

(12) **United States Patent**
Diekfuss et al.

(10) **Patent No.:** **US 12,140,464 B2**
(45) **Date of Patent:** ***Nov. 12, 2024**

(54) **PERMEABLE PAVEMENT MONITORING SYSTEM**

(71) Applicant: **P4 Infrastructure, Inc.**, Milwaukee, WI (US)

(72) Inventors: **Joseph A. Diekfuss**, Waukesha, WI (US); **Nicholas J. Hornyak**, Pewaukee, WI (US); **Christopher M. Foley**, Milwaukee, WI (US)

(73) Assignee: **P4 Infrastructure, Inc.**, Milwaukee, WI (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **18/301,787**

(22) Filed: **Apr. 17, 2023**

(65) **Prior Publication Data**
US 2023/0251124 A1 Aug. 10, 2023

Related U.S. Application Data
(63) Continuation of application No. 16/676,296, filed on Nov. 6, 2019, now Pat. No. 11,656,116.
(Continued)

(51) **Int. Cl.**
E01C 11/22 (2006.01)
E01C 3/00 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC **G01F 23/804** (2022.01); **E01C 3/003** (2013.01); **E01C 3/06** (2013.01); **E01C 11/226** (2013.01); **E01C 2201/20** (2013.01)

(58) **Field of Classification Search**
CPC G01F 23/804; E01C 3/003; E01C 3/06; E01C 11/226; E01C 2201/20
(Continued)

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,342,144 A 8/1994 McCarthy
8,388,260 B2 3/2013 Chen et al.
(Continued)

OTHER PUBLICATIONS

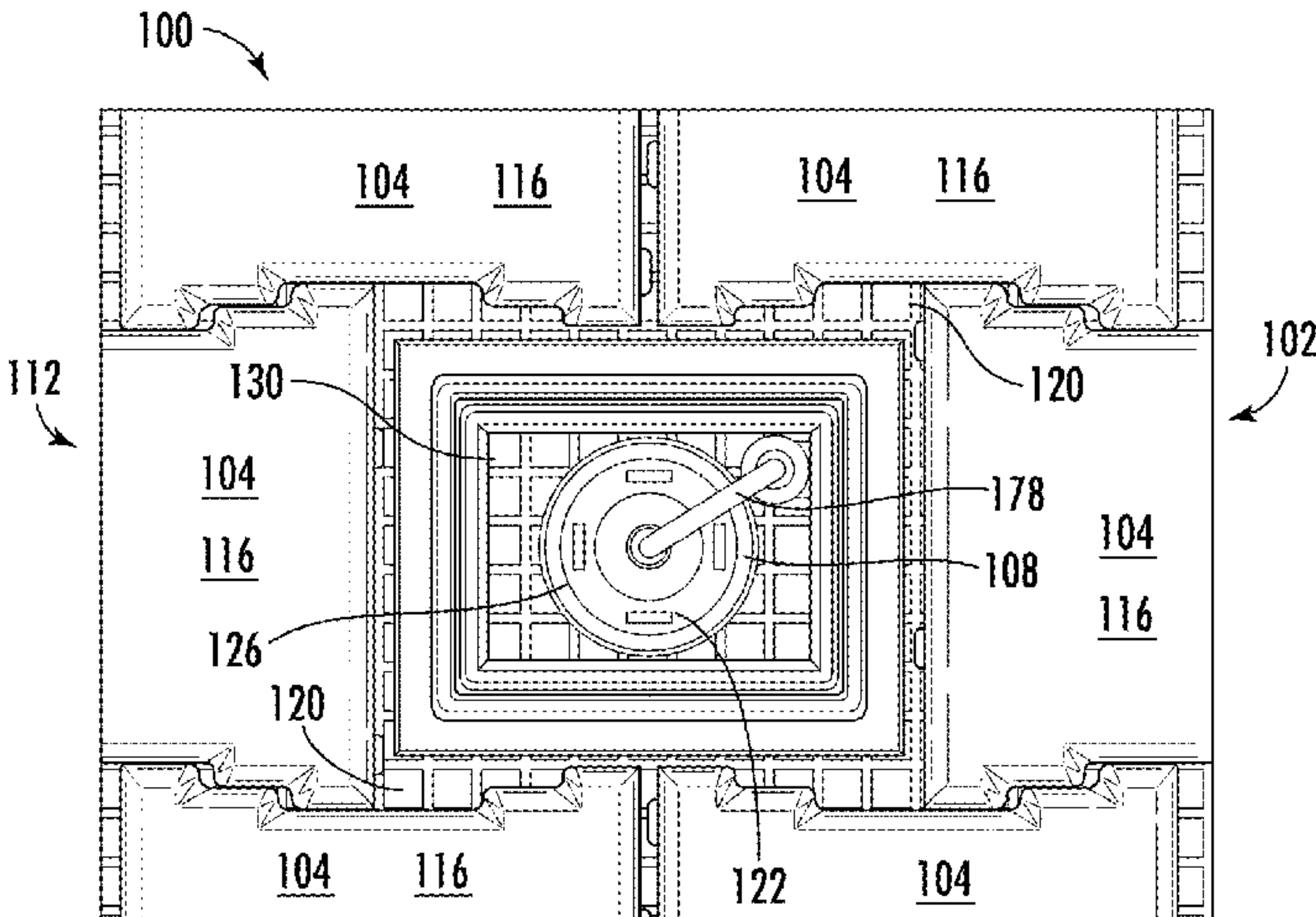
Kazemi, H., Rockaway, T.D., Rivard, J., Abdollahian, S. (2017), "Assessment of Surface Infiltration Performance and Maintenance of Two permeable pavement Systems in Kentucky", Journal of Sustainable Water in the Built Environment, Jun. 30, 2017, American Society of Civil Engineers, Reston, VA.
(Continued)

Primary Examiner — Raymond W Addie
(74) *Attorney, Agent, or Firm* — Reinhart Boerner Van Deuren s.c.

(57) **ABSTRACT**

Various embodiments of a system for monitoring drainage of a permeable pavement system are provided as well as various exemplary installation scenarios. In particular, embodiments of a permeable (or pervious) pavement management platform are disclosed herein. In embodiments, the pavement management platform provides a service that allows the user to determine vacuum maintenance needs for permeable (or pervious) pavement systems. Advantages of the platform include: subscription-based asset management platform as a service (PaaS), customized off-the-shelf water-level sensors, off-the-shelf tipping-bucket rain gauge, observation well installation consistent with industry standards, can be implemented in residential, commercial, municipal, county, and state systems, lithium-ion battery powered sensor, LoRA sensor to hub data transmission network, cellular data transmission from hub, electrical power for cellular data transmission hub (can be solar panel powered), real-time dashboarding of surface runoff storage, real-time dashboarding of ground water recharge rate, and permeability (clogging) threshold alerts, among others.

20 Claims, 16 Drawing Sheets



Related U.S. Application Data

- (60) Provisional application No. 62/757,027, filed on Nov. 7, 2018.
- (51) **Int. Cl.**
E01C 3/06 (2006.01)
G01F 23/80 (2022.01)
- (58) **Field of Classification Search**
USPC 404/2, 4, 17, 31–36, 72
See application file for complete search history.

References Cited

U.S. PATENT DOCUMENTS

2017/0294101 A1 10/2017 Stettler et al.
2020/0070220 A1 3/2020 Heinrichs

OTHER PUBLICATIONS

Chopra, M., Hardin, M., Gogo-Abite, I, Lassen, K. (2016). *Pavedrain Permeable Pavement*, Final Report, Stormwater Management Academy, University of Central Florida, Orlando, FL.

