, the battery cells are compressed together in sub-modules to maintain contact between the battery cells or intervening structures of each sub-module.

[0319] In a 71 st aspect, the battery pack system of aspect 38, wherein, for each battery module layer, all of the battery cells of the battery module layer are compressed together.

[0320] In a 72nd aspect, the battery pack system of aspect 38, wherein, for each battery module layer, discrete subsets of the battery cells of the battery module layer are compressed together in sub-modules.

[0321] In a 73rd aspect, the battery pack system of aspect 38, wherein each common battery pack is provided in a form factor having a generally rectangular shape with a pack length of 1100±150 mm, a pack height of 600±100 mm, and a pack width of 600±100 mm.

[0322] In a 74th aspect, the battery pack system of aspect 38, wherein at least one of the battery packs is provided in a T-shape, L-shape, boot-shape or stairstep-shape configuration.

[0323] In a 75th aspect, the battery pack system of aspect 74, wherein the at least one battery pack provided in the T-shape, L-shape, boot-shape or stairstep-shape configuration comprises an enclosure with one or more rail channels for assisting in nesting the battery pack with a rail or rails of a host vehicle.

[0324] In a 76th aspect, the battery pack system of aspect 38, wherein at least one of the battery packs is provided in a L-shape, boot-shape or stairstep-shape configuration with an overall pack length of 1100±150 mm, an overall pack height of 600±100 mm, an overall pack width of 600±100 mm, a lower step height of 425±75 mm, and an upper landing length of 600±100 mm.

[0325] In a 77th aspect, the battery pack system of aspect 38, wherein at least one of the battery packs is provided in a T-shape configuration with an overall pack length of 1250±150 mm, an overall pack height of 600±100 mm, an overall pack width of 2200±100 mm, a stem width of 600±100 mm, and a stem height of 200±75 mm.

[0326] In a 78th aspect, the battery pack system of aspect 38, wherein each battery cell is provided in a form factor having a generally rectangular prismatic shape with an aspect ratio of cell length to cell height of between 3:1 to 6:1.

[0327] In a 79th aspect, the battery pack system of aspect 38, wherein each battery cell is provided in a form factor having a generally rectangular prismatic shape with an aspect ratio of cell length to cell height of between 1:1 to 2:1.

[0328] In an 80th aspect, the battery pack system of aspect 38, wherein each battery cell is provided in a form factor having a generally rectangular prismatic shape with a cell length of 520±50 mm, a cell height of 125±10 mm, a cell thickness of 20±5 mm.

[0329] In an 81st aspect, the battery pack system of aspect 38, wherein each battery cell is provided in a form factor having a generally rectangular prismatic shape with a cell length of 175±50 mm, a cell height of 150±20 mm, a cell thickness of 45±5 mm.

[0330] In an 82nd aspect, a commercial vehicle is provided including a battery pack system according to any one of aspects 38-81.

[0331] In an 83rd aspect, a commercial vehicle comprising a chassis and a battery pack system according to any one of aspects 38-81 is provided, wherein the common battery packs are positionable along the chassis to optimize a weight distribution of the commercial vehicle.

[0332] In an 84th aspect, a commercial vehicle is provided comprising a chassis with chassis rails and a battery pack system according to any one of aspects 38-81, wherein the common battery packs are under the chassis rails or along the side of the chassis rails.

[0333] In an 85th aspect, a collection of commercial vehicles is provided, each commercial vehicle including a battery pack system according to any one of aspects 38-81, and including a common drivetrain system regardless of a number of the common battery packs that are connected in parallel for each commercial vehicle.

[0334] In an 86th aspect, a battery pack is provided, comprising: a plurality of battery cells arranged in an array to form a battery module layer; a lower thermal management device underlying and in thermal contact with the plurality of battery cells of the battery module layer; an upper thermal management device overlying and in thermal contact with the plurality of battery cells of the battery module layer; and a connecting manifold that extends between the lower thermal management device and the upper thermal management device and has at least one heat transfer medium passage arranged to provide fluid communication between the lower thermal management device and the upper thermal management device in order to facilitate distribution of a heat transfer medium through each of the lower thermal management device and the upper thermal management device during operation to provide heating or cooling functionality for the plurality of battery cells of the battery module layer.

[0335] In an 87th aspect, the battery pack of aspect 86, wherein each of the lower and upper thermal management device comprises an active heat exchanger having a generally planar manifold that includes at least one heat transfer medium passageway to facilitate the circulation of the heat transfer medium through the planar manifold during operation to assist in drawing heat away from the battery cells to cool the battery cells or, alternatively, supplying heat to the battery cells to heat the battery cells.

[0336] In an 88th aspect, the battery pack of aspect 87, wherein each active heat exchanger is a battery cold plate that is configured to provide cooling or heating of the battery cells in operation.

[0337] In an 89th aspect, the battery pack of aspect 88, wherein the connecting manifold is positioned at an end of the battery pack and extends vertically between the battery cold plates of the lower and upper thermal management devices.

[0338] In a 90th aspect, the battery pack of aspect 86, wherein the connecting manifold is configured to assist in securing the plurality of battery cells in place within the battery pack between the lower and upper thermal management devices.

[0339] In a 91st aspect, the battery pack of aspect 86, wherein the connecting manifold has a plurality of heat transfer medium passages for providing fluid communication between the lower thermal management device and the upper thermal management device, and wherein an end of at least one of the heat transfer medium passages is blocked to assist in routing the heat transfer medium through the battery pack in a desired path.

[0340] In a 92nd aspect, the battery pack of aspect 86, wherein the connecting manifold is configured to route the heat transfer medium through the lower and upper thermal management devices in series.

[0341] In a 93rd aspect, the battery pack of aspect 86, wherein the connecting manifold is configured to route the heat transfer medium through the lower and upper thermal management devices in parallel.

[0342] In a 94th aspect, the battery pack of aspect 86, wherein the battery pack includes a plurality of battery module layers stacked together, and wherein a respective connecting manifold is provided for each battery module layer.

[0343] In a 95th aspect, the battery pack of aspect 86, wherein the connecting manifold serves as one of opposing hold down members that assist in fixedly securing the battery cells within the battery pack between said hold down members.

[0344] In a 96th aspect, the battery pack of aspect 86, wherein the connecting manifold serves as a structural support between the lower and upper thermal management devices.

[0345] In a 97th aspect, the battery pack of aspect 86, wherein the connecting manifold includes at least two distinct heat transfer medium passages that are spaced apart from each other to be in fluid communication with different regions of the lower and upper thermal management devices.

[0346] In a 98th aspect, a battery pack is provided, comprising: a plurality of battery cells arranged in an array to form a battery module layer; and a thermal management device underlying and in direct thermal contact with the plurality of battery cells of the battery module layer, wherein discrete subsets of the plurality of battery cells of the battery module layer are held together in sub-modules with each sub-module being fixedly secured to the thermal management device and/or an adjacent sub-module.

[0347] In a 99th aspect, the battery pack of aspect 98, wherein the discrete subsets of the plurality of battery cells of the battery module layer are held together in the sub-modules via one or more straps, brackets or clamp arrangements.

[0348] In a 100th aspect, the battery pack of aspect 99, wherein the battery cells of each sub-module are held together by a pair of the straps, brackets or clamp arrangements provided on opposing ends of each sub-module.

[0349] In a 101st aspect, the battery pack of aspect 100, wherein the straps, brackets or clamp arrangements are connectable together in at least a longitudinal direction that is aligned with a direction in which the battery cells of the module layer extend in the array.

[0350] In a 102nd aspect, the battery pack of aspect 101, wherein the straps, brackets or clamp arrangements are further connectable together in a vertical direction that is normal to the direction in which the battery cells of the module layer extend in the array.