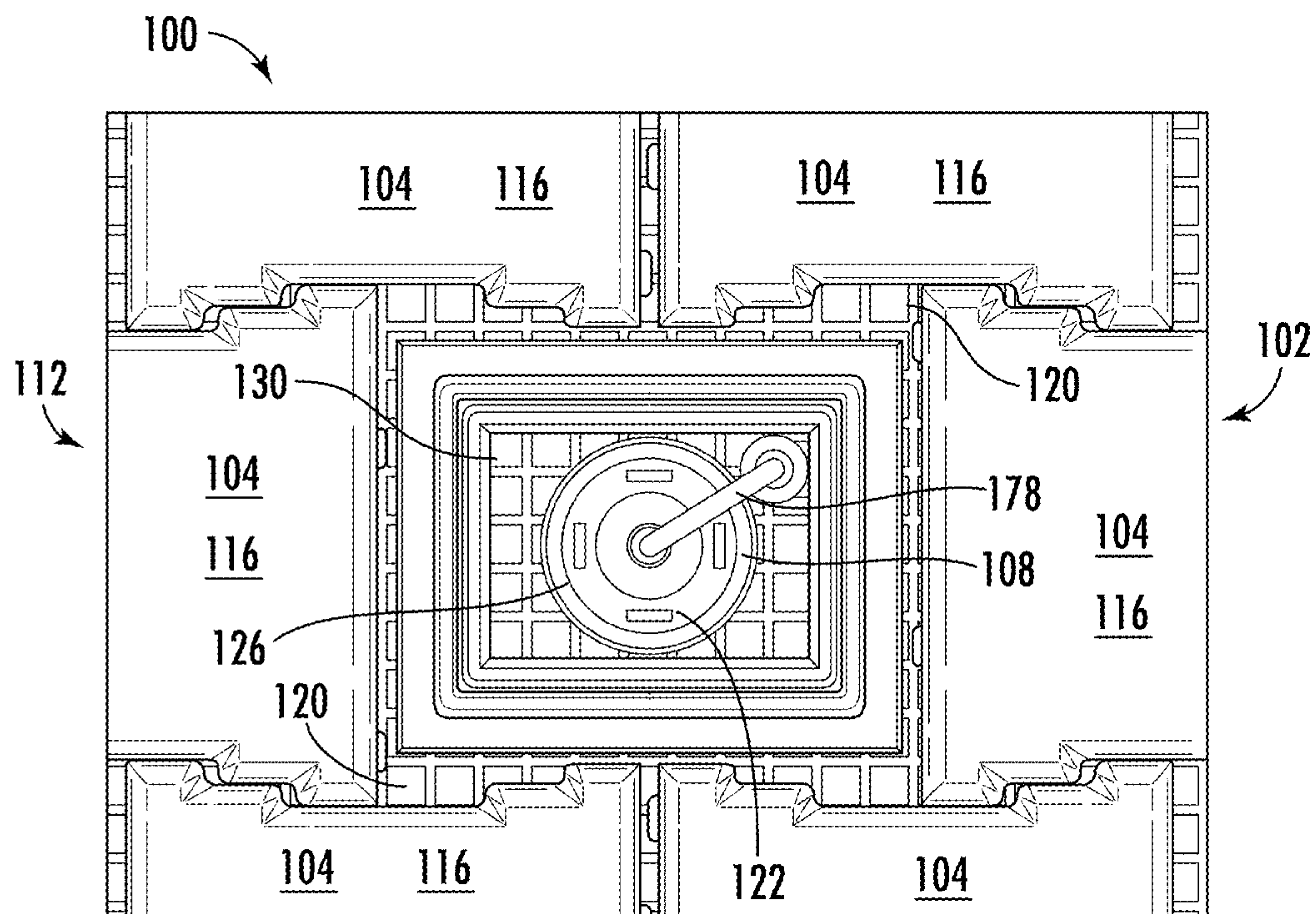


FIG. 1

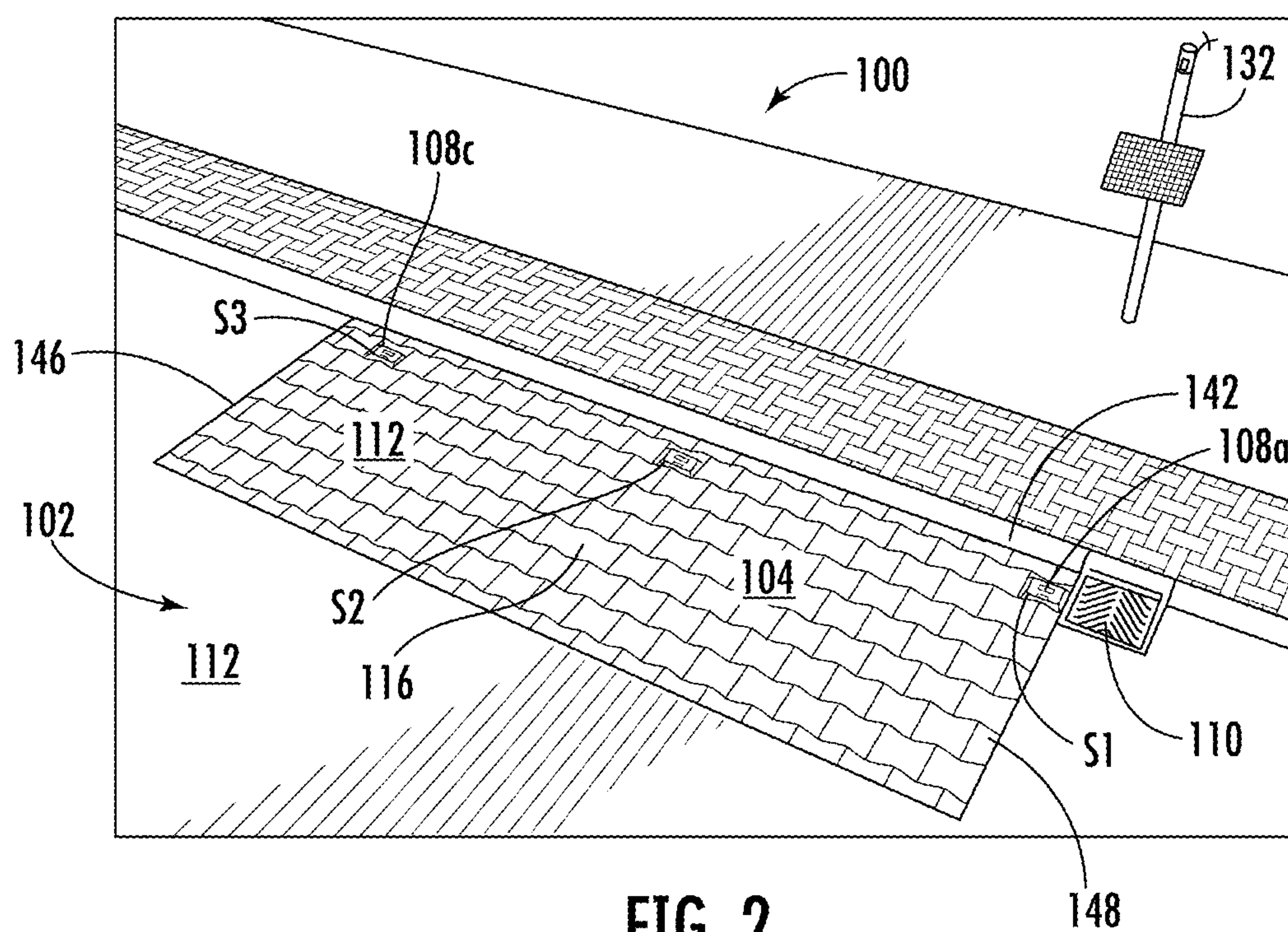


FIG. 2

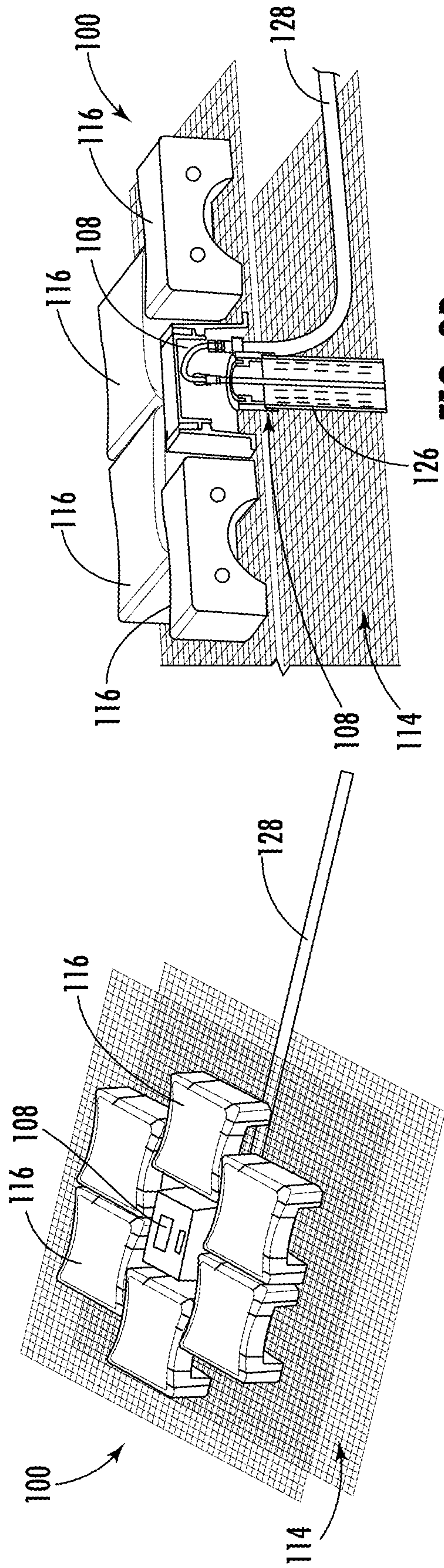


FIG. 3A

FIG. 3B

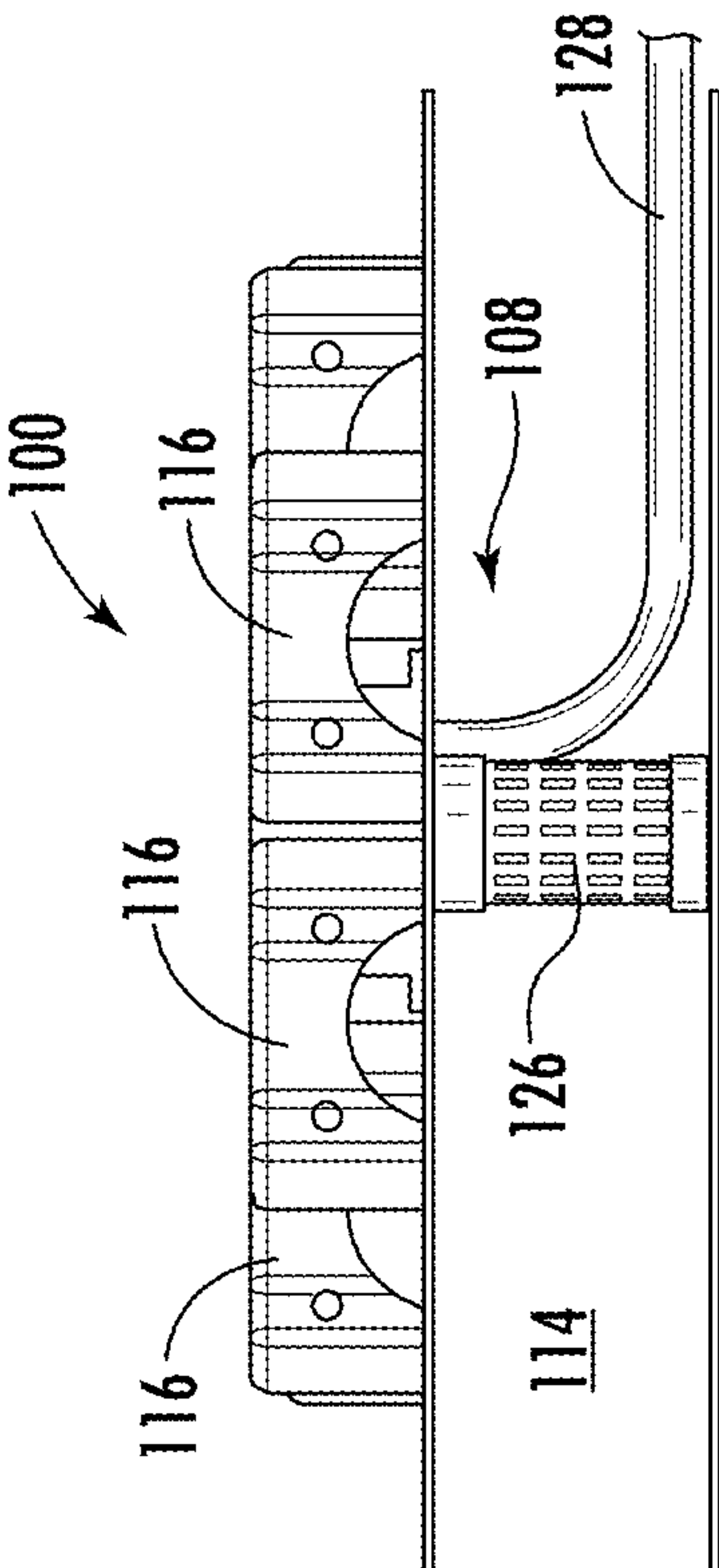


FIG. 3D

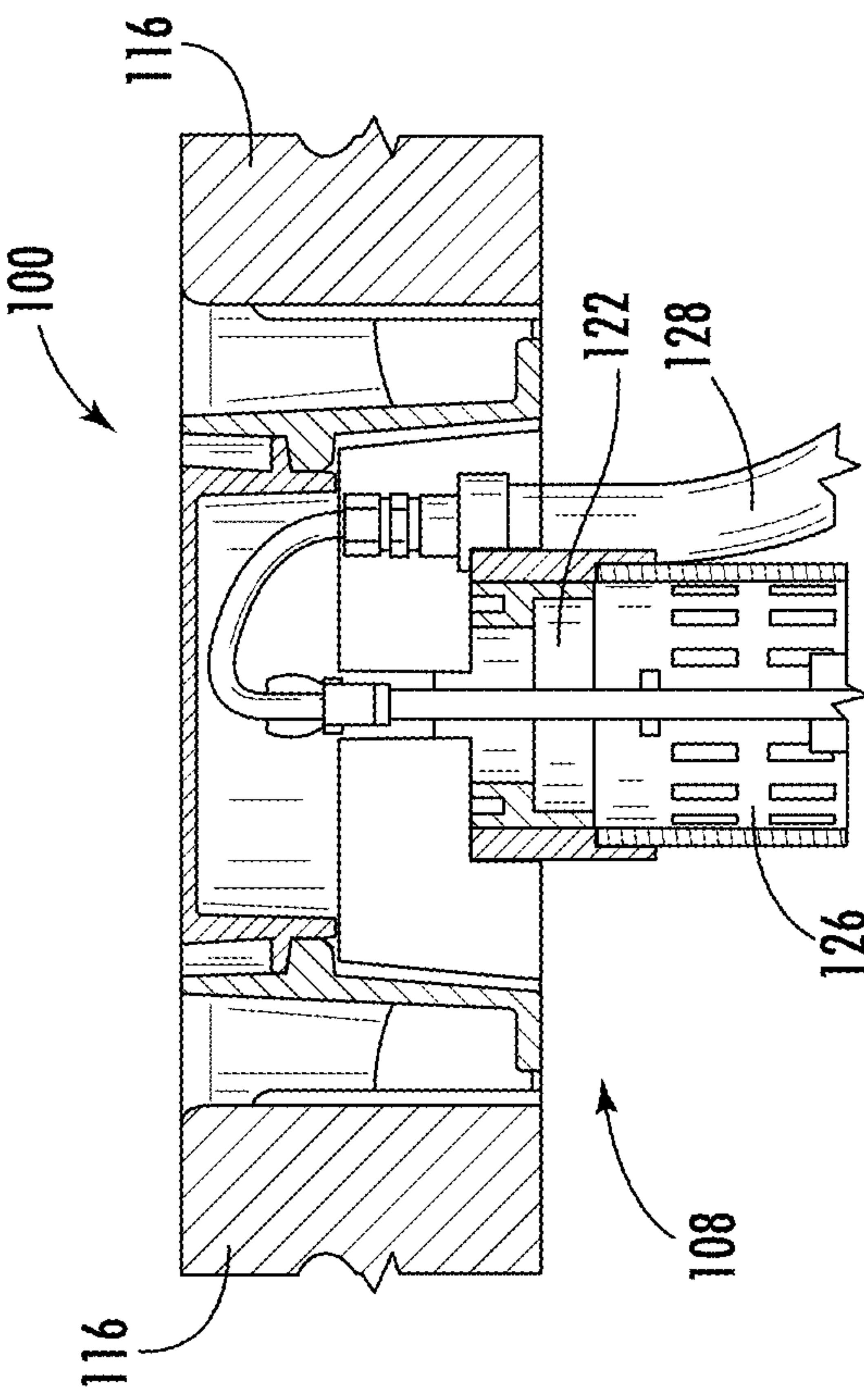


FIG. 3C

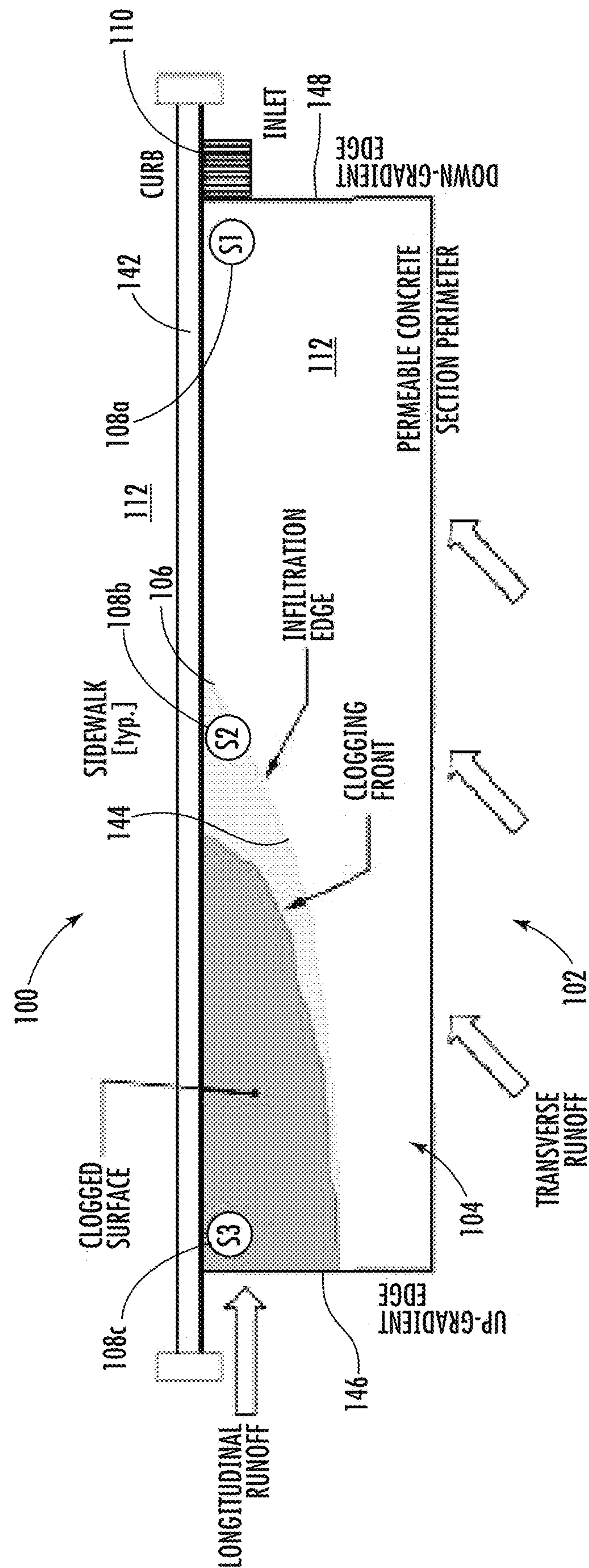


FIG. 4

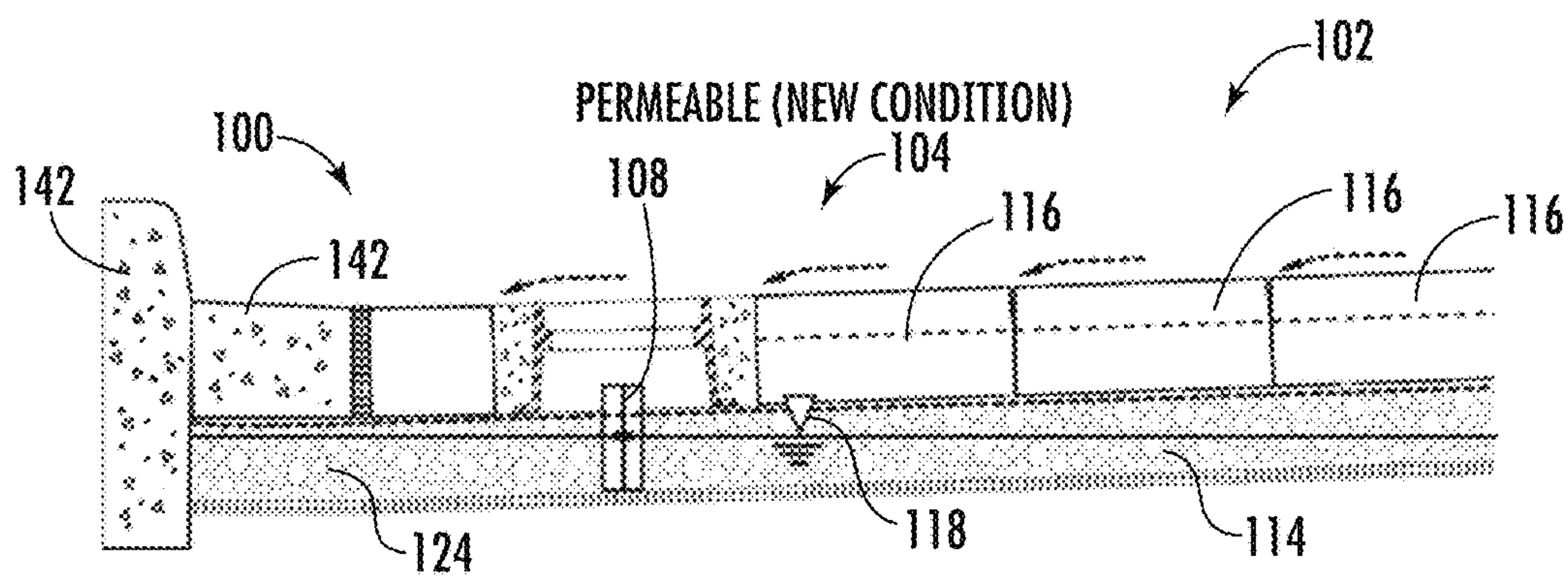


FIG. 5A

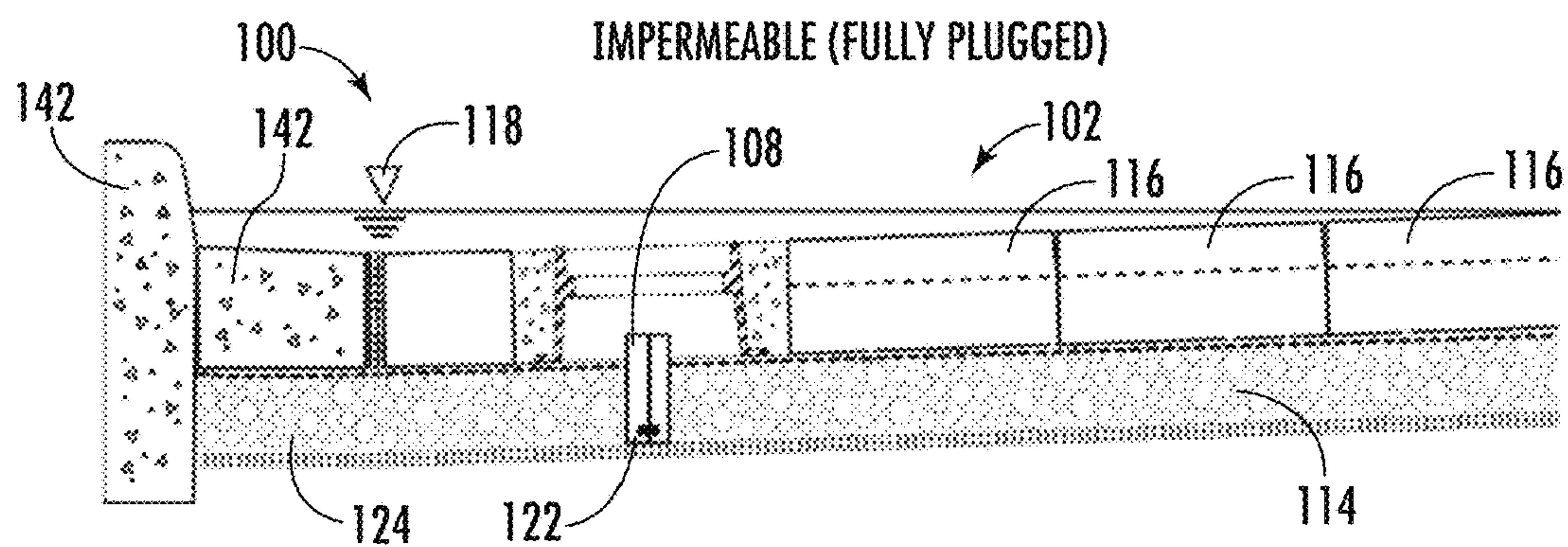


FIG. 5B

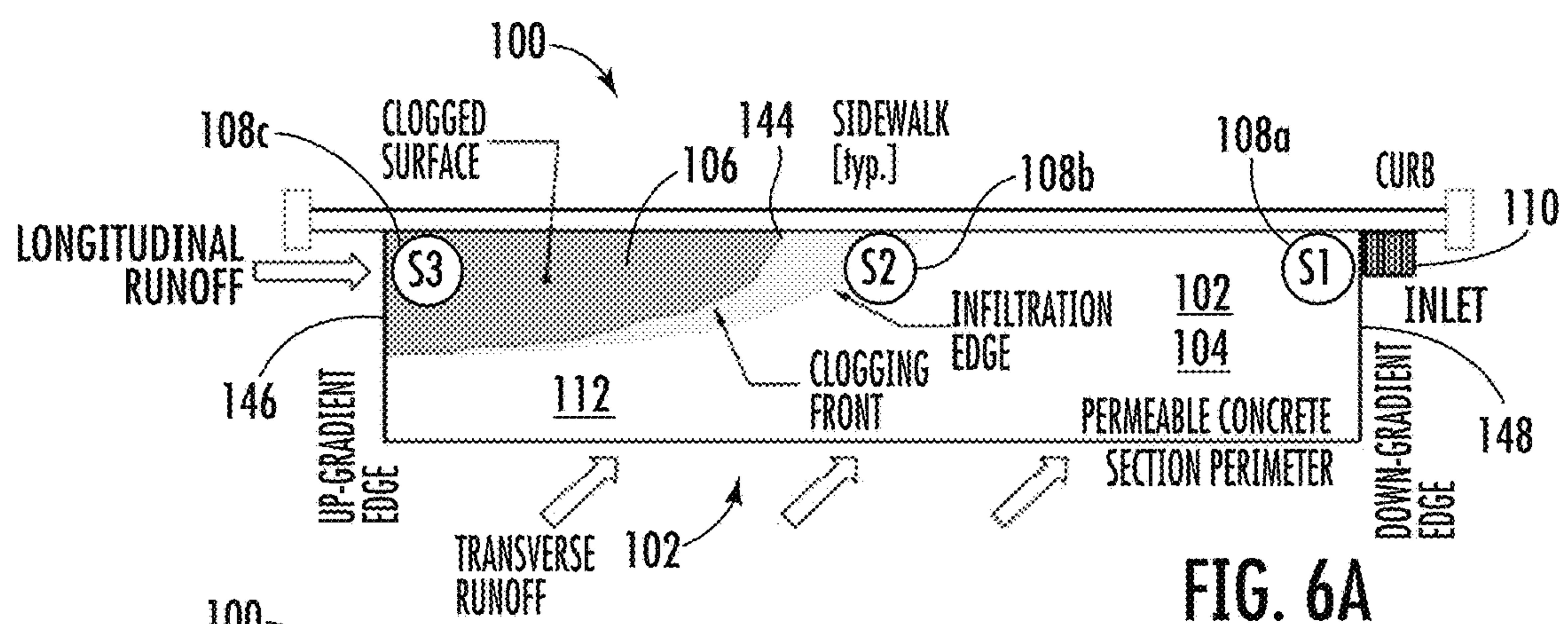


FIG. 6A

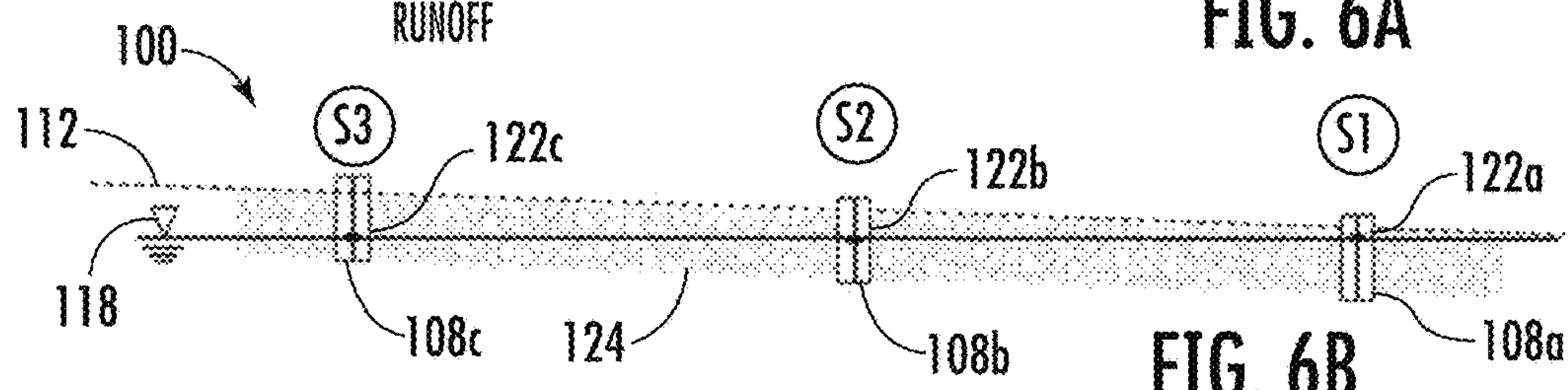
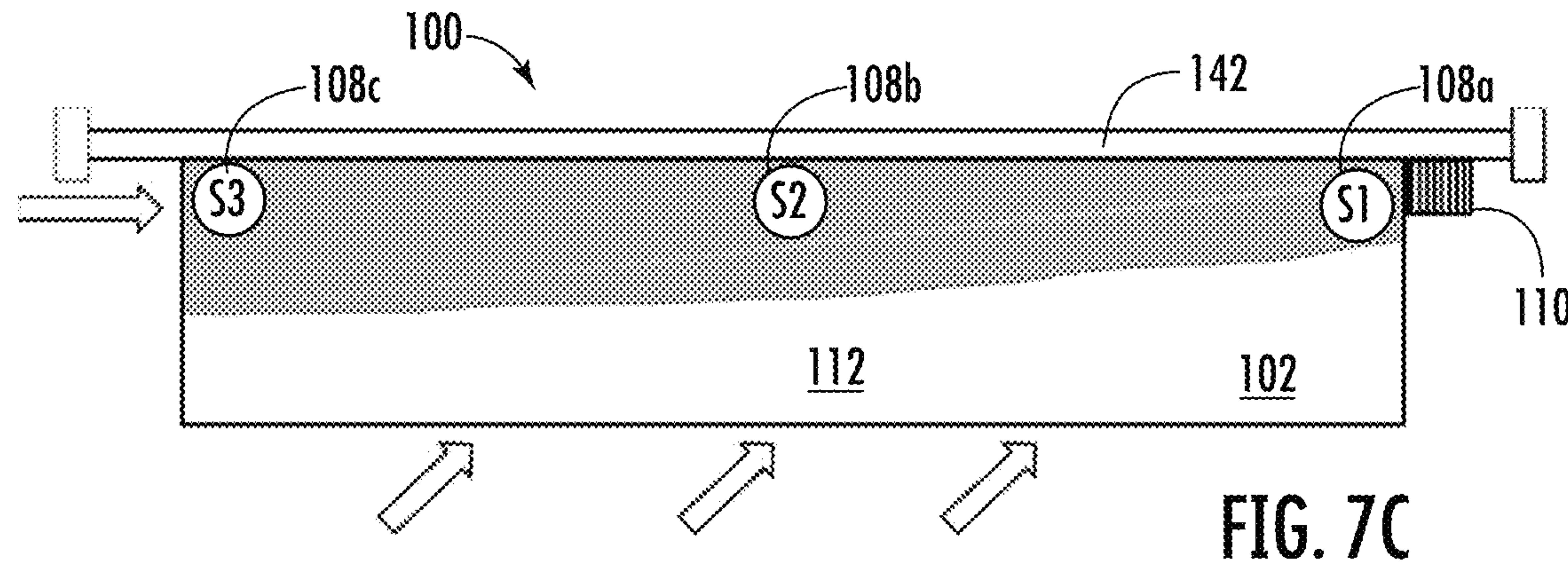
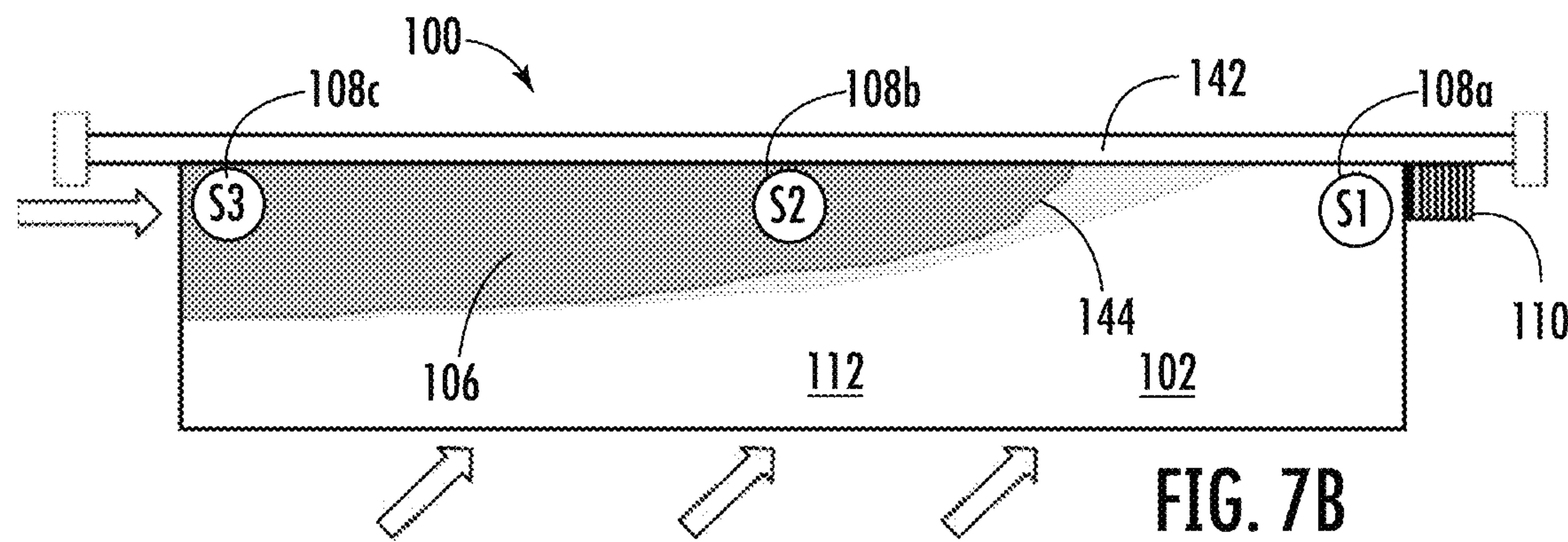
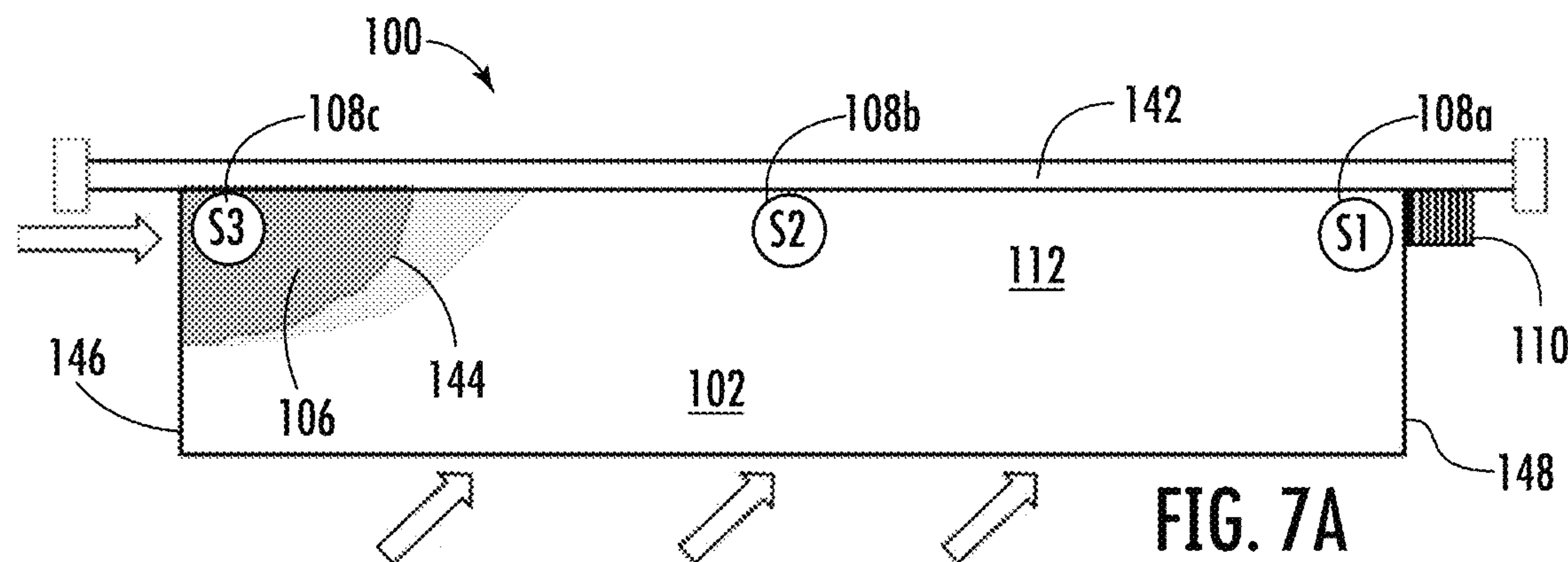