[0351] In a 103rd aspect, the battery pack of aspect 102, wherein the battery module layer is a first battery module layer, and wherein the battery pack further comprises: a further plurality of battery cells arranged in an array to form a second battery module layer that is positioned above the first battery module layer; and a further thermal management device overlying and in direct thermal contact with the battery cells of the first battery module layer and underlying and in direct thermal contact with the battery cells of the second battery module layer.

[0352] In a 104th aspect, the battery pack of aspect 103, further comprising: a plurality of structural supports extending between the thermal management device and the further thermal management device to support the further thermal management device in position above the thermal management device and assist in eliminating or reducing appreciable deflection of the further thermal management device.

[0353] In a 105th aspect, the battery pack of aspect 103, wherein the straps, brackets or clamp arrangements are connectable together in the vertical direction via the intermediary of the further thermal management device.

[0354] In a 106th aspect, the battery pack of aspect 99, wherein the straps, brackets or clamp arrangements are connectable together via fasteners or integrated interlock features.

[0355] In a 107th aspect, the battery pack of aspect 99, wherein the straps, brackets or clamp arrangements hold the battery cells of each sub-module together in a rigid manner to enable each sub-module to be independently manipulated in space during assembly of the sub-modules.

[0356] In a 108th aspect, the battery pack of aspect 99, wherein the straps, brackets or clamp arrangements hold the battery cells of each sub-module together in compression.

[0357] In a 109th aspect, the battery pack of aspect 99, wherein the straps, brackets or clamp arrangements fix each sub-module to the thermal management device in a manner that urges the battery cells into contact with the thermal management device or an intervening thermally conductive material.

[0358] In a 110th aspect, the battery pack of aspect 99, wherein the straps, brackets or clamp arrangements extend beyond end faces of the battery cells and include clearance on at least one side of the battery module layer for an elongated bus bar to span across the end faces of the battery cells on the at least one side of the battery module layer.

[0359] In a 111th aspect, the battery pack of aspect 98, wherein each sub-module comprises one or more end plates that provide thermal insulation between the sub-module and one or more adjacent sub-modules.

[0360] In a 112th aspect, the battery pack of aspect 98, wherein fire retardant material is provided between adjacent sub-modules.

[0361] In a 113th aspect, the battery pack of aspect 98, wherein each sub-module comprises thermal resistant material between each of at least some of the battery cells of the sub-module to prevent or delay the propagation of thermal runaway.

[0362] In a 114th aspect, the battery pack of aspect 98, wherein each sub-module comprises fire retardant material between each of at least some of the battery cells of the sub-module.

[0363] In a 115th aspect, the battery pack of aspect 98, further comprising: a battery pack frame to which the battery module layer is fixed; and a battery back enclosure that surrounds the battery pack frame.

[0364] In a 116th aspect, the battery pack of aspect 98, further comprising a further thermal management device overlying the battery module layer, and wherein the battery cells of the battery module layer are also in direct thermal engagement with the further thermal management device to facilitate heat transfer on both of opposing sides of the battery cells.

[0365] In a 117th aspect, the battery pack of aspect 98, wherein the thermal management device of the battery module layer comprises an active heat exchanger having a generally planar manifold that includes a heat transfer medium passageway to facilitate the circulation of a heat transfer medium through the manifold during operation to assist in drawing heat away from the battery cells to cool the battery cells or, alternatively, supplying heat to the battery cells to heat the battery cells.

[0366] In a 118th aspect, the battery pack of aspect 98, wherein the active heat exchanger of the battery module layer is a battery cold plate that is configured to provide cooling or heating of the battery cells in operation.

[0367] In a 119th aspect, the battery pack of aspect 98, wherein each of the discrete subsets of the plurality of battery cells of each sub module includes a same number of battery cells between two and ten battery cells.

[0368] In a 120th aspect, the battery pack of aspect 98, wherein the discrete subsets of the plurality of battery cells of the battery module layer are held together in the sub-modules with one or more fasteners that are aligned with, or recessed with respect to, an outer peripheral edge of the thermal management device.

[0369] In a 121st aspect, the battery pack of aspect 98, wherein the battery module layer is a first battery module layer, and wherein the battery pack further comprises: a second battery module layer including a further plurality of battery cells arranged in an array, the second battery module layer removably connectable to the first battery module layer in a vertically stacking arrangement.

[0370] In a 122nd aspect, the battery pack of aspect 121, wherein the second battery module layer is removably connectable to the first battery module layer in the vertical stacking arrangement with the thermal management device between, and in direct contact with, the first battery module layer and the second battery module layer.

[0371] In a 123rd aspect, the battery pack of aspect 121, wherein the second battery module layer is removably connectable to the first module layer in the vertical stacking arrangement with a further thermal management device between, and in direct contact with, the first battery module layer and the second battery module layer, and such that the first battery module layer is provided between opposing thermal management devices.

[0372] In a 124th aspect, the battery pack of aspect 121, wherein the second battery module layer is connectable to the first battery module layer on either of opposing sides of the first module layer.

[0373] In a 125th aspect, the battery pack of aspect 98, wherein each battery cell of each sub module extends substantially an entire length of the sub module.

[0374] In a 126th aspect, the battery pack of aspect 98, wherein at least two battery cells among the battery cells of each sub module are aligned end-to-end to extend substantially an entire length of the sub module.

[0375] In a 127th aspect, the battery pack of aspect 98, wherein at least one supplemental strap, bracket or clamp arrangement is proved between opposing ends of the sub module at an interface between adjacent battery cells that are aligned end-to-end.

[0376] In a 128th aspect, the battery pack of aspect 98, wherein each battery cell is provided in a form factor having a generally rectangular prismatic shape with an aspect ratio of cell length to cell height of between 3:1 to 6:1.

[0377] In a 129th aspect, the battery pack of aspect 98, wherein each battery cell is provided in a form factor having a generally rectangular prismatic shape with an aspect ratio of cell length to cell height of between 1:1 to 2:1.

[0378] In a 130th aspect, the battery pack of aspect 98, wherein each battery cell is provided in a form factor having a generally rectangular prismatic shape with a cell length of 520±50 mm, a cell height of 125±10 mm, a cell thickness of 20±5 mm.

[0379] In a 131st aspect, the battery pack of aspect 98, wherein each battery cell is provided in a form factor having a generally rectangular prismatic shape with a cell length of 175±50 mm, a cell height of 150±20 mm, a cell thickness of 45±5 mm.

[0380] In a 132nd aspect, a battery pack is provided, comprising: a first battery module including a plurality of battery cells coupled together in an array; a second battery module including a plurality of battery cells coupled together in an array; and a thermal management device underlying and in direct thermal contact with the plurality of battery cells of the first battery module, the second battery module connectable to the first battery module via one or more fasteners associated with each of the first battery module and the second battery module.

[0381] In a 133rd aspect, the battery pack of aspect 132, wherein the second battery module is connectable to the first battery module in a side-by-side arrangement with both the first and second battery modules fixed to the thermal management device to form a battery module layer.

[0382] In a 134th aspect, the battery pack of aspect 132, wherein the second battery module is connectable to the first battery module in a vertical stacking arrangement with the thermal management device between, and in direct contact with, the plurality of battery cells of the first battery module and the plurality of further battery cells of the second battery module.

[0383] In a 135th aspect, the battery pack of aspect 132, wherein the second battery module is connectable to the first battery module in a vertical stacking arrangement with a further thermal management device between, and in direct contact with, the plurality of battery cells of the first battery module and the plurality of further battery cells of the second battery module.

[0384] In a 136th aspect, a battery pack is provided, comprising: a plurality of battery cells arranged in an array to form a battery module layer; a lower thermal management device underlying and in direct thermal contact with the plurality of battery cells of the battery module layer; an upper thermal management device overlying and in direct thermal contact with the plurality of battery cells of the battery module layer; and a plurality of structural supports extending between the lower thermal management device and the upper thermal management device to support the upper thermal management device in position above the lower thermal management device.

[0385] In a 137th aspect, the battery back of aspect 136, wherein the plurality of structural supports are configured to support the upper thermal management device in position above the lower thermal management device to assist in eliminating or reducing appreciable deflection of the upper thermal management device.