FIG. 6B



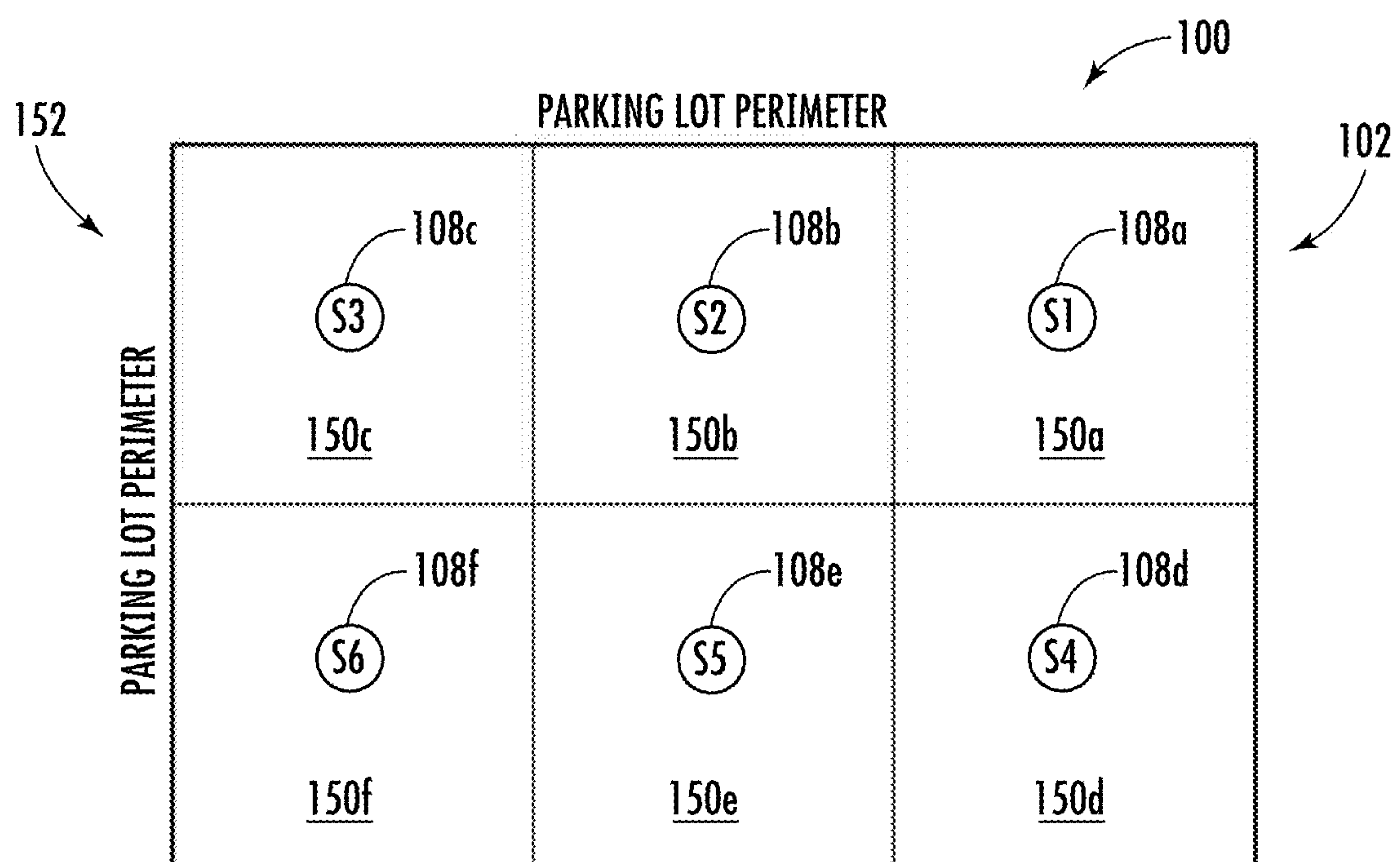


FIG. 8

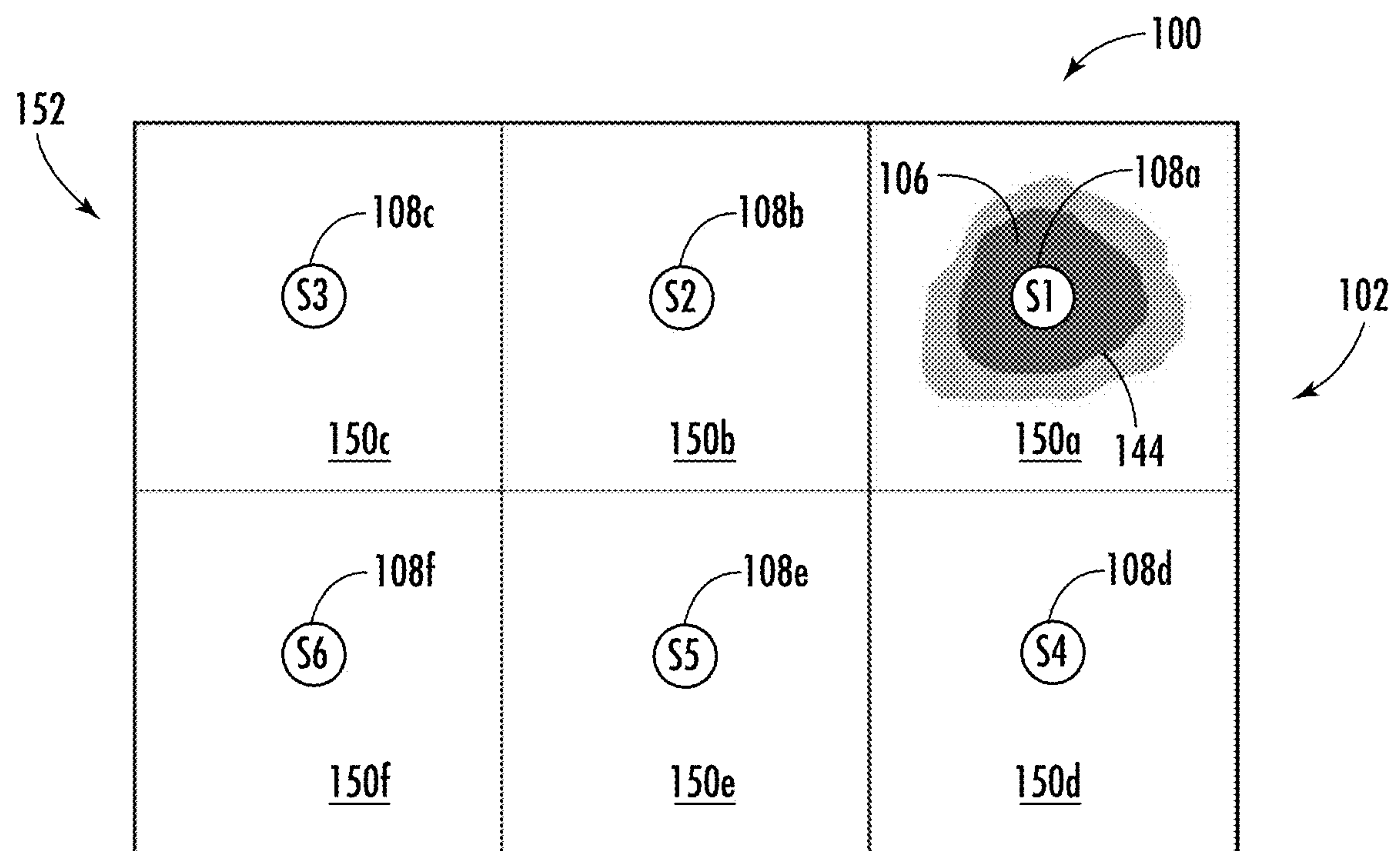


FIG. 9

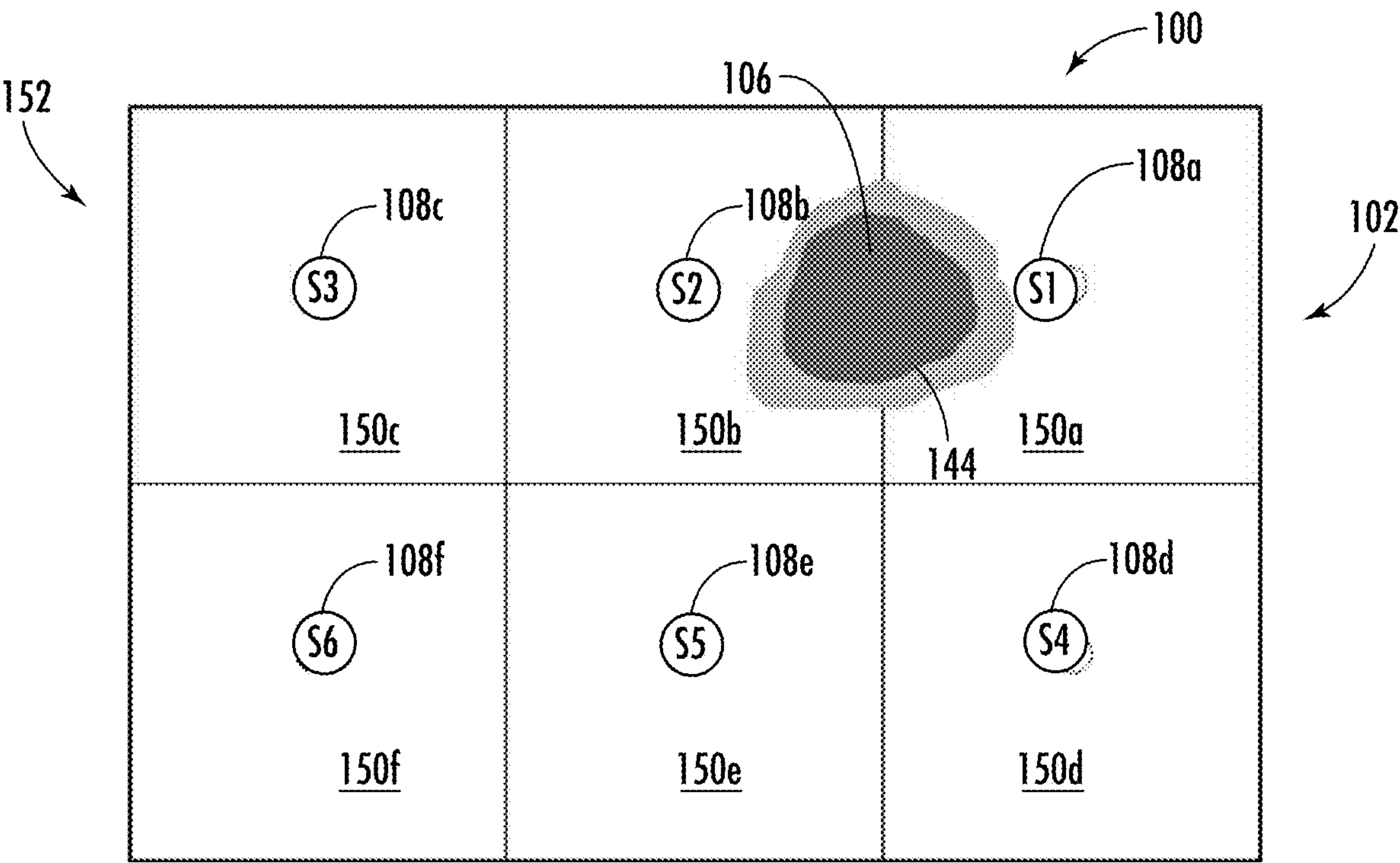


FIG. 10

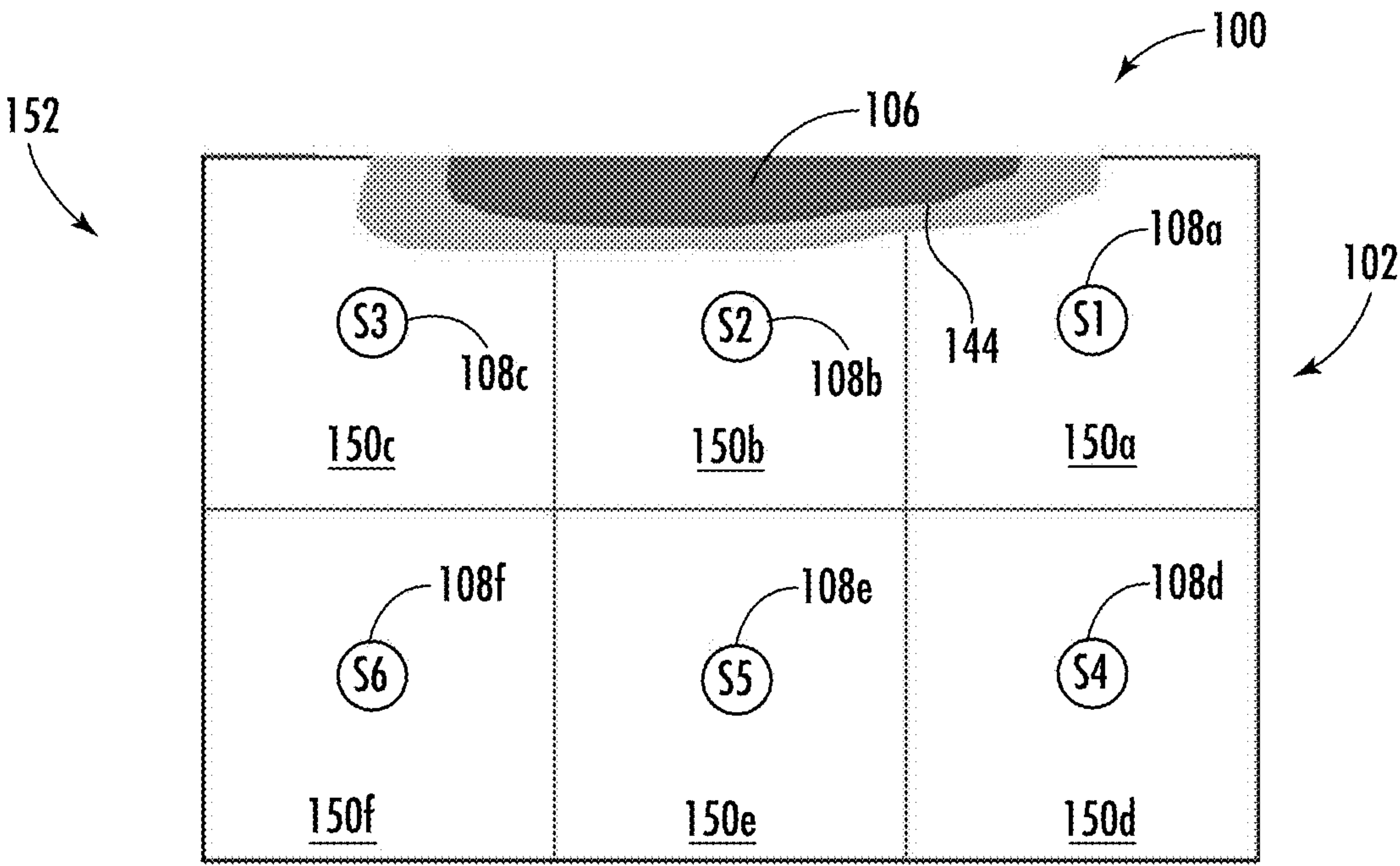


FIG. 11A

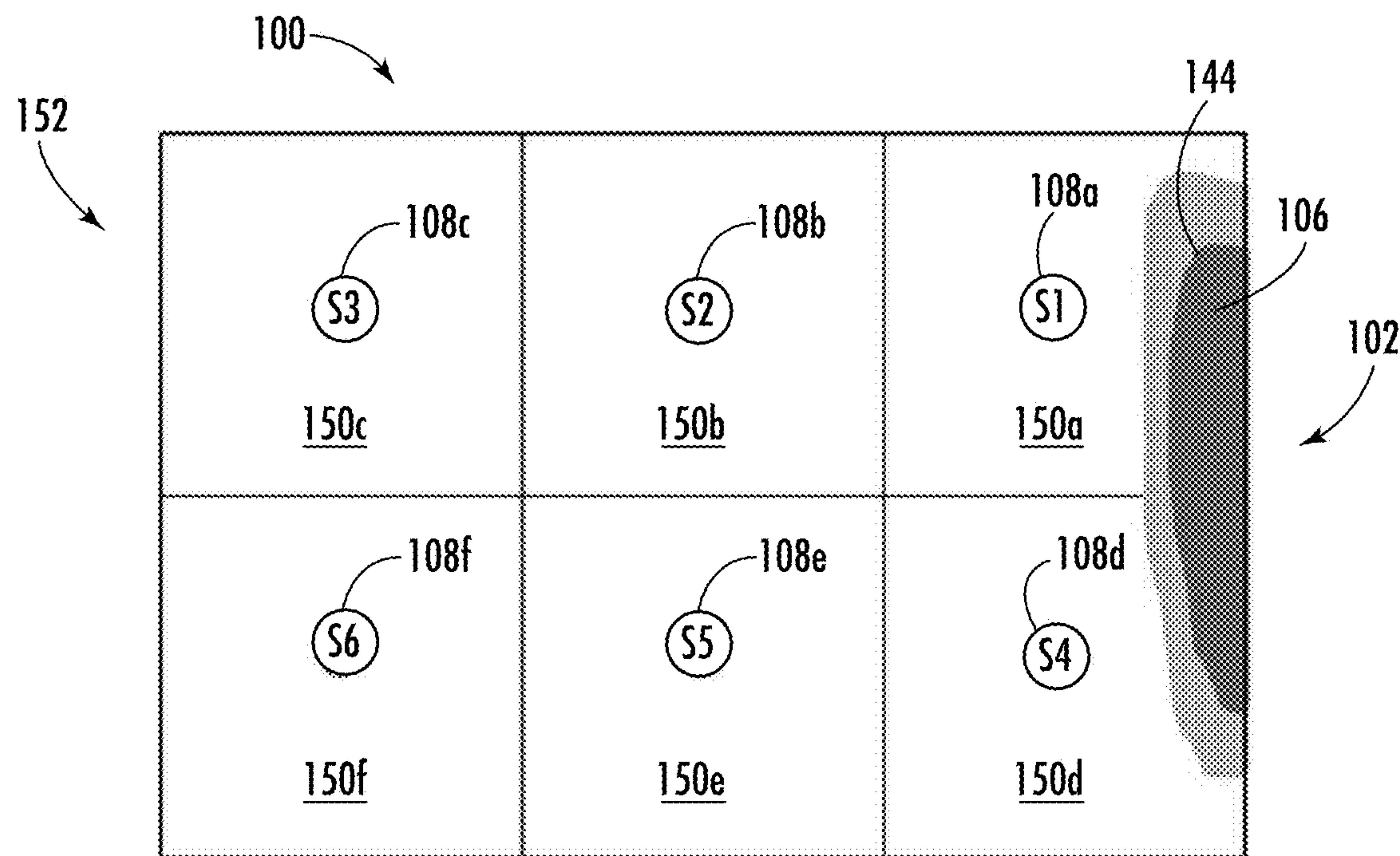


FIG. 11B

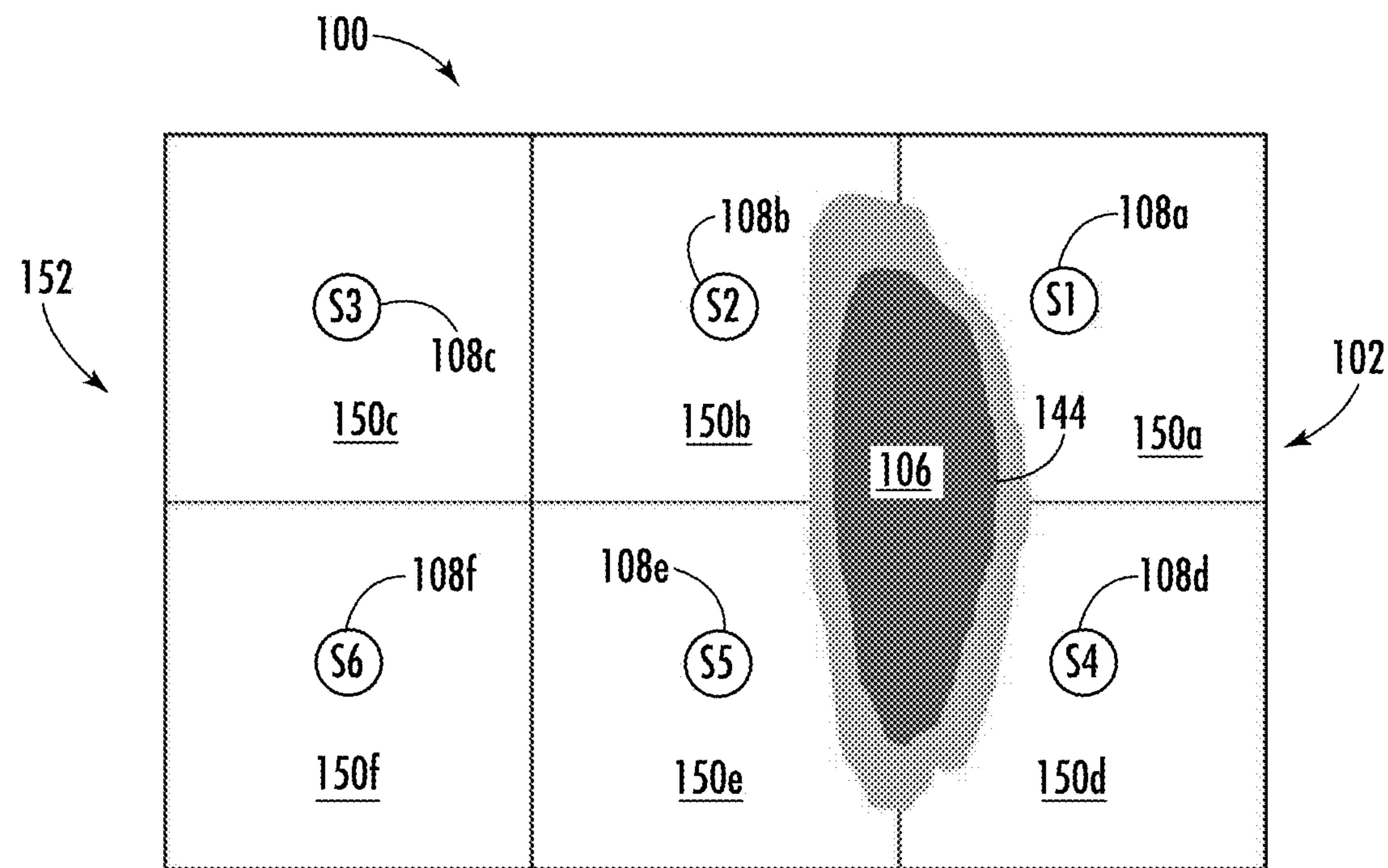


FIG. 12A

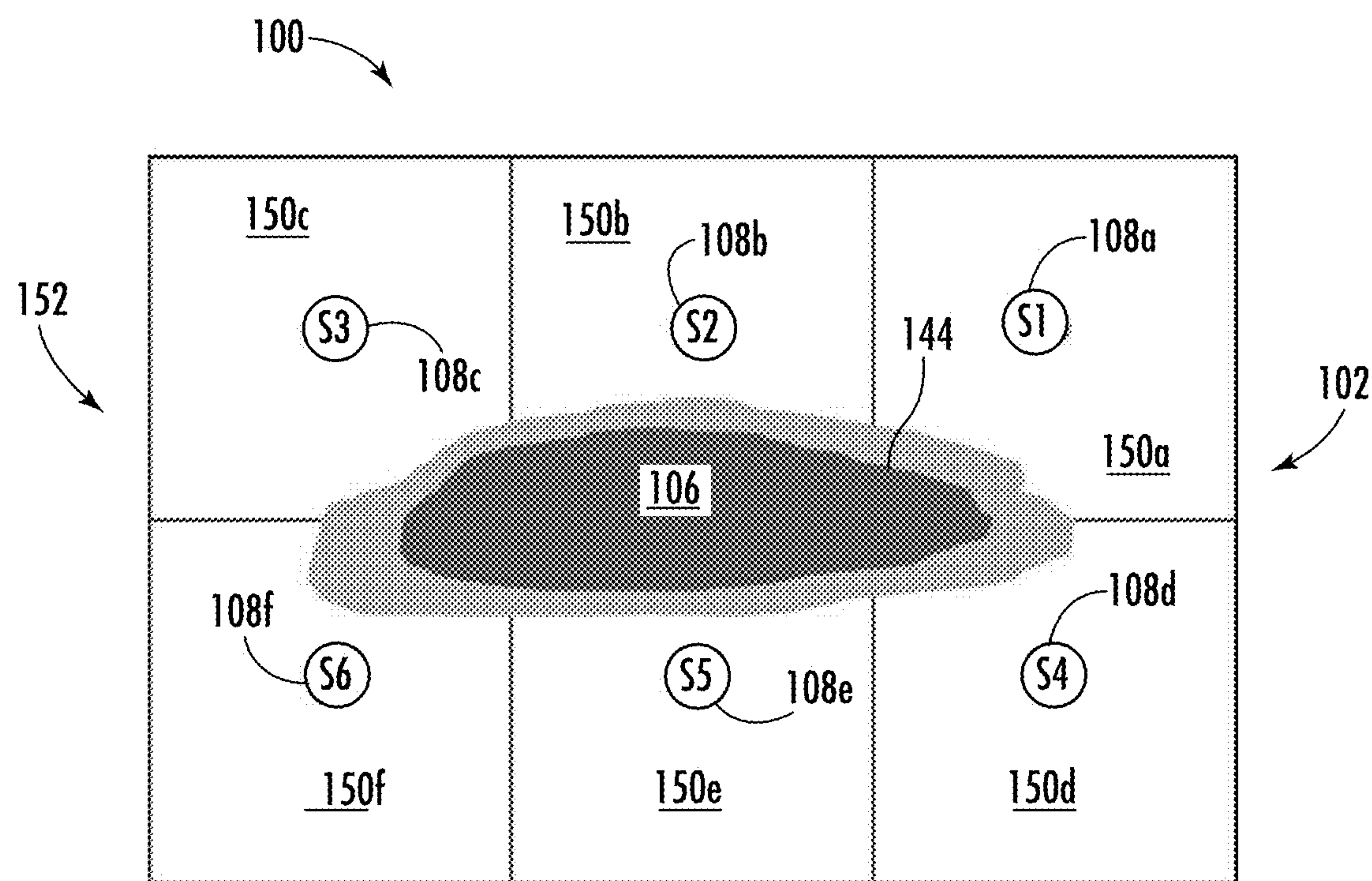


FIG. 12B

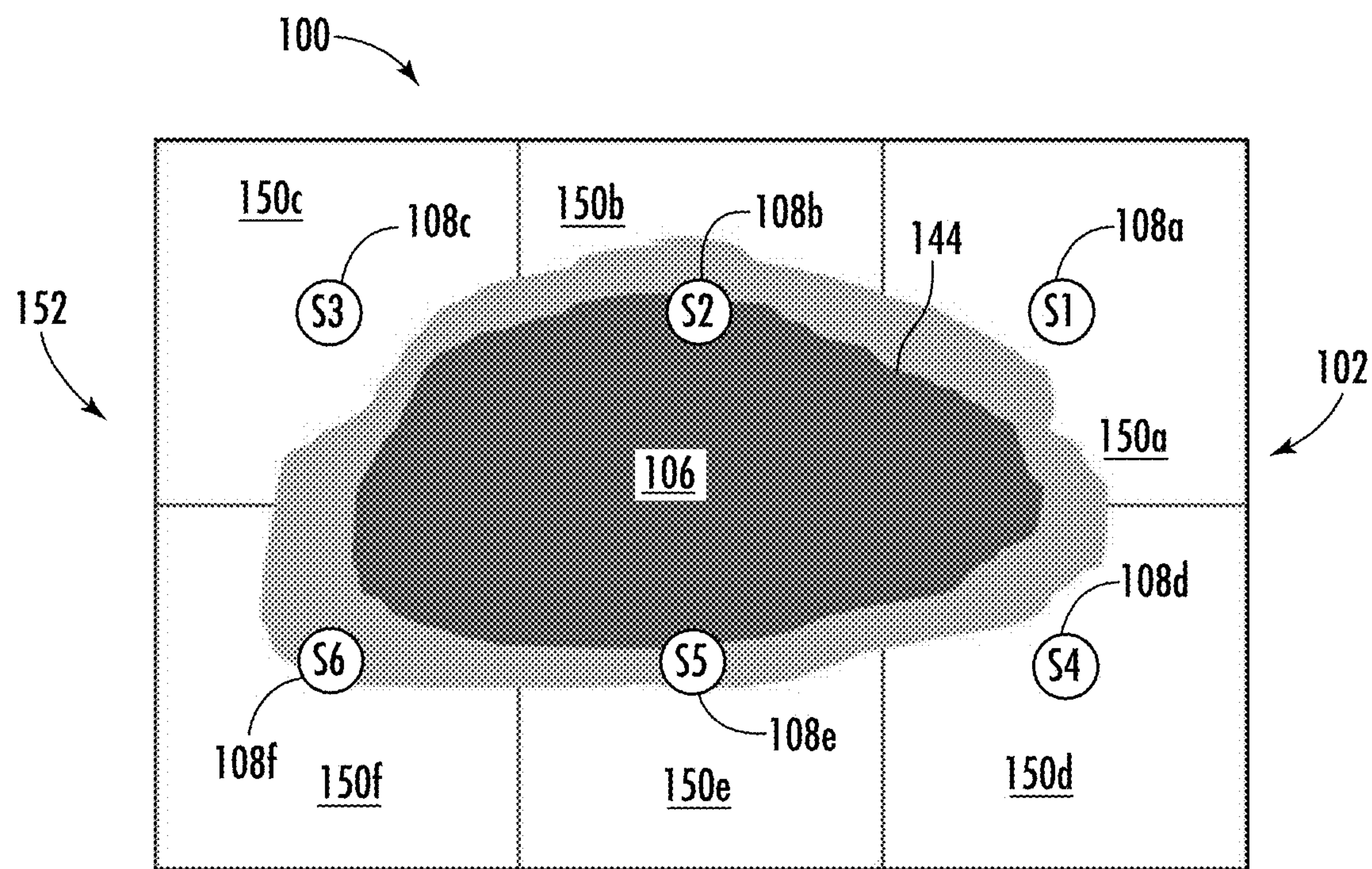


FIG. 12C

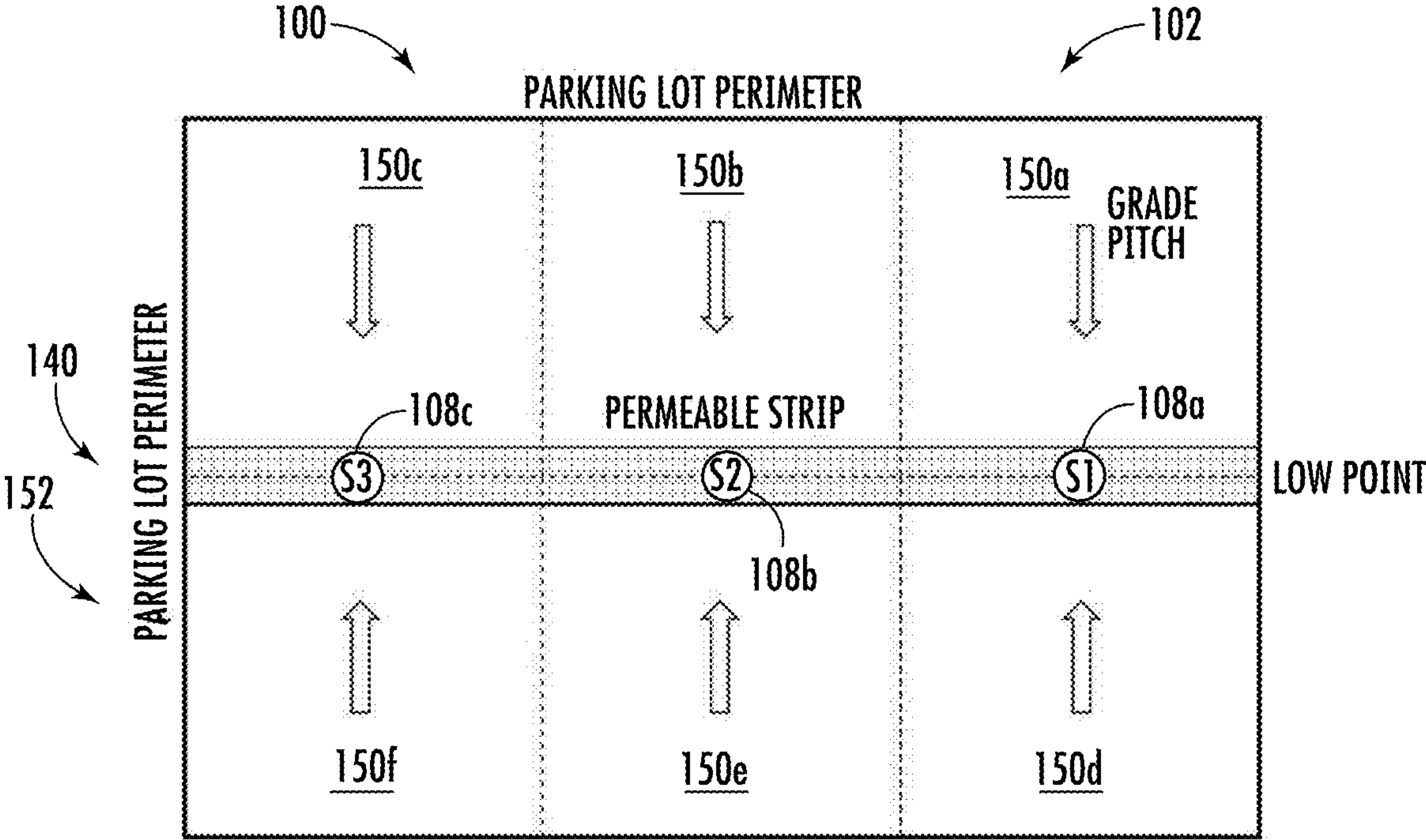


FIG. 13

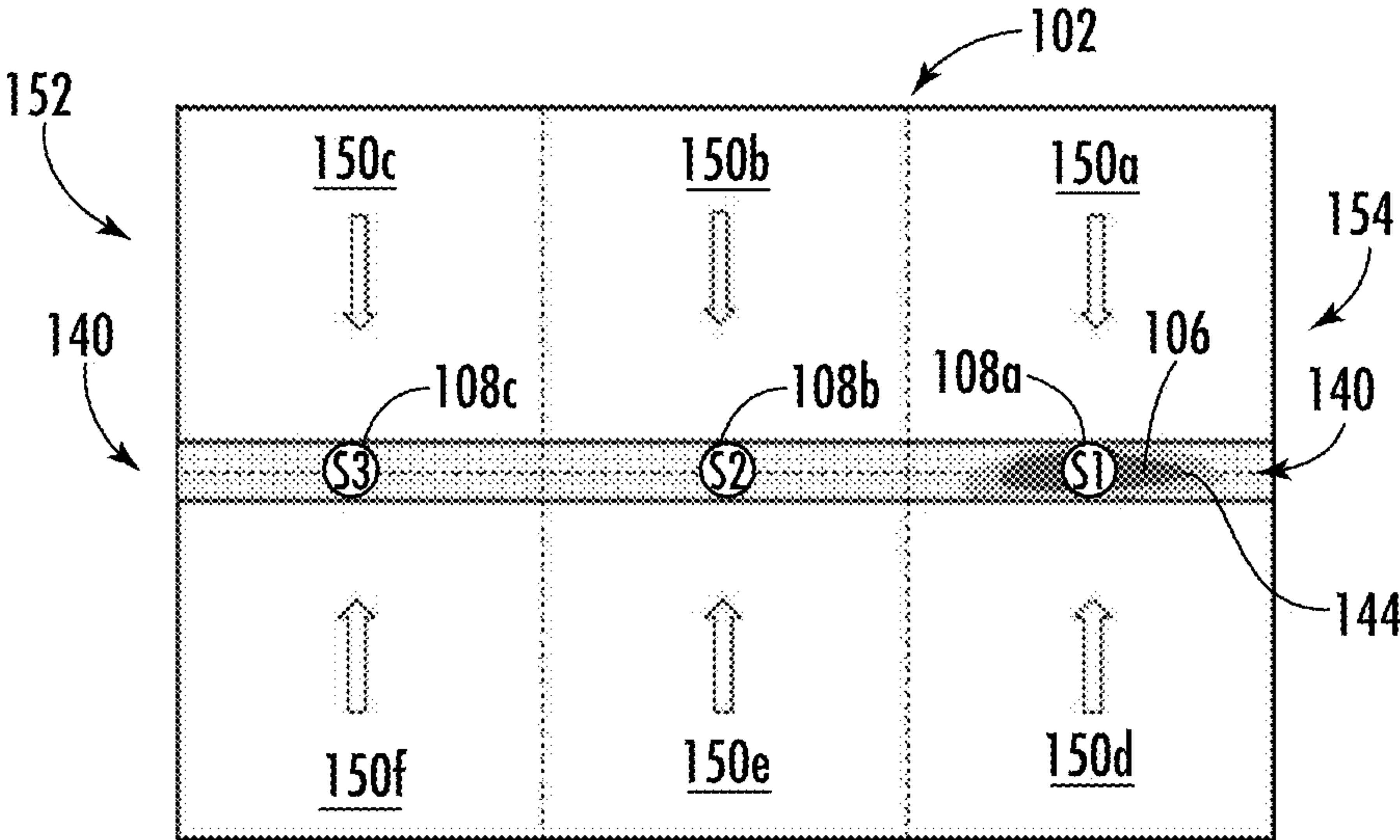


FIG. 14A

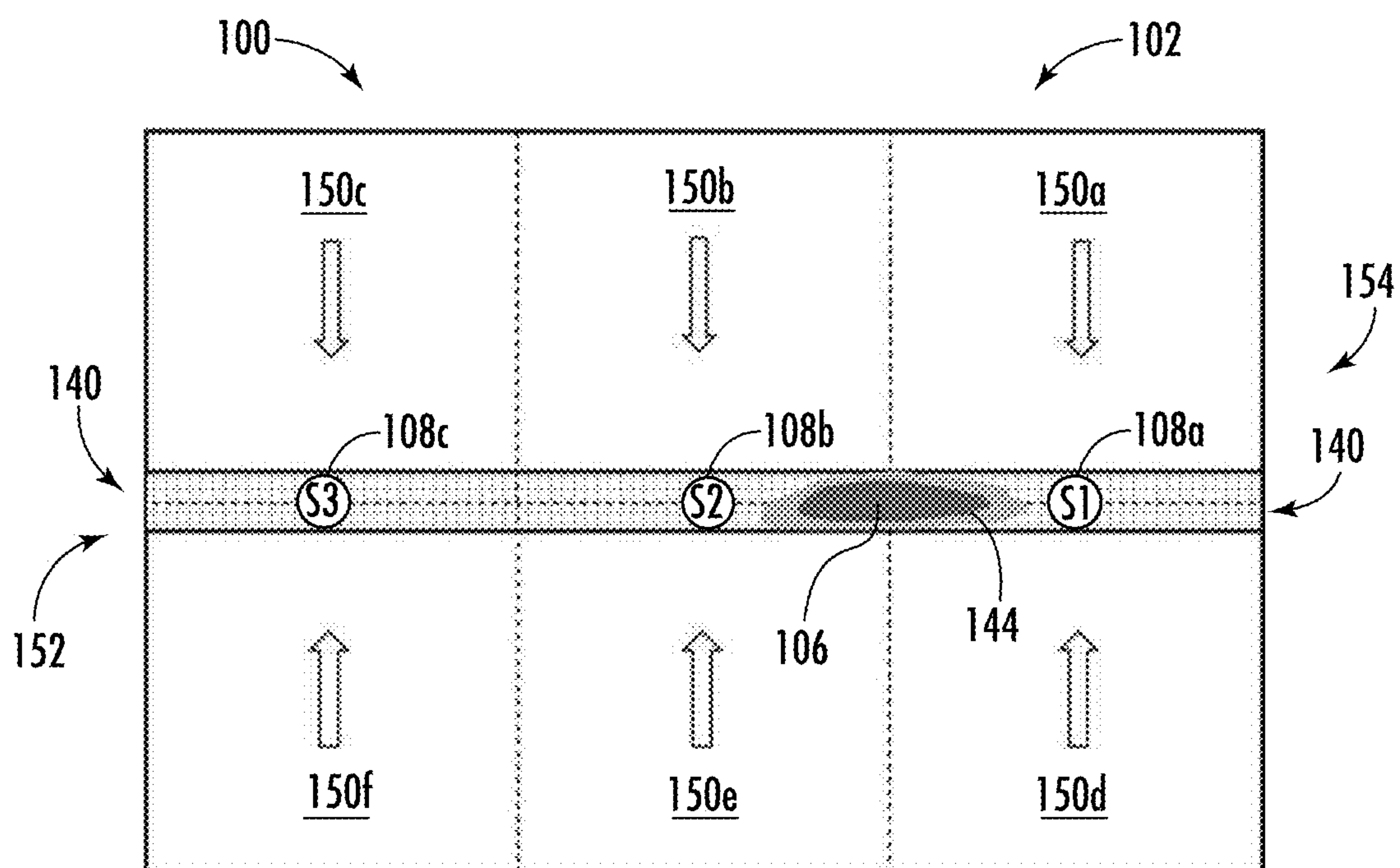