[0386] In a 138th aspect, the battery back of aspect 136, wherein the plurality of structural supports are removably attached to the lower and upper thermal management device.

[0387] In a 139th aspect, the battery back of aspect 136, wherein each of the plurality of structural supports comprises an elongate form factor that extends an entirety or substantially an entirety of a longitudinal length of the battery cells, or a longitudinal length of a plurality of the battery cells aligned end-to-end across the battery pack.

[0388] In a 140th aspect, the battery back of aspect 136, wherein the plurality of structural supports comprise at least two structural supports that are spaced apart along a longitudinal length of the battery module layer with at least some of the battery cells positioned therebetween.

[0389] In a 141st aspect, the battery back of aspect 136, wherein the plurality of structural supports comprise at least three structural supports that are spaced apart along a longitudinal length of the battery module layer in equidistant intervals with at least some of the battery cells positioned between adjacent structural supports.

[0390] In a 142nd aspect, the battery back of aspect 136, wherein discrete subsets of the plurality of battery cells of the battery module layer are held together in sub-modules with each sub-module being fixedly secured to at least one of the lower and upper thermal management devices and/or an adjacent sub-module.

[0391] In a 143rd aspect, the battery back of aspect 142, wherein each of the plurality of structural supports is positioned next to one of the sub-modules.

[0392] In a 144th aspect, the battery back of aspect 142, wherein the discrete subsets of the plurality of battery cells of the battery module layer are held together in the sub-modules via one or more straps, brackets or clamp arrangements, and wherein each of the plurality of structural supports interfaces with the one or more straps, brackets or clamp arrangements.

[0393] In a 145th aspect, the battery back of aspect 136, wherein the battery module layer is a first battery module layer, and wherein the battery pack further comprises: a further plurality of battery cells arranged in an array to form a second battery module layer that is positioned above the first battery module layer, the second battery module layer being supported by and in direct thermal contact with the upper thermal management device; a further thermal management device overlying the second battery module layer; and a further plurality of structural supports extending between the upper thermal management device and the further thermal management device to support the further thermal management device in position above the upper thermal management device.

[0394] In a 146th aspect, the battery back of aspect 136, wherein at least one of the structural supports provides thermal insulation between some of the plurality of battery cells in the battery module layer and others of the plurality of battery cells in the battery module layer.

[0395] In a 147th aspect, the battery back of aspect 136, wherein at least one of the structural supports is covered at least in part with a thermal insulation material.

[0396] In a 148th aspect, the battery back of aspect 136, wherein at least one of the structural supports is covered at least in part with a fire retardant material.

[0397] In a 149th aspect, the battery back of aspect 136, wherein each of the lower and upper thermal management devices comprises an active heat exchanger having a generally planar manifold that includes a heat transfer medium passageway to facilitate the circulation of a heat transfer medium through the manifold during operation to assist in drawing heat away from the battery cells to cool the battery cells or, alternatively, supplying heat to the battery cells to heat the battery cells.

[0398] In a 150th aspect, the battery back of aspect 136, wherein each active heat exchanger is a battery cold plate that is configured to provide cooling or heating of the battery cells in operation.

[0399] In a 151st aspect, the battery back of aspect 136, further comprising: a battery pack frame to which the battery module layer is fixed; and a battery back enclosure that surrounds the battery pack frame.

[0400] In a 152nd aspect, the battery back of aspect 136, wherein each of the lower thermal management device and the upper thermal management device comprises a generally planar manifold and includes a heat transfer medium passageway to facilitate the circulation of a heat transfer medium through the manifold during operation to assist in drawing heat away from the battery cells to cool the battery cells or, alternatively, supplying heat to the battery cells to heat the battery cells.

[0401] In a 153rd aspect, the battery back of aspect 136, wherein each of the plurality of structural supports comprises an elongate form factor that covers an entirety or substantially an entirety of a side surface of the battery cells, or a side surface of a plurality of the battery cells aligned end-to-end across the battery pack.

[0402] In a 154th aspect, the battery back of aspect 136, wherein the plurality of structural supports comprise at least two structural supports that are positioned on opposite sides of the battery module layer.

[0403] In a 155th aspect, the battery back of aspect 136, wherein discrete subsets of the plurality of battery cells of the battery module layer are held together in sub-modules via one or more straps, brackets or clamp arrangements, and wherein the plurality of structural supports cover at least a portion of the one or more straps, brackets, or clamp arrangements.

[0404] In a 157th aspect, the battery back of aspect 136, wherein a longitudinal length of the plurality of structural supports is greater than a longitudinal length of the plurality of battery cells, or a longitudinal length of a plurality of the battery cells aligned end-to-end across the battery pack.

[0405] In a 158th aspect, the battery back of aspect 136, wherein the plurality of structural supports are in direct contact with the lower thermal management device and the upper thermal management device.

[0406] In a 159th aspect, the battery back of aspect 136, wherein the plurality of structural supports are provided at ends of the battery module layer to protect the battery cells therebetween.

[0407] In a 160th aspect, the battery back of aspect 136, wherein the upper and lower thermal management devices define respective thermal paths above and below the plurality of battery cells, respectively, and the plurality of structural supports define respective additional thermal paths on longitudinal sides of the plurality of battery cells.

[0408] In a 161st aspect, the battery back of aspect 136, wherein the battery module layer includes thermal paths corresponding to each of a plurality of major surfaces of the battery module layer.

[0409] In a 162nd aspect, the battery back of aspect 161, wherein minor surfaces on at least one transverse end of the battery module layer are exposed to an external environment to facilitate connections to the plurality of battery cells.

[0410] In a 163rd aspect, the battery back of aspect 136, wherein each battery cell is provided in a form factor having a generally rectangular prismatic shape with an aspect ratio of cell length to cell height of between 3:1 to 6:1.

[0411] In a 164th aspect, the battery back of aspect 136, wherein each battery cell is provided in a form factor having a generally rectangular prismatic shape with an aspect ratio of cell length to cell height of between 1:1 to 2:1.

[0412] In a 165th aspect, the battery back of aspect 136, wherein each battery cell is provided in a form factor having a generally rectangular prismatic shape with a cell length of 520±50 mm, a cell height of 125±10 mm, and a cell thickness of 20±5 mm.

[0413] In a 166th aspect, the battery back of aspect 136, wherein each battery cell is provided in a form factor having a generally rectangular prismatic shape with a cell length of 175 mm±50 mm, a cell height of 150±20 mm, and a cell thickness of 45±5 mm.

[0414] In a 167th aspect, a method of regulating temperature of a battery pack that includes a plurality of battery cells arranged in an array and at least one heat exchanger associated with the array of battery cells is provided, the method comprising: supplying a heat exchange medium to the at least one heat exchanger in a first flow direction through a heat exchange passageway of the at least one heat exchanger such that a first subset of the battery cells located proximate to a first end of the heat exchange passageway is exposed to the heat exchange medium prior to a second subset of the battery cells located proximate to a second end of the heat exchange passageway; and subsequently, supplying the heat exchange medium to the at least one heat exchanger in a second flow direction through the heat exchange passageway in an opposite direction of the first flow direction such that the second subset of the battery cells located proximate to the second end of the heat exchange passageway is exposed to the heat exchange medium prior to the first subset of the battery cells located proximate to the first end of the heat exchange passageway.

[0415] In a 168th aspect, the method of aspect 167, wherein the supplying of the heat exchange medium to the at least one heat exchanger in the first flow direction and the subsequent supplying of the heat exchange medium to the at least one heat exchanger in the second flow direction are periodically repeated to assist in balancing an average temperature to which each of the first subset of the battery cells and the second subset of the battery cells are exposed during operation.