FIG. 14B

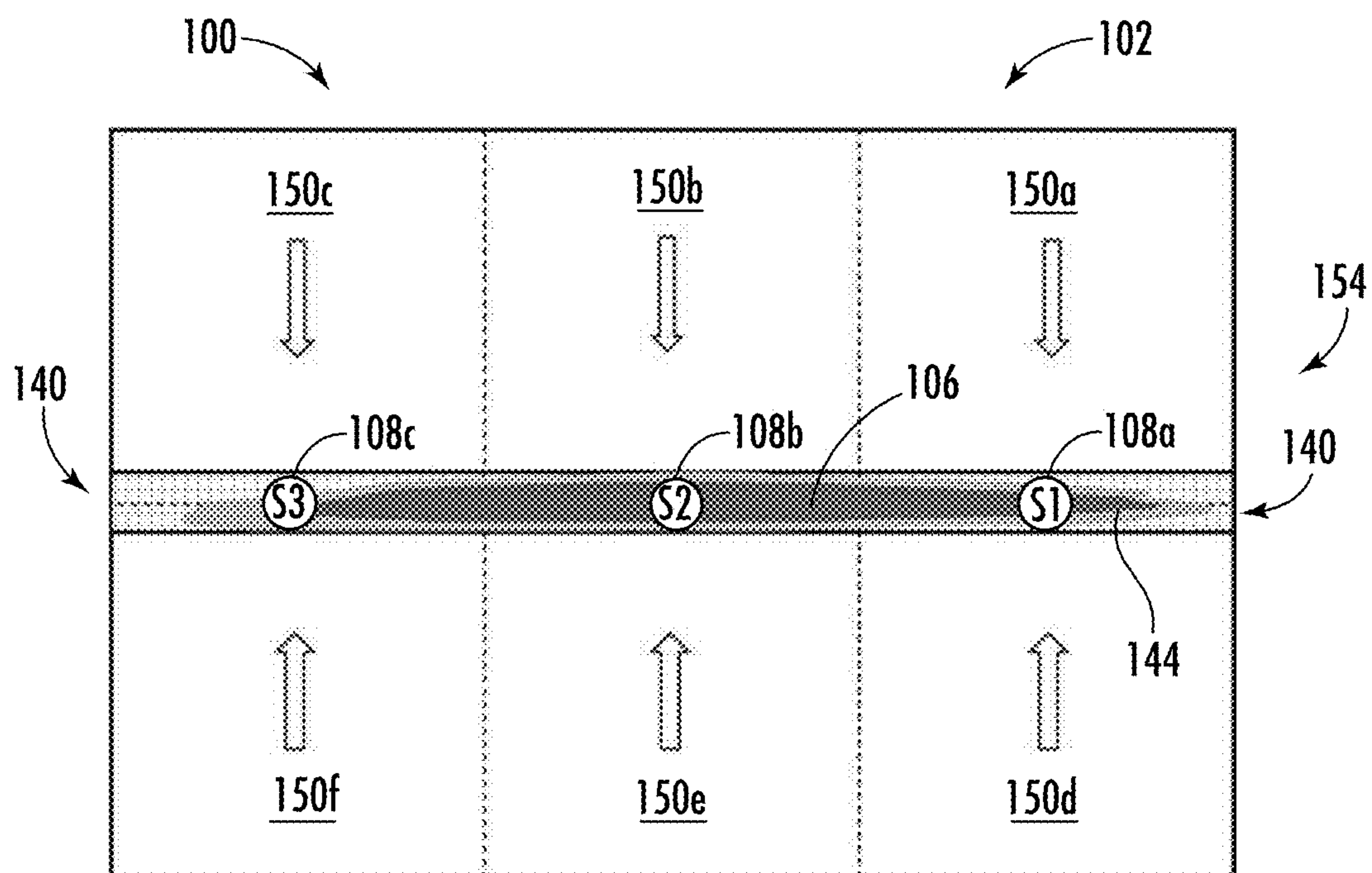
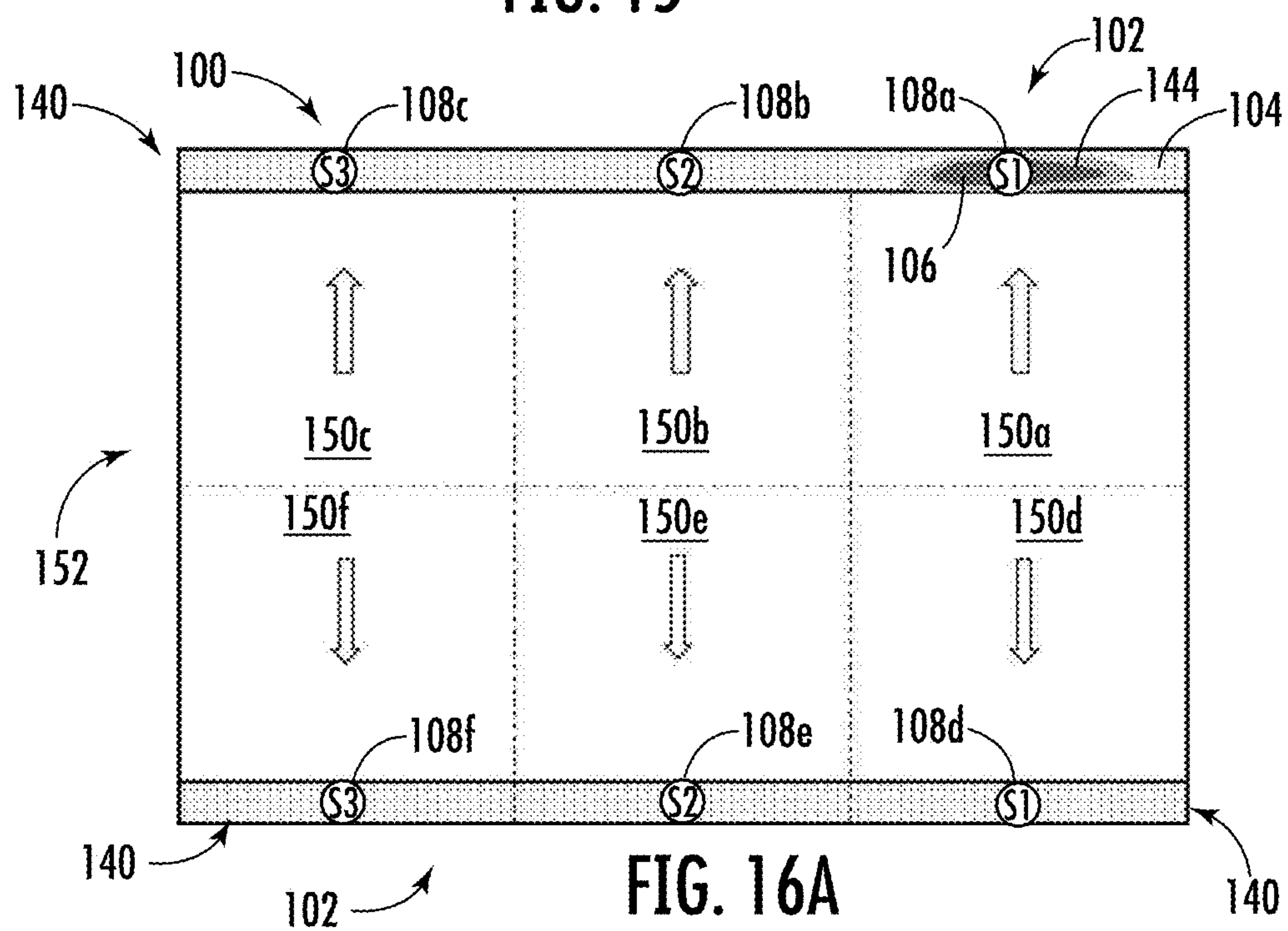
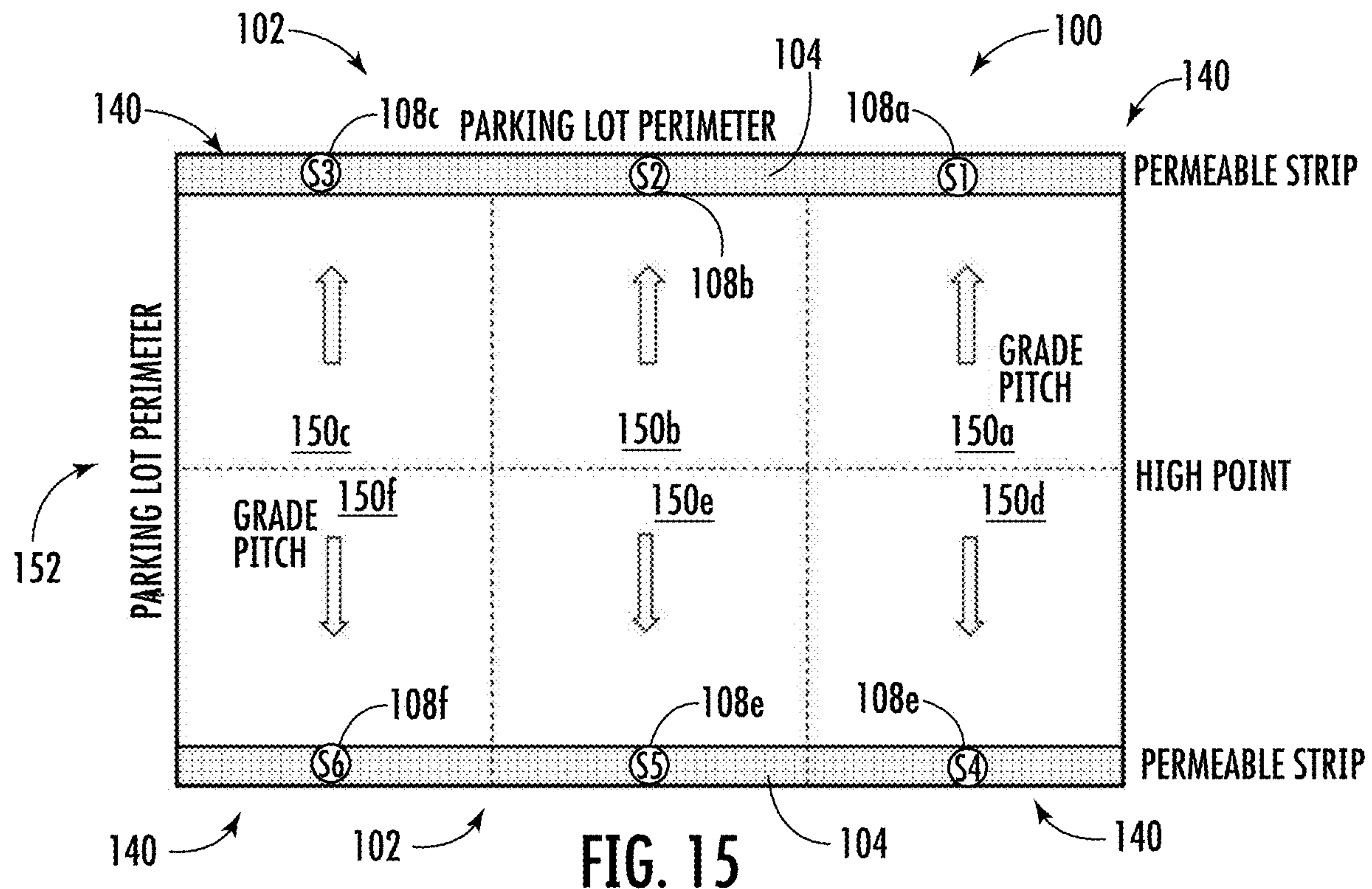
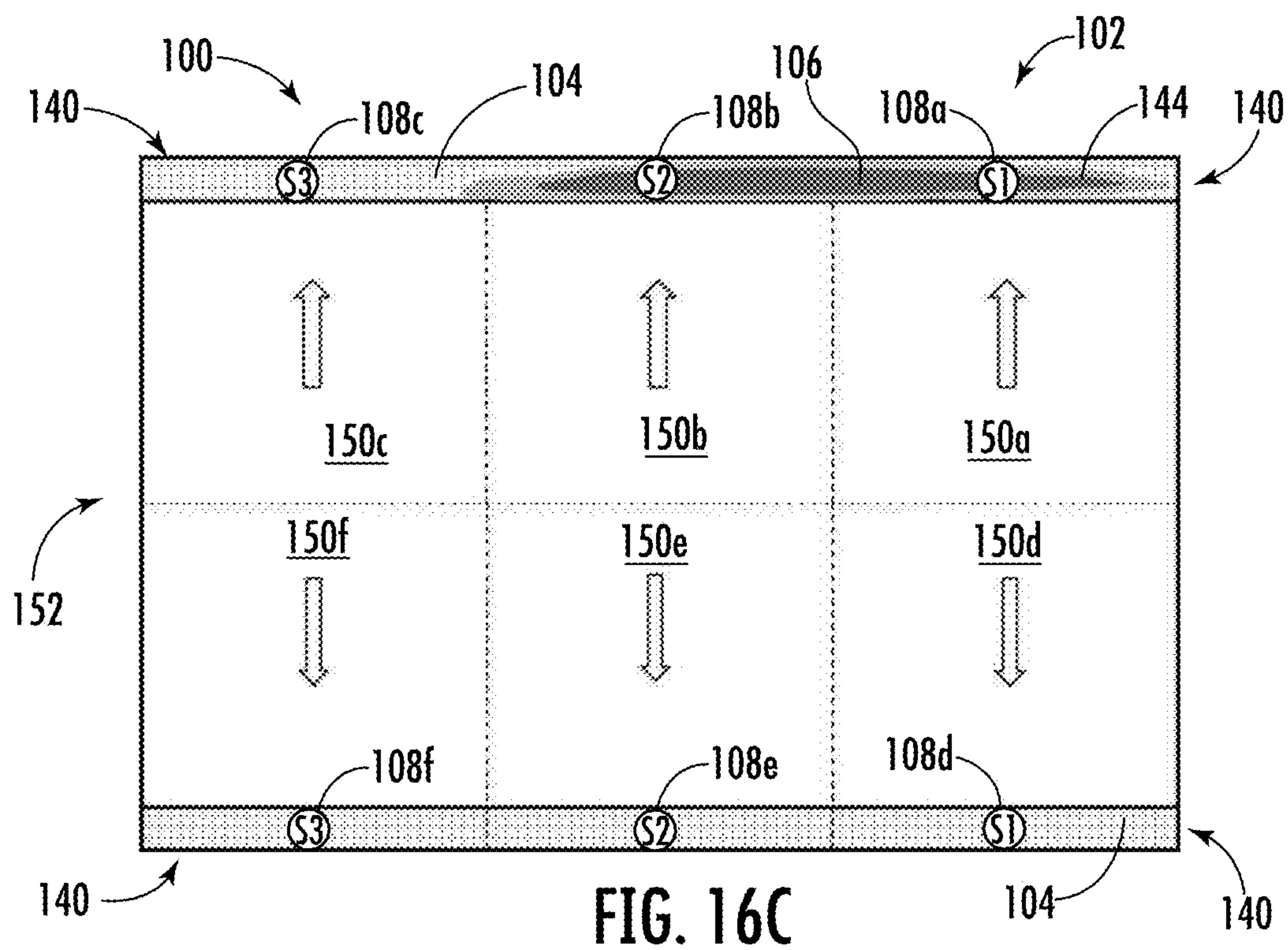
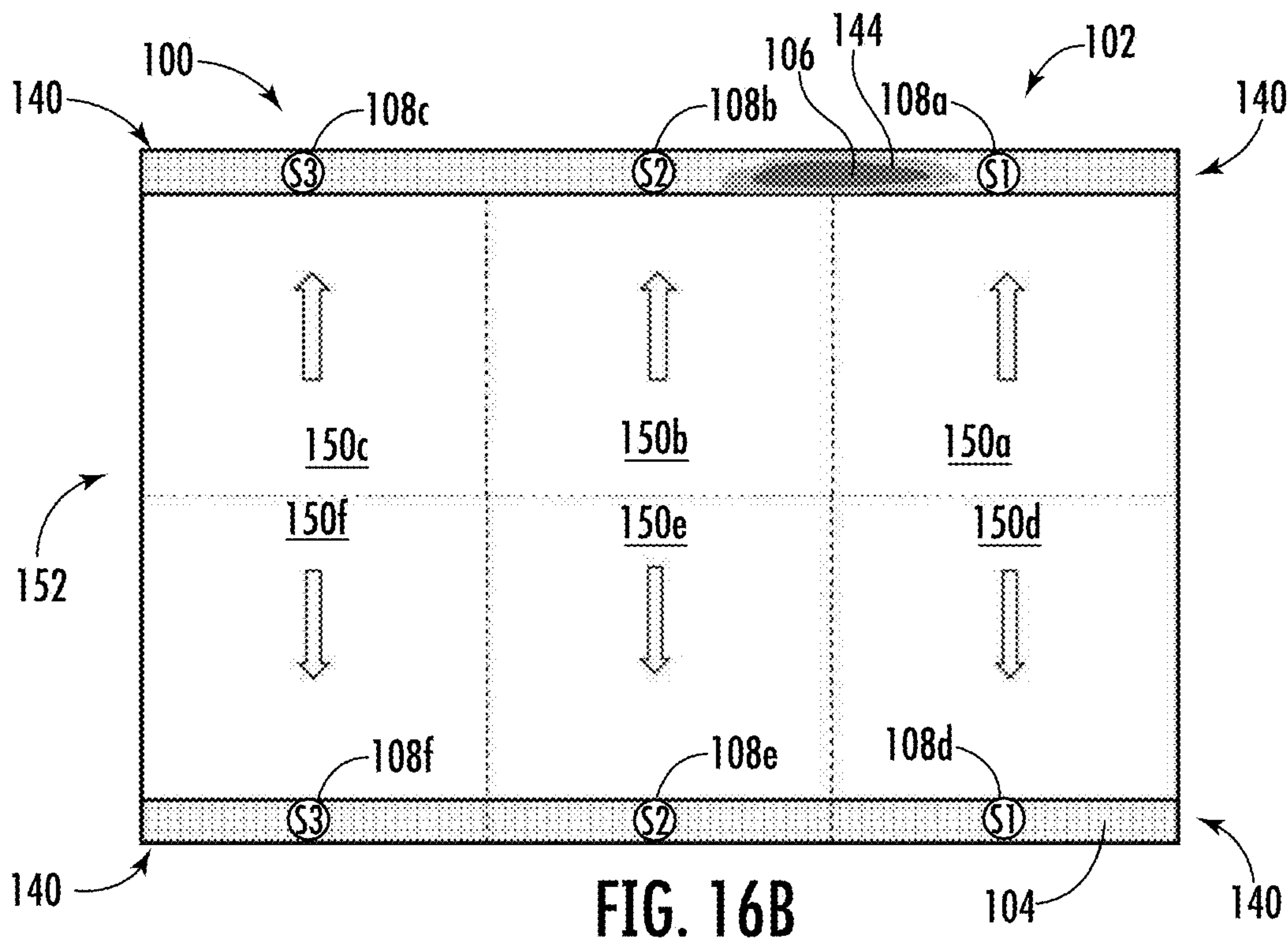
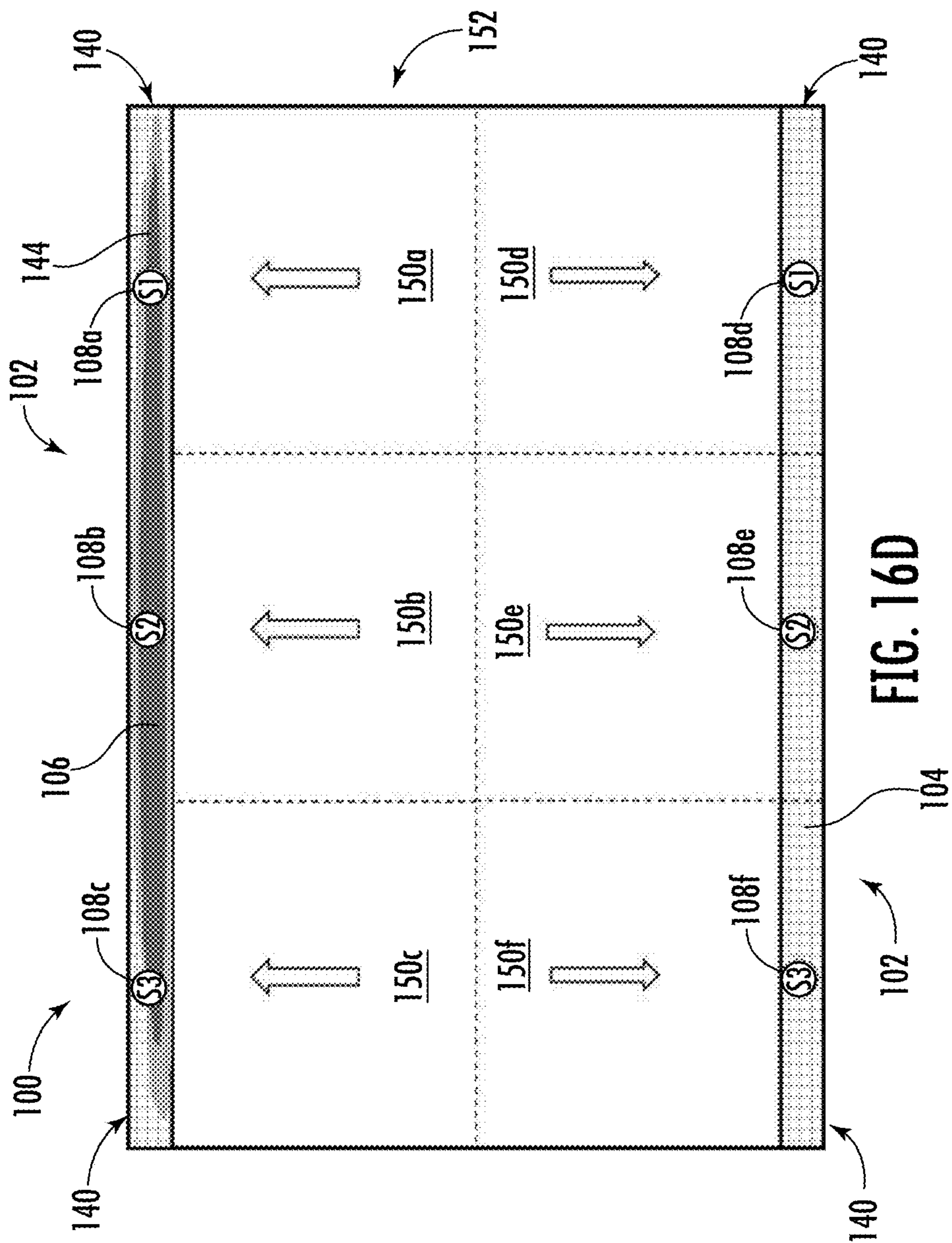


FIG. 14C







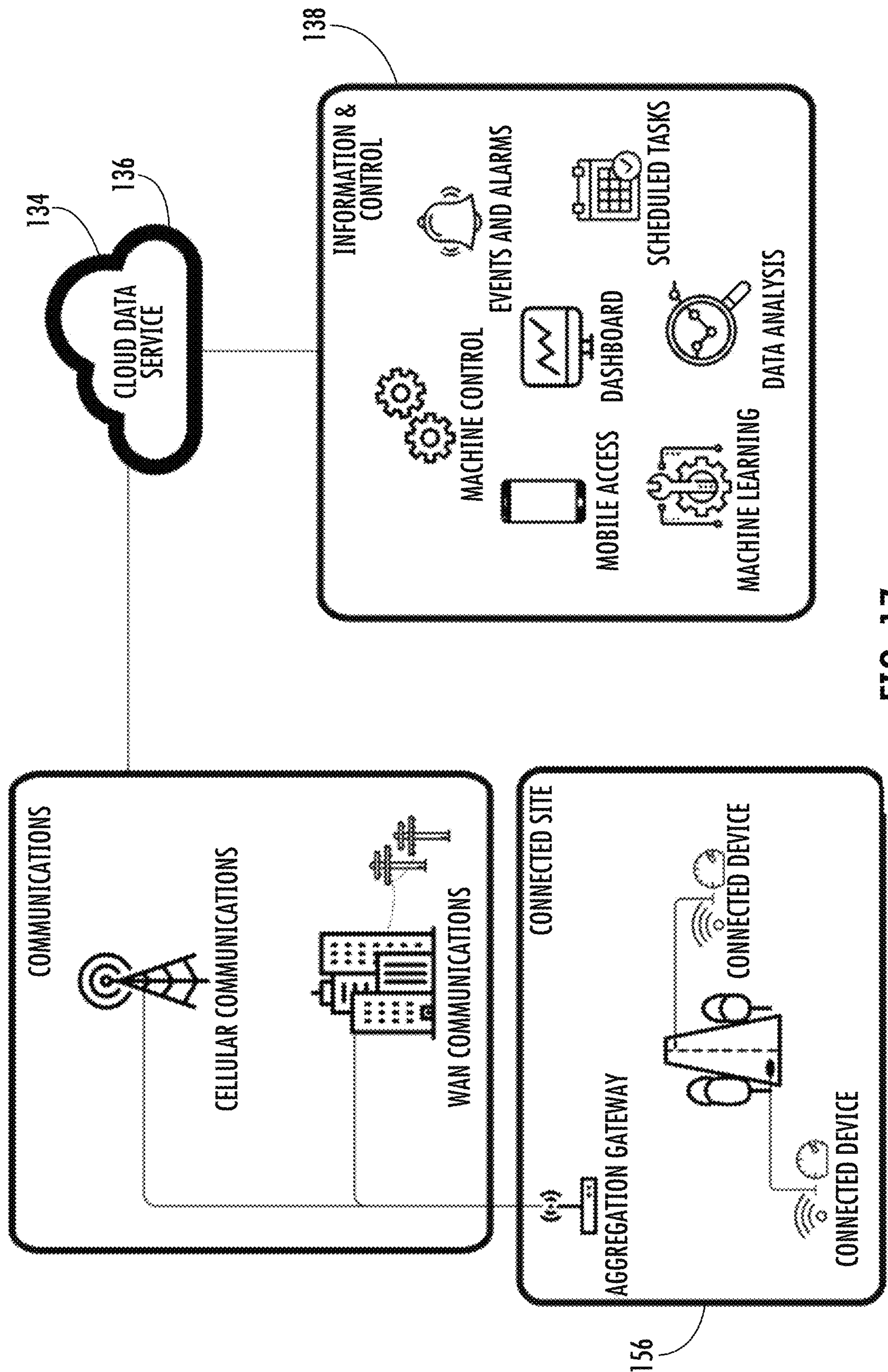
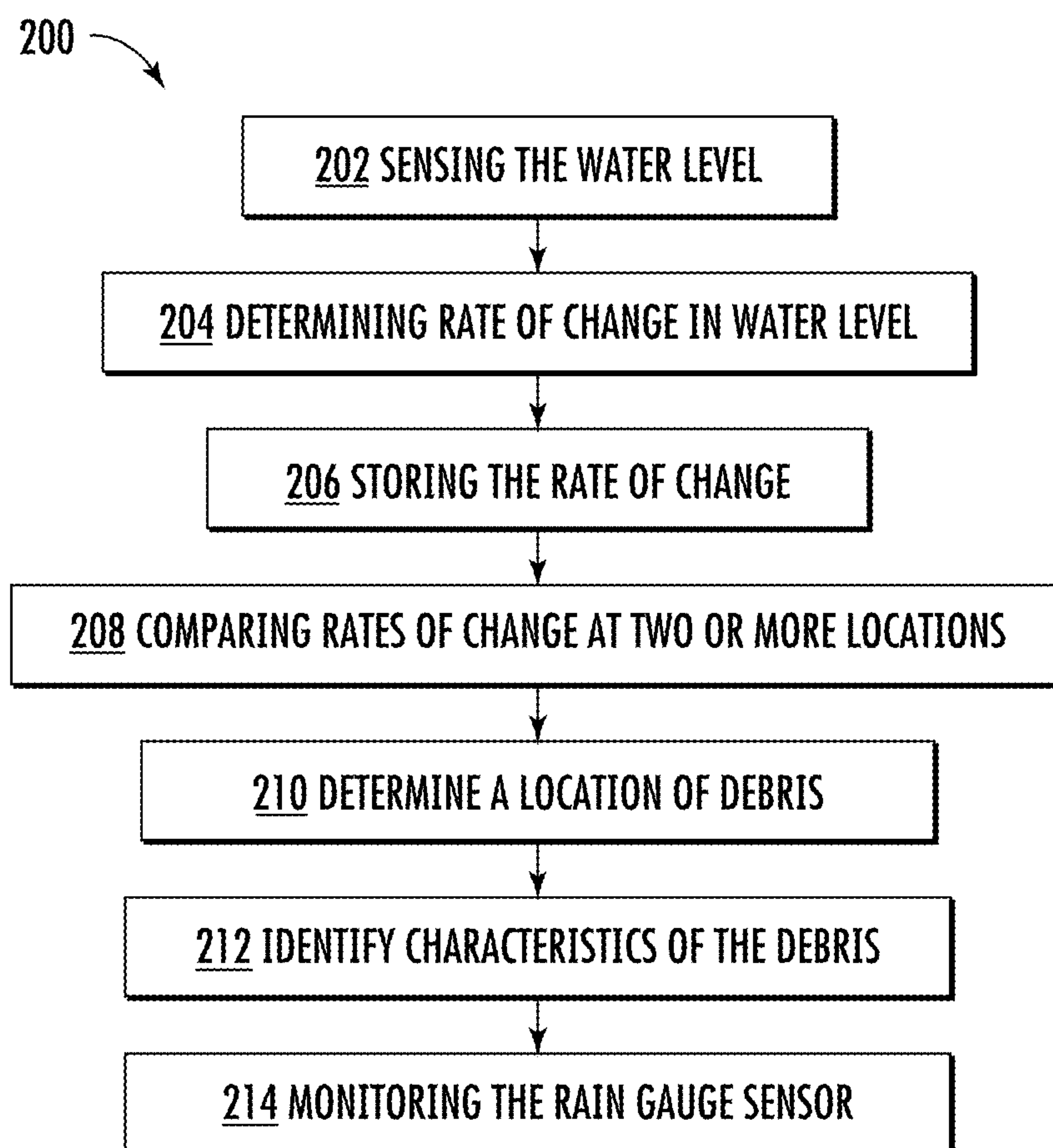


FIG. 17

**FIG. 18**

PERMEABLE PAVEMENT MONITORING SYSTEM

CROSS-REFERENCE TO RELATED PATENT APPLICATIONS

The present application is a continuation of U.S. application Ser. No. 16/676,296, filed Nov. 6, 2019, which claims the benefit of and priority to 62/757,027 filed on Nov. 11, 2018, each of which is incorporated herein by reference in its entirety.

BACKGROUND OF THE INVENTION

The present invention relates generally to the field of infrastructure monitoring. The present invention relates specifically to a permeable pavement sensor system that allows for monitoring of stormwater drainage.

Management of stormwater runoff is a significant issue in land development associated with private, industrial, municipal, county, and state infrastructure. Permeable pavement surfaces are a valuable tool in managing stormwater runoff associated with new land development and changes in existing land use. However, permeable pavement surfaces are subjected to debris and sediment carried from stormwater runoff, leaves from trees, rubbish from the public, and other sources that conspire to plug/clog the surface that was permeable at time of installation. The rate of, and location where, clogging and plugging occurs within the permeable surfaces is uncertain. As a result, permeable pavement surfaces require visual inspection to ensure that the surface is not clogged to such an extent that ponding or flooding of the surface will occur.

Owners of permeable pavement systems are forced to use experience (e.g. the surface has ponding today in several locations, or the surface has not shown ponding for several years) and visual inspection to assess the need for maintenance of the permeable surface to ensure rainfall flow from surface to subgrade. In the case of a private owner's two-acre parking lot, experience and visual inspection might not be too bad. In the case of a large commercial or institutional campus with acres of parking surface or large and widely distributed regions of permeable surfaces within municipalities, experience and visual inspection-based maintenance can be very costly.

Stormwater management and ground water recharge are at the essence of sustainability of civil infrastructure initiatives. However, there is precious little knowledge regarding the long-term efficacy of many novel infrastructure systems including permeable pavement surfaces. Greater use of permeable pavement systems in larger-scale stormwater management plans that include synergistic use of conveyance systems (e.g. storm sewer) and storage systems (e.g. retention systems, permeable surfaces with subgrade storage) cannot occur without effective management of both systems and a greater understanding of how each of these systems work. The ability for a permeable pavement system to store storm water and recharge groundwater is uncertain.

The progression of clogging throughout a permeable pavement surface needs to be done through visual inspection now. There is no mechanism for autonomously determining the extent of clogging over a permeable pavement surface and therefore, excessive visual maintenance schedules are followed. In other cases, no maintenance is conducted, or unplanned maintenance intervention is completed when surface clogging is extensive. The longer clogging is

allowed to occur, the more difficult maintenance becomes and the more unreliable the efficacy of the maintenance conducted is.

There is a need for autonomous detection of clogging extent within permeable pavement systems to drive rational maintenance interventions and prevent flooding. Furthermore, this autonomous system needs to be capable of scaling to geographically located permeable pavement systems to connect to other systems within the stormwater infrastructure network (e.g. stormwater conveyance systems) and facilitate integration into the maintenance and planning of civil infrastructure systems.

The customer needs in this regard can be considered as both latent and active. The problem is latent in that those that own permeable pavement surfaces know they have maintenance to conduct, know that there is not a systematic way to define when maintenance needs to occur other than through visual inspection or evidence of ponding, and they will be conducting maintenance in the future at an unknown time interval. As the scale of permeable pavement implementations increases, maintenance will become a greater problem to owners.

The permeable pavement industry-suppliers have active need as permeable pavement systems are being associated with maintenance headaches. The efficacy of these system's ability to recharge groundwater-levels is in question. Neither owners nor the industry currently have a solution to these problems.

SUMMARY OF THE INVENTION

Various embodiments of a system for monitoring drainage of a permeable pavement system are provided as well as various exemplary installation scenarios.

One embodiment describes a system for monitoring water-levels generated by water flowing through an area of a permeable surface into a water drainage structure situated below the permeable surface. The system includes a first water-level sensor located at a first position in the water drainage structure to generate first water-level data representative of the water-level at the first position and a second water-level sensor located at a second position in the water drainage structure to generate second water-level data representative of the water-level at the second position. Data memory and a data processor are coupled to the first and second water-level sensors. The memory stores water-level data sampled and processed from the sensors at a plurality of times t_0 to t_n . A water-level change rate r_1 to r_n associated with a first sensor is generated based upon first water-level data and stored in memory in reference to times t_1 to t_n . The system generates water-level change rates rr_1 to rr_n associated with a second sensor and based upon water-level data that is stored in memory with reference to times t_1 to t_n . The system compares rates r_1 to r_n to rates rr_1 to rr_n for a select group of times t_1 to t_n to generate comparison data c_1 to c_n . The system stores the comparison data in memory in reference to at least one of the first and second water-level change rates rr_1 or rr_n . The system then determines and stores the comparison data changes over time in reference to the at least one of the water-level change rates associated with the first and/or second sensor.

Another embodiment describes a paved system that includes a water drainage structure, a rigid permeable surface, several water-level sensors, memory and a data processor. The rigid permeable surface is supported above the drainage structure to permit water to flow from the surface into the structure. The water-level sensors are located at

respective locations within the drainage structure and generate respective water-level data representative of the water-level at the respective locations. Memory and a data processor are coupled to the water-level sensors. The memory stores the water-level data from each of the water-level sensors in reference to times t_0 to t_n . The data processor generates and stores the water-level rate change data for each water-level sensor in reference to times t_1 to t_n . The processor compares water-level rate changes from all sensors from time t_1 to t_n and identifies the water-level sensors which have relative water-level rate changes which slow relative to the water-level rate changes of the other of the sensors from time t_1 to t_n .

In another embodiment, a method for determining debris accumulation at various locations on a permeable surface supported above a drainage structure that is situated below the permeable surface, is described. The method includes sensing water-levels at various predetermined locations within the drainage structure for times t_0 to t_n and determining the rate of water-level change at each location based upon the water-level change for the respective locations. The rate of water-level changes for each of the locations in reference to times t_1 to t_n is stored, compared and used to determine locations at which the relative rate of water-level change is slowing in reference to the water-level change of the other sensors. From this data, the method determines a location of debris accumulation based upon the location(s) at which relative water-level change slows.

In some embodiments of a permeable (or pervious) pavement management platform, the pavement management platform provides a service that allows the user to determine vacuum maintenance needs for permeable (or pervious) pavement systems. Advantages of the platform include: subscription-based asset management platform as a service (PaaS), customized off-the-shelf water-level sensors (FPI Sensor Systems—Eagan, MN), off-the-shelf tipping-bucket rain gauge (Texas Electronics, Inc.—Texas), observation well installation consistent with industry standards, can be implemented in residential, commercial, municipal, county, and state systems, lithium-ion battery powered sensor, LoRA sensor to hub data transmission network, cellular data transmission from hub, electrical power for cellular data transmission hub (can be solar panel powered), real-time dashboarding of surface runoff storage, real-time dashboarding of ground water recharge rate, and permeability (clogging) threshold alerts (e.g. 25%, 50%), among others.

The owner of a permeable pavement system will be able to: determine the extent to which the permeable pavement is clogged from remote locations, remotely determine if vacuum maintenance is needed, avoid human inspection visits to determine clogging extent, have the evaluation of maintenance need independent of pavement system dimension and type (e.g. a large parking lot or long stretch of permeable shoulder will have significantly greater inspection and maintenance evaluation costs), demonstrate groundwater recharge rates, demonstrate surface runoff volume kept out of conveyance systems (e.g. storm sewer), remove the costs associated with human inspection of permeable pavement, conduct vacuum maintenance only when needed rather than regularized cycles, and more effectively manage financial resources by using vacuum-truck services rather than incurring capitalized equipment costs, annual equipment maintenance costs, annual fuel costs, and annual labor costs.

Additional features and advantages will be set forth in the detailed description that follows, and in part will be readily apparent to those skilled in the art from the description or

recognized by practicing the embodiments as described in the written description and claims hereof, as well as the appended drawings.

It is to be understood that both the foregoing general description and the following detailed description are merely exemplary, and are intended to provide an overview or framework to understand the nature and character of the claims.

The accompanying drawings are included to provide a further understanding and are incorporated in and constitute a part of this specification. The drawings illustrate one or more embodiment(s), and together with the description serve to explain principles and the operation of the various embodiments. Alternative exemplary embodiments relate to other features and combinations of features as may be generally recited in the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

This application will become more fully understood from the following detailed description, taken in conjunction with the accompanying figures, wherein like reference numerals refer to like elements in which:

FIG. 1 depicts a top view of a permeable pavement water-level sensor, according to an exemplary embodiment;

FIG. 2 depicts a permeable pavement installation with a rain intensity measuring device, according to an exemplary embodiment;

FIGS. 3A-D depict additional views of permeable pavement water-level sensors, according to an exemplary embodiment;

FIG. 4 depicts permeable pavement clogging progression, according to an exemplary embodiment;

FIGS. 5A-B depict permeable pavement system clogging scenarios, according to an exemplary embodiment;

FIG. 6A depicts stormwater storage and FIG. 6B depicts sensor height for the stormwater storage shown in FIG. 6A, according to an exemplary embodiment;

FIGS. 7A-C depicts clogging front progression various positions;

FIG. 8 depicts a Flat Parking Lot Condition with entire parking surface as permeable pavement, according to an exemplary embodiment;

FIG. 9 depicts Clogging Condition 1 in Application 2;

FIG. 10 depicts Clogging Condition 2 in Application 2;

FIGS. 11A-B depict Perimeter Clogging Condition 3 for Parking Lot Application 2;

FIGS. 12A-C depict Interior Clogging Condition 4 for Parking Lot Application 2;

FIG. 13 depicts a Saddle-Type Parking Lot Condition with single permeable pavement strip, according to an exemplary embodiment;

FIGS. 14A-C depict clogging scenarios for Parking Lot Application 3, according to an exemplary embodiment;

FIG. 15 depicts a Crowned Parking Lot Condition with double permeable pavement strips, according to an exemplary embodiment;

FIGS. 16A-D depict exemplary clogging scenarios for Parking Lot Application 3, according to an exemplary embodiment; and

FIG. 17 is a schematic depiction of a wireless (cloud) based asset management platform, according to an exemplary embodiment.