[0416] In a 169th aspect, the method of aspect 167, wherein the supplying of the heat exchange medium to the at least one heat exchanger in the first flow direction and the subsequent supplying of the heat exchange medium to the at least one heat exchanger in the second flow direction is performed by a pump operating in a common direction and wherein a direction of flow through the heat exchange passageway is switchable by actuation of one or more control valves of a heat exchange medium supply system.

[0417] In a 170th aspect, the method of claim **167**, wherein the supplying of the heat exchange medium to the at least one heat exchanger in the first flow direction and the subsequent supplying of the heat exchange medium to the at least one heat exchanger in the second flow direction is performed without changing a pump's operation and wherein a direction of flow through the heat exchange passageway is switchable by actuation of one or more control valves of a heat exchange medium supply system.

[0418] In a 171st aspect, the method of aspect 167, wherein the supplying of the heat exchange medium to the at least one heat exchanger in the first flow direction and the subsequent supplying of the heat exchange medium to the at least one heat exchanger in the second flow direction are each carried out alternately over an extended period of time.

[0419] In a 172nd aspect, the method of aspect 171, wherein the extended period of time exceeds 30 minutes, 1 hour, 2 hours, 3 hours, 4 hours, 5 hours, 6 hours, 8 hours, 10 hours, 12 hours, 24 hours, 36 hours or 48 hours, and/or is less than 1 hour, 2 hours, 3 hours, 4 hours, 5 hours, 6 hours, 8 hours, 10 hours, 12 hours, 24 hours, 36 hours or 48 hours.

[0420] In a 173rd aspect, the method of aspect 167, wherein two or more pumps supply the heat exchange medium in opposite directions and the pumps are operated alternately to supply the heat exchange medium to the at least one heat exchanger.

[0421] In a 174th aspect, the method of aspect 167, wherein the battery pack includes a plurality of battery module layers that are stacked in a vertical direction, each battery module layer including a respective plurality of battery cells arranged in a planar array and a respective heat exchanger, and wherein the heat exchange passageway extends through each of the heat exchangers of the battery module layers.

[0422] In a 175th aspect, the method of aspect 174, wherein the first subset of the battery cells is located in a lowermost one of the battery module layers, and the second subset of the battery cells is located in an uppermost one of the battery module layers, or wherein the first subset of the battery cells is located in an uppermost one of the battery module layers, and the second subset of the battery cells is located in a lowermost one of the battery module layers.

[0423] In a 176th aspect, the method of aspect 167, further comprising: monitoring a temperature profile of the battery pack; and switching from the supplying of the heat exchange medium to the at least one heat exchanger in the first flow direction to the supplying of the heat exchange medium to the at least one heat exchanger in the second flow direction based at least in part on said monitoring.

[0424] In a 177th aspect, the method of aspect 167, wherein the monitoring of the temperature profile of the battery pack includes measuring a temperature of the battery pack proximate to the battery cells at the first end of the heat exchange passageway and measuring a temperature of the battery pack proximate to the battery cells at the second end of the heat exchange passageway.

[0425] In a 178th aspect, the method of aspect 167, wherein the supplying of the heat exchange medium in a first flow direction and the supplying of the heat exchange medium in the second flow direction are performed alternately by a single bi-directional pump.

[0426] In a 179th aspect, a system is provided, comprising: a battery pack including a plurality of battery cells arranged in an array and at least one heat exchanger, and wherein a heat exchange passageway extends through the at least one heat exchanger; and a heat exchange media supply system including one or more heat exchange media supply conduits and one or more multi-way valves for reconfiguring the heat exchange media supply system between a first supply configuration, in which the heat exchange media supply system is configured to supply a heat exchange medium through the heat exchange media passageway of the battery pack in a first flow direction, and a second supply configuration, in which the heat exchange media supply system is configured to supply the heat exchange medium through the heat exchange media passageway of the battery pack in a second flow direction opposite the first flow direction.

[0427] In a 180th aspect, the system of aspect 179, wherein, during operation with the heat exchange media supply system in the first supply configuration, a first subset of the battery cells located proximate to a first end of the heat exchange media passageway is exposed to the heat exchange medium prior to a second subset of the battery cells located proximate to a second end of the heat exchange media passageway, and wherein, during operation with the heat exchange media supply system in the second supply configuration, the second subset of the battery cells located proximate to the second end of the heat exchange media passageway is exposed to the heat exchange medium prior to the first subset of the battery cells located proximate to the first end of the heat exchange media passageway.

[0428] In a 181st aspect, the system of aspect 179, further comprising: a controller operable to periodically actuate the one or more multi-way valves to reconfigure the heat exchange media supply system from the first supply configuration to the second supply configuration, and vice versa.

[0429] In a 182nd aspect, the system of aspect 179, further comprising: one or more temperature sensors associated with one or more battery cells of the battery pack for monitoring a temperature profile of the battery pack.

[0430] In a 183rd aspect, the system of aspect 179, further comprising: one or more temperature sensors associated with one or more battery cells of the battery pack for monitoring a temperature profile of the battery pack; and a controller in communication with the one or more temperature sensors and including a memory configured to store instructions and at least one processor configured to execute the instructions to: detect, via the one or more temperature sensors, whether a temperature of a first subset of the battery cells proximate a first end of the heat exchange media passageway exceeds a temperature of a second subset of the battery cells proximate a second end of the heat exchange media passageway by a threshold value over time; and periodically actuate the one or more multi-way valves to reconfigure the heat exchange media supply system from the first supply configuration to the second supply configuration, and vice versa, in response to the detecting.

[0431] In a 184th aspect, the system of aspect 179, wherein the one or more multi-way valves are manually actuatable to selectively reconfigure the heat exchange media supply system from the first supply configuration to the second supply configuration, and vice versa.

[0432] In a 185th aspect, the system of aspect 179, wherein the battery pack includes a plurality of battery module layers that are stacked in a vertical direction, each battery module layer including a respective plurality of battery cells arranged in a planar array and a respective heat exchanger and wherein the heat exchange media passageway extends through each of the respective heat exchanger of the battery module layers.

[0433] In a 186th aspect, the system of aspect 179, wherein the system includes a single four-way valve for reconfiguring the heat exchange media supply system between the first supply configuration and the second supply configuration.

[0434] In a 187th aspect, the system of aspect 179, wherein the system includes exactly two multi-way valves for collectively reconfiguring the heat exchange media supply system between the first supply configuration and the second supply configuration.

[0435] In an 188th aspect, a battery pack is provided, comprising: a plurality of battery module layers stacked together to form a multi-layer battery stack, each battery module layer including a plurality of battery cells arranged in an array; and a battery pack enclosure surrounding the multi-layer battery stack, the battery enclosure including one or more crumple zones configured to deform in response to an impact event to assist in protecting the multi-layer battery stack from damage.

[0436] In a 189th aspect, the battery pack of aspect 188, wherein the battery pack enclosure includes a respective crumple zone adjacent each of at least two major sides of the multi-layer battery stack.

[0437] In a 190th aspect, the battery pack of aspect 188, wherein the battery pack enclosure includes a respective crumple zone adjacent each of longitudinal sides of the multi-layer battery stack and each of top and bottom sides of the multi-layer battery stack.

[0438] In a 191st aspect, the battery pack of aspect 188, wherein each of the one or more crumple zones is formed by a shell structure with a plurality of internal structural partitions and a plurality of internal cavities defined at least in part by the shell structure and internal structural partitions.

[0439] In a 192nd aspect, the battery pack of aspect 188, wherein the battery pack enclosure includes one or more heat transfer medium passageways to facilitate the circulation of a heat transfer medium through at least a portion of the battery pack enclosure to assist in drawing heat away from the battery cells to cool the battery cells or, alternatively, supplying heat to the battery cells to heat the battery cells.

[0440] In a 193rd aspect, the battery pack of aspect 188, wherein the multi-layer battery stack further includes one or more thermal management devices in thermal contact with at least some of the battery cells and having one or more heat transfer medium passageways, and wherein the one or more heat transfer medium passageways of the battery pack enclosure are in fluid communication with the one or more heat transfer medium passageways of the one or more thermal management devices of the multi-layer battery stack.

[0441] In a 194th aspect, the battery pack of aspect 193, wherein each of the one or more thermal management devices of the multi-layer battery stack is an active heat exchanger having the one or more heat transfer medium passageways for circulating the heat transfer medium for cooling or heating purposes.

[0442] In a 195th aspect, the battery pack of aspect 194, wherein each of the one or more active heat exchangers of the multi-layer battery stack is a battery cold plate that is configured to provide cooling or heating of the battery cells in operation.

[0443] In a 196th aspect, the battery pack of aspect 195, wherein each battery cold plate extends laterally beyond the battery cells on each of opposing sides of the battery pack to present a stack of battery cold plates that terminate adjacent a side wall of the battery pack enclosure and assist in protecting the battery cells from potential damage arising from a side impact event to the battery pack enclosure.

[0444] In a 197th aspect, the battery pack of aspect 188, wherein the battery pack enclosure is formed by a plurality of enclosure parts joined together.

[0445] In a 198th aspect, the battery pack of aspect 197, wherein the enclosure parts include a plurality of side components joined together to form a tubular structure that circumferentially surrounds the multi-layer battery stack.

[0446] In a 199th aspect, the battery pack of aspect 198, wherein each of the plurality of side components are structural extrusions having a constant cross-sectional profile over a longitudinal length thereof.

[0447] In a 200th aspect, the battery pack of aspect 198, wherein the enclosure parts include opposing end parts removably coupleable to the tubular structure formed by the plurality of side components to enclose the multi-layer battery stack.

[0448] In a 201st aspect, the battery pack of aspect 200, wherein the opposing end parts sealingly engage with a respective one of opposing mating interfaces at longitudinal ends of the tubular structure formed by the plurality of side components to seal the multi-layer battery stack within the battery pack enclosure.

[0449] In a 202nd aspect, the battery pack of aspect 201, wherein each of the opposing mating interfaces are provided with dual sealing surfaces to provide redundant sealing between each of the opposing end parts and the opposing mating interfaces at longitudinal ends of the tubular structure formed by the plurality of side components.

[0450] In a 203rd aspect, the battery pack of aspect 188, further comprising:

[0451] a battery pack rack including a plurality of rack members, wherein each battery module layer is secured to a respective rack member, and wherein the rack members are coupled directly to the battery pack enclosure.

[0452] In a 204th aspect, the battery pack of aspect 188, wherein the battery enclosure includes a plurality of rack members formed integrally therewith, and wherein each battery module layer is secured to a respective pair of rack members.

[0453] In a 205th aspect, the battery pack of aspect 188, wherein the rack members are arranged and spaced to apply a compressive load on the battery module layers to assist in maintaining the battery module layers of the multi-layer battery stack in thermal contact with each other.

[0454] In a 206th aspect, the battery pack of aspect 188, wherein the one or more crumple zones are formed by a shell structure with a curved or tapered outer surface to increase a volume of the one or more crumple zones proximate a major side of the multi-layer battery stack.

[0455] In a 207th aspect, the battery pack of aspect 206, wherein the curved or tapered outer surface has a vertex corresponding to a centerline through the major side of the multi-layer battery stack.

[0456] In a 208th aspect, the battery pack of aspect 188, wherein each of the one or more crumple zones has a volume proximate peripheral edges thereof that is different from a volume proximate a center of the crumple zone.

[0457] In a 209th aspect, the battery pack of aspect 188, wherein the multi-layer battery stack is disposed in direct contact with a surface of the battery pack enclosure underlying the multi-layer battery stack, and wherein at least one major side surface of battery pack enclosure is spaced from the multi-layer battery stack.

[0458] In a 210th aspect, the battery pack of aspect 188, wherein the battery pack enclosure comprises a shell with two spaced apart layers joined together by a plurality of structural supports to define one or more air gaps between the two layers corresponding to the one or more crumple zones.

[0459] In a 211th aspect, the battery pack of aspect 210, wherein the battery pack enclosure further includes end parts removably coupleable to the shell, wherein each end part includes dual sealing surfaces to provide redundant sealing between each of the end parts and the two layers of the shell.

[0460] In a 212th aspect, the battery pack of aspect 210, wherein the plurality of structural supports are arranged normal to the two layers of the shell.

[0461] In a 213th aspect, the battery pack of aspect 210, wherein the shell includes a plurality of distinct shell portions joined together to form the shell.

[0462] In a 214th aspect, the battery pack of aspect 213, wherein each of the plurality of distinct shell portions include a respective plurality of structural supports that are spaced equidistant from each other across the respective distinct shell portion.

[0463] In a 215th aspect, the battery pack of aspect 214, wherein structural supports proximate peripheral edges of each distinct shell portion are positioned closer to each other than structural supports proximate a center of each distinct shell portion to increase a structural strength of the shell proximate the peripheral edges of each distinct shell portion and define the one or more crumple zones proximate the center of each distinct shell portion.

[0464] In a 216th aspect, the battery pack of aspect 188, wherein each battery cell is provided in a form factor having a generally rectangular prismatic shape with an aspect ratio of cell length to cell height of between 3:1 to 6:1.

[0465] In a 217th aspect, the battery pack of aspect 188, wherein each battery cell is provided in a form factor having a generally rectangular prismatic shape with an aspect ratio of cell length to cell height of between 1:1 to 2:1.

[0466] In a 218th aspect, the battery pack of aspect 188, wherein each battery cell is provided in a form factor having a generally rectangular prismatic shape with a cell length of 520±50 mm, a cell height of 125±10 mm, a cell thickness of 20±5 mm.

[0467] In a 219th aspect, the battery pack of aspect 188, wherein each battery cell is provided in a form factor having a generally rectangular prismatic shape with a cell length of 175±50 mm, a cell height of 150±20 mm, a cell thickness of 45±5 mm.

[0468] In a 220th aspect, a battery pack is provided, comprising: a plurality of battery cells arranged in an array to form a battery array; at least one thermal management device associated with the battery array; and a battery pack enclosure in which the battery array and the thermal management device are accommodated, the battery pack enclosure including: an enclosure tray to which the battery array is fixedly mounted, the enclosure tray including a tray floor and tray sidewalls extending upwardly from the tray floor to define an internal tray cavity, and the enclosure tray further including a sealing interface around a perimeter of the tray sidewalls at a mouth of the enclosure tray; and an enclosure cover configured to mate with the enclosure tray at the sealing interface to enclose the battery array in a sealed manner, the enclosure cover comprising an upper cover portion integrally joined with a lower cover portion, the lower cover portion including a corresponding sealing interface to mate with the sealing interface of the enclosure tray, and wherein a rigidity of the lower cover portion in a vicinity of the sealing interface exceeds a rigidity of the upper cover portion in a vicinity of an interface between the upper cover portion and the lower cover portion.

[0469] In a 221st aspect, the battery pack of aspect 220, wherein the interface between the upper cover portion and the lower cover portion of the enclosure cover is characterized by a weld seam.

[0470] In a 222nd aspect, the battery pack of aspect 221, wherein the weld seam between the upper cover portion and the lower cover portion of the enclosure cover is offset from the corresponding sealing interface of the lower cover portion by a distance sufficient to avoid appreciable thermal distortion of a sealing surface of the corresponding sealing interface.

[0471] In a 223rd aspect, the battery pack of aspect 222, wherein the weld seam is offset from the corresponding sealing interface of the lower cover portion by at least 100 mm.

[0472] In a 224th aspect, the battery pack of aspect 220, wherein a gasket is provided between the sealing interface of the tray enclosure and the corresponding sealing interface of the lower cover portion of the enclosure cover.

[0473] In a 225th aspect, the battery pack of aspect 224, wherein at least one of the sealing interface of the enclosure tray and the corresponding sealing interface of the lower cover portion of the enclosure cover includes a trench formed therein for receiving the gasket.

[0474] In a 226th aspect, the battery pack of aspect 220, wherein the enclosure cover is devoid of any electrical connectors, fittings or interfaces or fluid connectors, fittings or interfaces.

[0475] In a 227th aspect, the battery pack of aspect 220, wherein the battery pack enclosure includes one or more electrical connectors, fittings or interfaces for electrical power or signal transmission, and wherein all of the one or more electrical connectors, fittings or interfaces are coupled directly to the enclosure tray such that all electrical connections for the battery pack may be carried out via the enclosure tray.

[0476] In a 228th aspect, the battery pack of aspect 220, wherein the battery pack enclosure includes one or more fluid connectors, fittings or interfaces for heat transfer medium transmission, and wherein all of the one or more fluid connectors, fittings or interfaces are coupled directly to the enclosure tray such that all fluid connections for the battery pack may be carried out via the enclosure tray.

[0477] In a 229th aspect, the battery pack of aspect 220, wherein the upper cover portion and the lower cover portion of the enclosure cover define an internal cover cavity with a volume greater than a volume of the internal tray cavity to accommodate a majority of the battery array.

[0478] In a 230th aspect, the battery pack of aspect 220, wherein the interface between the upper cover portion and the lower cover portion of the enclosure cover is positioned closer to the sealing interface of the lower cover portion than to an outermost surface of the upper cover portion.

[0479] In a 231st aspect, a battery pack is provided, comprising: a plurality of battery module layers stacked in a vertical direction to form a multi-layer battery stack, each battery module layer including a plurality of battery cells arranged in a linear array, and each battery cell including a vent valve located on an end face thereof; and a battery pack frame including a plurality of frame members, wherein each battery module layer is secured to a respective frame member; and a plurality of vent isolators, each vent isolator associated with a respective one of the battery module layers and configured to assist in isolating discharged matter from the vent valve of any one of the battery cells of the battery module layer from the vent valves of battery cells of other battery module layers and to assist in directing the discharged matter away from the end face of the battery cell.

[0480] In a 232nd aspect, the battery pack of aspect 231, wherein each vent isolator is coupled to a respective one of the frame members.

[0481] In a 233rd aspect, the battery pack of aspect 231, wherein each vent isolator is integrally formed with a respective one of the frame members.

[0482] In a 234th aspect, the battery pack of aspect 231, wherein each vent isolator spans a series of the battery cells of the battery module layer, and includes a linear array of vent apertures with each vent aperture being aligned with a respective one of the vent valves of the series of the battery cells of the battery module layer.

[0483] In a 235th aspect, the battery pack of aspect 234, wherein each vent isolator includes a separator or wall of material between adjacent vent apertures to assist in preventing discharged matter from one of the vent valves associated with the adjacent vent apertures from directly impacting the other one of the vent valves associated with the adjacent vent apertures.

[0484] In a 236th aspect, the battery pack of aspect 234, wherein each vent aperture defines at least a portion of a guide, conduit or passageway that assists in routing discharged matter away from the vent valve associated with the vent aperture and away from the end face of the battery cell.

[0485] In a 237th aspect, the battery pack of aspect 236, wherein the at least a portion of the guide, conduit or passageway defined by each vent aperture assists in routing discharged matter toward a debris collection space provided adjacent the battery pack frame at a periphery of the battery pack.

[0486] In a 238th aspect, the battery pack of aspect 231, further comprising: for each battery module layer, one or more debris dams that assist in holding at least some of the linear array of battery cells in place and that assist in protecting at least a portion of each end face of those battery cells.

[0487] In a 239th aspect, the battery pack of aspect 231, wherein the one or more debris dams are shaped to direct debris away from each end face of the at least some of the linear array of battery cells.

[0488] In a 240th aspect, the battery pack of aspect 231, wherein the one or more debris dams are shaped to direct debris toward a debris collection space provided adjacent the battery pack frame at a periphery of the battery pack.

[0489] In a 241st aspect, the battery pack of aspect 231, further comprising: a battery pack enclosure surrounding the multi-layer battery stack and the battery pack frame, and wherein the battery pack frame is coupled to the battery pack enclosure with a debris collection space formed at a periphery of the multi-layer battery stack to receive debris upon a discharge of debris from one or more of the vent valves.

[0490] In a 242nd aspect, the battery pack of aspect 241, wherein the debris collection space is elongated and spans an entirety or substantially an entirety of a longitudinal length of the linear array of the battery cells of each battery module layer.

[0491] In a 243rd aspect, the battery pack of aspect 241, wherein the debris collection space is provided between the battery pack frame and the battery pack enclosure.

[0492] In a 244th aspect, the battery pack of aspect 241, wherein the debris collection space is provided at one or both of opposing ends of the battery pack to collect debris after the debris passes between the battery module layers of the multi-layer battery stack.

[0493] In a 245th aspect, the battery pack of aspect 241, wherein at least a portion of a surface area of the battery pack enclosure in a vicinity of the vent valves of the battery cells is covered with a fire retardant material.

[0494] In a 246th aspect, the battery pack of aspect 231, wherein at least a portion of a surface area of the end face of each battery cell is covered with a fire retardant material.

[0495] In a 247th aspect, the battery pack of aspect 231, wherein, for each battery module layer, the battery cells are arranged with vents thereof positioned on one or more of opposing sides of the battery module layer.

[0496] In a 248th aspect, the battery pack of aspect 231, wherein, for each battery module layer, the battery cells are arranged with vents thereof aligned in a stacking direction of the battery module layers.

[0497] In a 249th aspect, the battery pack of aspect 231, wherein each battery cell is provided in a form factor having a generally rectangular prismatic shape with an aspect ratio of cell length to cell height of between 3:1 to 6:1.

[0498] In a 250th aspect, the battery pack of aspect 231, wherein each battery cell is provided in a form factor having a generally rectangular prismatic shape with an aspect ratio of cell length to cell height of between 1:1 to 2:1.

[0499] In a 251st aspect, the battery pack of aspect 231, wherein each battery cell is provided in a form factor having a generally rectangular prismatic shape with a cell length of 520±50 mm, a cell height of 125±10 mm, a cell thickness of 20±5 mm.

[0500] In a 252nd aspect, the battery pack of aspect 231, wherein each battery cell is provided in a form factor having a generally rectangular prismatic shape with a cell length of 175 mm±50 mm, a cell height of 150±20 mm, and a cell thickness of 45±5 mm.

[0501] In a 253rd aspect, the battery pack of aspect 231, wherein the discharged matter is a hot gas with entrained debris.

[0502] In a 254th aspect, the battery pack of aspect 231, wherein each of the plurality of vent isolators are bare metal.

[0503] In a 255th aspect, the battery pack of aspect 231, wherein each of the plurality of vent isolators include a fire retardant coating.

[0504] In a 256th aspect, the battery pack of aspect 231, wherein each of the plurality of battery cells are coated with a fire retardant material.

[0505] In a 257th aspect, the battery pack of aspect 231, further comprising: a fire retardant material associated with at least some of the plurality of vent isolators or at least some of the plurality of battery cells, or both.

[0506] In a 258th aspect, a battery pack is provided, comprising: a plurality of battery module layers stacked to form a multi-layer battery stack, each battery module layer including a plurality of battery cells, and each battery cell including a vent valve located on an end face thereof; and at least one vent isolator, each vent isolator associated with a respective one of the battery module layers and configured to assist in isolating discharged matter from the vent valve of any one of the battery cells of the battery module layer from the vent valves of other battery cells and to assist in directing the discharged matter away from the end face of the battery cell.

[0507] In a 259th aspect, the battery pack of aspect 258, wherein the plurality of battery cells includes a plurality of rows and columns of prismatic battery cells in each battery module layer.

[0508] In a 260th aspect, the battery pack of aspect 259, wherein the at least one vent isolator includes one vent isolator associated with each row of battery cells and corresponding vent valves in the row.

[0509] In a 261st aspect, the battery pack of aspect 258, wherein each vent isolator includes a pair of spaced apart rails and a top plate disposed on the pair of spaced apart rails to define a debris collection space that assists with directing the discharged matter away from the end face of the battery cells.

[0510] In a 262nd aspect, the battery pack of aspect 261, wherein each vent isolator further includes a bottom plate including a plurality of apertures corresponding to the vent valves of the respective battery cells associated with each vent isolator.

[0511] In a 263rd aspect, the battery pack of aspect 258, wherein the end face of each battery cell is a top face of each battery cell.

[0512] In a 264th aspect, the battery pack of aspect 258, wherein each battery module layer includes the plurality of battery cells arranged in rows, and the at least one vent isolator includes vent isolators associated with each row of battery cells, each vent isolator configured to assist in isolating discharged matter from the vent valve of any one of the battery cells in a row from the vent valves of other battery cells in other rows of the same battery module layer.

[0513] In a 265th aspect, the battery pack of aspect 258, wherein a length of each at least one vent isolator is greater than a width of each of the battery cells.

[0514] In a 266th aspect, a battery pack is provided, comprising: a plurality of battery module layers stacked to form a multi-layer battery stack, each battery module layer including a plurality of battery cells arranged in an array, and each battery cell including a vent valve configured to discharge matter upon a fault condition of the battery cell; a battery pack enclosure surrounding the multi-layer battery stack; at least one sensor provided within the battery pack enclosure and operable to detect a change in at least one characteristic of the battery pack enclosure over time associated with discharged matter from the vent valve of at least one of the battery cells during a thermal runaway event; and a status indicator in communication with the at least one sensor operable to provide at least one warning indication in response to the detected change in the at least one characteristic over time in the battery pack enclosure associated with discharged matter from the vent valve of at least one of the battery cells via the at least one sensor.

[0515] In a 267th aspect, the battery pack of aspect 266, further including an air gap between the multi-layer battery stack and the battery pack enclosure, the at least one sensor being a pressure sensor and the at least one characteristic being pressure, the pressure sensor operable to detect a change in pressure of the air gap over time.

[0516] In a 268th aspect, the battery pack of aspect 267, wherein the status indicator is operable to provide the at least one warning indication in response to the change in pressure over time in the battery pack enclosure exceeding a threshold rate.

[0517] In a 269th aspect, the battery pack of aspect 268, wherein the threshold rate is between and including 50 Pascals per second and 150 Pascals per second.

[0518] In a 270th aspect, the battery pack of aspect 268, wherein the status indicator is operable to provide the at least one warning indication in response to the change in pressure over time in the battery pack enclosure exceeding the threshold rate for at least a threshold duration.

[0519] In a 271 st aspect, the battery pack of aspect 270, wherein the threshold duration is at least 3 seconds.

[0520] In a 272nd aspect, the battery pack of aspect 270, wherein the status indicator is operable to not provide the at least one warning indication in response to the change in pressure over time in the battery enclosure less than the threshold rate, or greater than the threshold rate but for less than the threshold duration.

[0521] In a 273rd aspect, the battery pack of aspect 266, wherein at least one sensor is a pressure sensor and the at least one characteristic is pressure, and wherein the status indicator is operable to not provide the at least one warning indication in response to variations in pressure over time associated with vibration or operational temperature of the multi-layer battery stack, or both.

[0522] In a 274th aspect, the battery pack of aspect 266, wherein the at least one warning indication is a haptic signal, a visual alert, an auditory alert, or any combination thereof.

[0523] In a 275th aspect, the battery pack of aspect 266, wherein the battery pack enclosure includes a relief valve configured to expel pressure accumulated in the battery pack enclosure that exceeds a threshold enclosure pressure.

[0524] In a 276th aspect, the battery pack of aspect 275, wherein the relief valve is configured to expel pressure accumulated in the battery pack enclosure upon detection of one or more thermal runaway events via the pressure sensor.

[0525] In a 277th aspect, the battery pack of aspect 266, wherein the at least one sensor is a pressure sensor and the at least one characteristic is pressure, the pressure sensor operable to distinguish between changes in pressure over time in the battery cell enclosure associated with vibration, temperature of the multi-layer battery stack, or both, and changes in pressure over time associated with the discharged matter from the vent valve of the at least one of the battery cells.

[0526] In a 278th aspect, the battery pack of aspect 266, wherein the at least one characteristic is pressure, and the change in pressure over time associated with the discharged matter from the vent valve of the at least one of the battery cells corresponds to a sudden change in pressure rate over a short time.

[0527] In a 279th aspect, the battery pack of aspect 278, wherein the sudden change in pressure rate is at least 50 Pascals per second and the short time is between and includes 3 seconds and 5 seconds.

[0528] In a 280th aspect, the battery pack of aspect 266, wherein each battery cell is provided in a form factor having a generally rectangular prismatic shape with an aspect ratio of cell length to cell height of between 3:1 to 6:1.

[0529] In a 281st aspect, the battery pack of aspect 266, wherein each battery cell is provided in a form factor having a generally rectangular prismatic shape with a cell length of 520±50 mm, a cell height of 120±10 mm, a cell thickness of 15±5 mm.

[0530] In a 282nd aspect, the battery pack of aspect 266, further including an air gap between the multi-layer battery stack and the battery pack enclosure, the at least one sensor being a gas sensor and the at least one characteristic being gas concentration, the gas sensor operable to detect a change in gas concentration of the air gap.

[0531] In a 283rd aspect, the battery pack of aspect 282, wherein the status indicator is operable to provide the at least one warning indication in response to the change in gas concentration in the battery pack enclosure exceeding a threshold concentration.

[0532] In a 284th aspect, the battery pack of aspect 283, wherein the status indicator is operable to not provide the at least one warning indication in response to the change in gas concentration in the battery enclosure being less than the threshold concentration.

[0533] In a 285th aspect, a method is provided, comprising: detecting a change in at least one characteristic over time in a space between a battery pack enclosure and a multi-layer battery stack in the battery pack enclosure with at least one sensor, the change in the at least one characteristic over time associated with discharged matter from a vent valve of at least one battery cell in the multi-layer battery stack during a thermal runaway event; and providing at least one warning indication with a status indicator in communication with the pressure sensor in response to the detected change in the at least one characteristic over time via the at least one sensor.

[0534] In a 286th aspect, the method of aspect 285, wherein the multi-layer battery stack includes a plurality of battery module layers stacked together with each battery module layer including a plurality of battery cells arranged in an array, and each battery cell including the vent valve configured to discharge matter upon a fault condition of the battery cell.

[0535] In a 287th aspect, the method of aspect 285, wherein the at least one sensor is a pressure sensor and the at least one characteristic is a pressure, and wherein the providing the at least one warning indication with the status indicator includes providing the at least one warning indication in response to a detected change in pressure rate that exceeds a threshold rate for at least a threshold duration.

[0536] In a 288th aspect, the method of aspect 287, wherein the threshold rate is between and including 50 Pascals per second and 150 Pascals per second.

[0537] In a 289th aspect, the method of aspect 287, wherein the threshold duration is between and including 3 second and 5 seconds.

[0538] In a 290th aspect, the method of aspect 287, wherein the at least one sensor is a pressure sensor and the at least one characteristic is a pressure, the method further comprising: not providing the at least one warning indication with the status indicator in response to a change in pressure less than the threshold rate, or less than the threshold duration.

[0539] In a 291 st aspect, the method of aspect 285, wherein the at least one sensor is a pressure sensor and the at least one characteristic is a pressure, the method further comprising: not providing the at least one warning indication with the status indicator in response to variations in pressure associated with vibration or operational temperature of the multi-layer battery stack, or both.

[0540] In a 292nd aspect, the method of aspect 285, wherein at least one sensor is a pressure sensor and the at least one characteristic is a pressure, and wherein the providing the at least one warning indication with the status indicator includes providing the at least one warning indication in response to a detected change in pressure rate over a threshold value.

[0541] In a 293rd aspect, the method of aspect 285, further comprising: expelling pressure accumulated in the battery pack enclosure with a relief valve upon exceeding a threshold enclosure pressure.

[0542] In a 294th aspect, the method of aspect 285, further comprising: expelling pressure accumulated in the battery pack enclosure with a relief valve in response to detecting the thermal runaway event via the pressure sensor.

[0543] In a 295th aspect, the method of aspect 285, wherein the at least one sensor is a gas sensor and the at least one characteristic is a gas concentration, the detecting the change in the at least one characteristic over time including detecting a change in gas concentration of the air gap.

[0544] In a 296th aspect, the method of aspect 295, wherein the providing the at least one warning indication with the status indicator includes providing the at least one warning indication in response to the change in gas concentration in the battery pack enclosure exceeding a threshold concentration.

[0545] In a 297th aspect, the method of aspect 296, further comprising: not providing the at least one warning indication in response to the change in gas concentration in the battery enclosure being less than the threshold concentration.

Additional Considerations

[0546] The devices, systems and methods of the disclosure each have several innovative aspects, no single one of which is solely responsible or required for the desirable attributes disclosed herein. The various features and processes described above may be used independently of one another, or may be combined in various ways. All possible combinations and subcombinations are intended to fall within the scope of this disclosure. Various modifications to the implementations described in this disclosure may be readily apparent to those of ordinary skill in the art, and the generic principles defined herein may be applied to other implementations. Thus, the claims are not intended to be limited to the implementations shown herein, but are to be accorded the widest scope consistent with this disclosure, the principles and the novel features disclosed herein.

[0547] Certain features that are described in this specification in the context of separate implementations also can be implemented in combination in a single implementation. Conversely, various features that are described in the context of a single implementation also can be implemented in multiple implementations separately or in any suitable subcombination. Moreover, although features may be described above as acting in certain combinations and even initially claimed as such, one or more features from a claimed combination can be excised from the combination, and the claimed combination may be directed to a subcombination or variation of a subcombination. No single feature or group of features is necessary or indispensable to each and every embodiment.

[0548] Conditional language used herein, such as, among others, “can,” “could,” “might,” “may,” “e.g.,” and the like, unless specifically stated otherwise, or otherwise understood within the context as used, is generally intended to convey that certain embodiments include, while other embodiments do not include, certain features, elements and/or steps. Thus, such conditional language is not generally intended to imply that features, elements and/or steps are in any way required for one or more embodiments. The terms “comprising,” “including,” “having,” and the like are synonymous and are used inclusively, in an open-ended fashion, and do not exclude additional elements, features, acts, operations, and so forth. Also, the term “or” is used in its inclusive sense (and not in its exclusive sense) so that when used, for example, to connect a list of elements, the term “or” means one, some, or all of the elements in the list. In addition, the articles “a,” “an,” and “the” as used in this application and the appended claims are to be construed to mean “one or more” or “at least one” unless specified otherwise.

[0549] Moreover, although aspects of the various embodiments have been described in the context of battery packs for commercial vehicles, such as long-haul tractors, it is appreciated that aspects of the embodiments of the battery packs and battery pack technology described herein, may be applicable to other applications, including, for example, personal vehicles and heavy duty industrial equipment.

[0550] In general, in the following claims, the terms used should not be construed to limit the claims to the specific embodiments disclosed in the specification and the claims, but should be construed to include all possible embodiments along with the full scope of equivalents to which such claims are entitled.

1. A battery pack, comprising:

a plurality of battery module layers stacked in a vertical direction to form a multi-layer battery stack, each battery module layer including a plurality of battery cells arranged in a linear array, and each battery cell including a vent valve located on an end face thereof; and

a battery pack frame including a plurality of frame members, wherein each battery module layer is secured to a respective frame member; and

a plurality of vent isolators, each vent isolator associated with a respective one of the battery module layers and configured to assist in isolating discharged matter from the vent valve of any one of the battery cells of the battery module layer from the vent valves of battery cells of other battery module layers and to assist in directing the discharged matter away from the end face of the battery cell.

2. The battery pack of claim **1**, wherein each vent isolator is coupled to a respective one of the frame members or integrally formed with a respective one of the frame members.

3. (canceled)

4. The battery pack of claim **1**, wherein each vent isolator spans a series of the battery cells of the battery module layer, and includes a linear array of vent apertures with each vent aperture being aligned with a respective one of the vent valves of the series of the battery cells of the battery module layer.

5. The battery pack of claim **4**, wherein each vent isolator includes a separator or wall of material between adjacent vent apertures to assist in preventing discharged matter from one of the vent valves associated with the adjacent vent apertures from directly impacting the other one of the vent valves associated with the adjacent vent apertures.

6. The battery pack of claim **4**, wherein each vent aperture defines at least a portion of a guide, conduit or passageway that assists in routing discharged matter away from the vent valve associated with the vent aperture and away from the end face of the battery cell.

7. (canceled)

8. The battery pack of claim **1**, further comprising:

for each battery module layer, one or more debris dams that assist in holding at least some of the linear array of battery cells in place and that assist in protecting at least a portion of each end face of those battery cells.

9. (canceled)

10. (canceled)

11. The battery pack of claim **1**, further comprising:

a battery pack enclosure surrounding the multi-layer battery stack and the battery pack frame, and

wherein the battery pack frame is coupled to the battery pack enclosure with a debris collection space formed at a periphery of the multi-layer battery stack to receive debris upon a discharge of debris from one or more of the vent valves.

12-16. (canceled)

17. The battery pack of claim **1**, wherein, for each battery module layer, the battery cells are arranged with vents thereof positioned on one or more of opposing sides of the battery module layer.

18. The battery pack of claim **1**, wherein, for each battery module layer, the battery cells are arranged with vents thereof aligned in a stacking direction of the battery module layers.

19-23. (canceled)

24. The battery pack of claim **1**, wherein each of the plurality of vent isolators are bare metal or include a fire retardant coating.

25. (canceled)

26. The battery pack of claim **1**, wherein each of the plurality of battery cells are coated with a fire retardant material.

27. The battery pack of claim **1**, further comprising: a fire retardant material associated with at least some of the plurality of vent isolators or at least some of the plurality of battery cells, or both.

28. A battery pack, comprising:

a plurality of battery module layers stacked to form a multi-layer battery stack, each battery module layer including a plurality of battery cells, and each battery cell including a vent valve located on an end face thereof; and

at least one vent isolator, each vent isolator associated with a respective one of the battery module layers and configured to assist in isolating discharged matter from the vent valve of any one of the battery cells of the battery module layer from the vent valves of other battery cells and to assist in directing the discharged matter away from the end face of the battery cell.

29. The battery pack of claim **28**, wherein the plurality of battery cells includes a plurality of rows and columns of prismatic battery cells in each battery module layer.

30. The battery pack of claim **29**, wherein the at least one vent isolator includes one vent isolator associated with each row of battery cells and corresponding vent valves in the row.

31. The battery pack of claim **28**, wherein each vent isolator includes a pair of spaced apart rails and a top plate disposed on the pair of spaced apart rails to define a debris collection space that assists with directing the discharged matter away from the end face of the battery cells.

32. The battery pack of claim **31**, wherein each vent isolator further includes a bottom plate including a plurality of apertures corresponding to the vent valves of the respective battery cells associated with each vent isolator.

33. The battery pack of claim **28**, wherein the end face of each battery cell is a top face of each battery cell.

34. The battery pack of claim **28**, wherein each battery module layer includes the plurality of battery cells arranged in rows, and the at least one vent isolator includes vent isolators associated with each row of battery cells, each vent isolator configured to assist in isolating discharged matter from the vent valve of any one of the battery cells in a row from the vent valves of other battery cells in other rows of the same battery module layer.

35. The battery pack of claim **28**, wherein a length of each at least one vent isolator is greater than a width of each of the battery cells.

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