FIG. 18 shows a method for determining debris accumulation at locations on a permeable surface of the type supported above a drainage structure situated below the permeable surface, according to an exemplary embodiment.

While the invention will be described in connection with certain preferred embodiments, there is no intent to limit it to those embodiments. On the contrary, the intent is to cover all alternatives, modifications and equivalents as included within the spirit and scope of the invention as defined by the appended claims.

DETAILED DESCRIPTION

FIG. 1 illustrates a permeable pavement application or system 100. An operator or user of system 100 desires to know where clogging is occurring. For example, the user of a plan area 102 with permeable pavement 104 considers vacuuming portions of a parking lot or traffic lane when clogged instead of the entire plan area 102, to reduce cost. However, vacuuming clogged plan areas 102, or a clog 106 utilizes high mobilization costs, for example, to send a truck to the location of the plan area 102, inspect the clog 106, and vacuum the clogged water and debris. A single float sensor 108 used to determine flooding in the low point, e.g., of a parking lot or immediately upstream of an inlet 110, senses and indicates the clog 106, but will not characterize how or where the clog 106 is occurring. The single sensor 108 only indicates that clogging has occurred, but fails to characterize how much or where the clogging occurred.

Up-gradient clogging has been recognized in permeable pavement 104 systems 100. See, e.g., Kazemi, H., Rockaway, T. D., Rivard, J., Abdollahian, S. (2017), "Assessment of Surface Infiltration Performance and Maintenance of Two permeable pavement Systems in Kentucky", *Journal of Sustainable Water in the Built Environment*, Jun. 30, 2017, American Society of Civil Engineers, Reston, VA, which is incorporated by reference herein in its entirety. Using the progression of a clog 106, a clogging "wave" is captured using sensors 108. Sensors 108 are installed in a systematic manner that includes an up gradient plan area 102 from a stormwater inlet 110 within the permeable pavement 104 paved plan area 102.

Sensors 108 are placed at the lowest elevations (i.e. where water exits the site in a 100% impervious surface 112 condition) as well as all local low spots (i.e. anywhere in a parking lot interior where a catch basin would be required in a 100% impervious surface 112 condition). For example, in FIG. 1, sensors 108 are placed at locations S_1 , S_2 , and S_3 . A minimum of 2 sensors 108 per parking lot or curb section (e.g., plan area 102) are used to increase reliability. For example, if a sensor 108 goes offline (e.g., loses power) or stops working correctly, other sensors 108 will still detect clogging. Advantageously, multi-sensors 108 provide a more holistic picture of the plan area 102 or site and enhance indications, e.g., of where clogging is taking place and how much clogging has occurred within the plan area 102. For example, multi-sensors 108 predict and monitor the extent of clogging in relation to roadway and/or parking applications.

In a roadway application, generally the top subgrade or surface 112 is shaped to match the gradient of the pavement, such that the drainage structure 114 height is uniform and the surface 112 is less permeable than the open graded stone used in the drainage structure 114. Water permeating through the pavers 116 of plan area 102 flows to sensors 108 at locations S_1 , S_2 , and S_3 in low spots/elevations regardless of whether clogging occurs at the top subgrade or surface 112.

Rainfall intensity (rainfall per hour) is generally assumed to be sufficiently greater than the permeability of the subgrade surface 112. For example, some rain events (e.g.,

where the rainfall intensity is less than the permeability of the subgrade) will not trigger the float sensors 108. Other rain events (e.g., where the rainfall intensity is significantly greater than the permeability of the subgrade surface 112) exceed the capacity of float sensors 108. In such instances, a rainfall intensity, duration, and frequency (e.g. 1-hour duration for a 10, 50, 100-year frequency) is determined for the particular drainage structures 114 and/or plan area 102. The design of drainage structure 114 and plan area 102 are used to calibrate the capacity of sensors 108. The rate at which a float sensor 108 rises and/or lowers during or after a rain event is estimated based on this design.

A "rational method" is used to estimate and determine infiltration volume and tributary volume for each sensor 108. The rational method is defined as:

$$Q = \frac{c \cdot i \cdot A}{Z} = c \cdot i \cdot A$$

in which "Z" is a conversion factor (1.0 for U.S. customary units), "c" is a surface 112 runoff coefficient (0.85-0.95 for asphalt pavement and 0.00 for ideal clean unclogged permeable pavement 104 plan areas 102), "i" is average rainfall intensity (in./hr.), and "A" is the pavedrain catchment area (acres), e.g., plan area 102.

The rational method expression relies on several assumptions. Time of concentration for drainage plan area 102 is assumed to be less than the duration of peak rainfall intensity. Computed runoff is assumed directly proportional to rainfall intensity. Rainfall intensity is assumed uniform throughout duration of the storm. Frequency of occurrence for the peak discharge is assumed to be the same as the frequency of the rainfall producing that event. Uniform distribution of rainfall over the drainage plan area 102, a scalable 10 minute duration, and a maximum plan area 102 watershed of 200 acres, are also assumed.

A modified rational method expression is used in the implementation of permeable pavement system 100. The infiltration rate into the permeable pavement system is given by,

$$Q_i = (1-c) \cdot i \cdot A$$

For highly permeable pavement 104, the runoff coefficient "c" is very small or close to 0.0. For impervious surfaces 112, the runoff coefficient "c" is close to 1.0.

Runoff coefficients of specific permeable pavement are being studied per ASTM C1701/C1701M-09 on two-year-old, uncleaned permeable pavement installations. (See Chopra, M., Hardin, M., Gogo-Abite, I, Lassen, K. (2016). *PERMEABLE PAVEMENT permeable pavements*, Final Report, Stormwater Management Academy, University of Central Florida, Orlando, FL, which is incorporated herein by reference in its entirety). The study indicates that the average infiltration rate is over 1,500 in/hr. By way of comparison, other non-permeable systems hover around 3 in/hr. Therefore, a reasonable assumed c-value for permeable pavement 104 is zero (0).

Other variables affecting water-levels are considered when sizing drainage structures 114 beneath pavers 116 in a permeable pavement 104 installation, however, for any given rain event, all the other variables are either constant or measured during the event. This allows system 100 to measure clogging from one rain event and apply the measurement to the next rain event.

FIG. 1 is a top view of an exemplary embodiment of a permeable pavement water-level sensor system 100. Pavers

116 surround a sensor 108 that detects a water-level 118 (FIGS. 5A and 5B). Small gaps 120 between paver 116 joints make system 100 permeable to water. Water flows into sensor 108 and adjusts a float 122 located in an aggregate storage layer 124. In some embodiments, sensor 108 is located in a perforated pipe 126 and includes a PVC conduit 128 in a drainage structure 114. System 100 monitors water-levels 118 generated by water flowing through permeable surface 112 area into a water storage system or drainage structure 114 below the surface 112. In some embodiments, permeable surface 112 includes a pavement with water flow openings that drain into the water drainage structure 114 or storage system. In other embodiments, pavement sections or pavers 116 are spaced apart to generate a permeable surface with water flow openings that open into the storage system 100.

FIG. 2 shows a newly installed curb section (e.g., on June 1st) with sensor 108, the same as or similar to sensor 108 of FIG. 1. Detailed views of sensor 108 and system 100 configuration are illustrated in FIG. 3. With reference to FIGS. 1-3, sensor 108 includes electronic float 122 located in aggregate storage layer 124. In some embodiments, sensor 108 is low-power with a deep cycle marine battery 130 charged from solar energy. A tipping bucket rain gauge 132 is used to measure rainfall intensity, also powered off deep-cycle marine battery 130. Sensor 108 is housed in perforated pipe 126 in aggregate storage layer 124. Sensor 108 is powered via a PVC conduit 128 buried in drainage structure 114. In some embodiments, drainage structure 114 is a tank or a constructed storage system 100 to store or divert runoff water. In other embodiments, the water drainage structure is porous stone fill.

In some embodiments, two or more sensors 108 are located within system 100 to monitor and detect clogging events. For example, a three sensor 108 system 100 includes a first water-level sensor 108a located at a first position or location S₁ relative to a second sensor 108b at location S₂, and/or a third sensor 108c at location S₃. Each sensor 108 at each location S₁, S₂, and/or S₃, generates water-level data 134 representative of the water-level 118 at that location S₁, S₂, or S₃. The generated data 134 is stored, for example, in electronic memory 136 where it can be processed with a data 134 processor 138.

As will generally be understood from the description below, sensors 108 are placed in various locations S₁, S₂, S₃, or more based on the plan area 102 design and clogging patterns. For example, system 100 can be configured for curb/gutter applications that drain to a rainwater inlet 110 or stormwater drain. Similarly, system 100 can be configured to detect clogging in flat parking lot, paved flat surfaces, with or without permeable pavement 104 strips, and/or in other watershed or plan areas 102. For example, system 100 can prevent agricultural flooding in a field, residential flooding in a flood zone, and/or commercial flooding (e.g., with permeable and/or impermeable layers), and may also be implemented in run-off or storage systems 100 drain facilities to confirm proper operation of the storm system 100 drainage facility. Some of these applications are outlined generally in the figures and description that follows.

Application 1—Curb, Gutter and Inlet Application

The application in FIGS. 2 and 4 includes three sensors 108 at locations S₁, S₂, and S₃. Location S₁ is closest to the “overflow” stormwater inlet 110 or drain. Locations S₂ and S₃ are evenly spaced in low areas 140 throughout the length

of permeable pavement 104 defining a permeable area that is located near or adjacent to a roadway gutter 142.

As a hypothetical example, twelve (12) rain events are assumed over the course of a year. Each event has the same intensity (inches of rainfall per hour) and duration (e.g., hours) occurring on the first day of each month (e.g., each event is temporally spaced 1 month from the other). During the first few rain events minimal to no clogging of the permeable pavement 104 occurs, since system 100 is free of clogs 106. Three sensors 108 (e.g., at locations S₁, S₂, and S₃) experience similar water-level 118 readings with a slight time delay in the rate r_1 , r_2 , and r_3 of elevation rise in each sensor 108 at locations S₁, S₂, and S₃. In other words, in the unclogged system of FIG. 2, sensor 108 at location S₃ experiences a rate r_3 change that is greater than r_2 and r_1 , at locations S₂ and S₁, respectively. Sensor 108b at location S₂ experiences a rate change r_2 that is greater than r_1 at location S₁, but less than r_3 at location S₃. Similarly, sensor 108a at location S₁ experiences a rate change r_1 that is less than the rate changes r_2 and r_3 seen at locations S₂ and S₃ respectively. However, upon reaching a steady state the rate of changes r_1 , r_2 , and r_3 , for each sensor 108 at locations S₁, S₂, and S₃, respectively; are approximately equal.

This is best illustrated by looking at the direction of flow in the unclogged case and the clogged case of FIG. 2. In the unclogged case, sensors 108 receive run-off in a direction parallel (longitudinal direction) and perpendicular (transverse direction) to gutter 142 and the permeable pavement 104 in the paved plan area 102. At the beginning of an event in unclogged operation, sensors 108a, 108b, and 108c at locations S₁, S₂, and S₃ receive approximately equal transverse runoff, whereas the runoff in the longitudinal direction is greatest at location S₃, followed by S₂, and then S₁, which has the greatest permeable paved area in the longitudinal direction. Once the system reaches steady state, all three sensors 108 receive approximately equal longitudinal runoff.

In a clogged state, as shown in FIG. 4, sensor 108c at S₃ “taps out” or exceeds the capacity to measure additional runoff. Thus the rate r_3 of change at sensor 108c approaches zero. Sensor 108b at location S₂ receives the longitudinal runoff that passes through clog 106 and the transverse runoff resulting in a slightly elevated rate r_2 , whereas sensor 108a at location S₁ receives approximately equal runoff as in the unclogged case, and retains approximately the same rate r_1 . In other words, as clog 106 develops over time (e.g., after several rain events) it follows a defined and recognizable pattern. Because, in the application of FIG. 4, the pavement slopes in a manner that creates surface 112 runoff in the longitudinal and transverse directions, debris that will cause clogging of the permeable pavement 104 progresses from left to right in FIG. 4. Clogging begins at sensor 108c and moves toward sensor 108a and inlet 110 over time. Therefore, with each rain event a delay in the readings at location S₃ is observed comparing the data 134 with the first couple of events. The extent to which a significant percentage of surface 112 of permeable pavement 104 is plugged identifies the maintenance objectives and provides motivation for sensor 108 placement and the sensor system 100.

FIG. 5A shows a fully permeable surface 112 where all runoff is directed to the storage system 100 aggregate layer below. FIG. 5B shows a clogged permeable pavement 104 surface 112 and no surface 112 runoff drains into the storage system 100 aggregate layer. With reference to FIG. 5A, when the permeable pavement 104 system 100 is unplugged/unclogged and operating at 100% efficiency, surface 112 runoff enters storage system 100 in both the transverse and longitudinal directions as shown in FIG. 4. Sensor S₃

receives the most surface **112** runoff initially as runoff will be traveling from impermeable pavement located “upstream” of the permeable pavement **104** segment and overflow/clog inlet **110**. A subgrade surface **112** slope results in water accumulation in the storage system **100** layer below (FIGS. 6A-B).

FIGS. 6A-B show system **100** at steady state without clogging (perfectly pervious) that defines a water-level **118**. When a clog front **144** and/or the permeable pavement **104** surface **112** is plugged, system **100** detects the location and amount of flooding. Clogging of permeable pavement **104** surface **112** generally begins at the up-gradient edge **146** (FIG. 4) where the most significant portion of debris enters permeable pavement **104** plan area **102**. As runoff moves across the clogged areas, it migrates the clog front **144** towards the down-gradient edge **148** and inlet **110**.

With reference to FIGS. 4-6B, when permeable pavement **104** surface **112** is completely free from debris and the all joints are open, sensor **108c** at location S_3 experiences the first rate r_3 change and rises first as the most runoff (longitudinal and transverse) in system **100** accumulates. Sensors **108b** and **108a** experience a lower rate r_2 and r_3 change, because these locations S_2 and S_3 experience predominantly transverse runoff (e.g., longitudinal runoff is clogged at location S_2). At or near the end of the rainfall event, sensors **108a**, **108b**, and **108c** all rise to the water-level **118** in the storage system **100** layer (FIGS. 6A-B) as the water moves into the storage system **100**.

If the permeable pavement **104** surface **112** is completely and perfectly plugged (perfectly impervious), system **100** performs like a traditional impervious pavement drainage system, e.g., with no rise at any of the three sensors **108a**, **108b**, **108c**, because there is no migration of runoff into storage system **100**.

A system **100** that is neither perfectly impervious nor perfectly pervious (e.g., a real system between the theoretical limits) has a clog front **144**, as shown in FIGS. 7A-C, that progresses from up-gradient edge **146** to down-gradient edge **148**. As clog **106** covers a sensor **108**, runoff is directed to the next unclogged downstream sensor **108**. The runoff volume directed to the next down-gradient sensors **108** causes a relative increase in the rising rate r_1 and/or r_2 of change for the down-gradient sensors **108**, compared to up-gradient sensor **108** locations (e.g., S_3). System **100** assess the relative position of the clog front **144** by examining relative rise rates r_1 , r_2 , and r_3 of float sensors **108a**, **108b**, and **108c** in locations S_1 , S_2 , and S_3 .

FIG. 7A illustrates a clog **106** in a first position covering sensor **108c**. Specifically, sensor **108c** at location S_3 is beneath a clogged permeable pavement **104** surface **112**. Sensors **108b** and **108a** are in clog **106** free locations S_2 and S_1 . Runoff reaches locations S_2 and S_1 without infiltration into the up-gradient permeable pavement **104** surface **112**. As such, sensor **108b** at location S_2 rises more rapidly (e.g., experiences a rate r_2 of change) than sensor **108a** at location S_1 . Sensor **108c** at location S_3 rises the slowest (e.g., experiences the slowest rate r_3 of change) of the three sensors **108** as the rise at location S_3 is dictated by a water-level **118** that pushes up-gradient and fills down gradient (FIGS. 6A-B) and includes transverse runoff affecting the water-level **118** rise and sensed rate r_3 of change. Relatively speaking, FIG. 7A depicts a reasonably well-defined portion of the permeable pavement surface **112** as being plugged. The relative behavior of sensors **108a**, **108b**, **108c** S_1 , S_2 , S_3 in this case would indicate roughly 25% of the permeable pavement **104** surface **112** is clogged.

As clog front **144** progresses in FIG. 7B towards down-gradient edge **148** of the permeable pavement **104** system **100**, surface **112** runoff is pushed into location S_1 , causing sensor **108a** to experience a high rate r_1 of change. Rates r_2 and r_3 of rise in sensors **108b** and **108c** include predominantly transverse runoff and any migration of the water in storage system **100** layer flowing in the up-gradient direction. Thus, sensor **108a** at location S_1 rises the quickest (e.g., experiences the greatest rate r_1 of change), followed by sensor **108b**, which is followed by sensor **108c**. The sensors **108** behavior indicates a clog **106** range between 25% to 50% of the permeable pavement **104** surface **112** being clogged.

As clog front **144** progresses in FIG. 7C it extends from up-gradient to down-gradient edges **146** and **148**. Sensors **108** at locations S_1 , S_2 and S_3 rise from predominantly transverse runoff and migration of runoff through the aggregate storage system **100**. The sensors **108** rise is relatively slow compared to the rises of sensors **108** in FIGS. 7B and 7A. Sensor **108** behavior indicates approximately 50% or more of the permeable pavement **104** surface **112** is clogged.

To correlate multiple sensor **108** readings to clogged surface **112** plan area **102**, the expected rates (e.g., r_1 , r_2 , r_3 , and/or others) are determined relative to the locations (e.g., S_1 , S_2 , S_3 , and/or others) and mapped. Traditionally, vacuum maintenance is only performed during bi-annual inspection cycles or when 50% of the joints are clogged or otherwise filled with dirt/debris. In contrast, system **100**, for example, recommends individualized maintenance only when sensor **108c** at location S_3 triggers first, e.g., after initiation of tipping bucket rain gauge **132**.

For example, electronic memory **136** and a data **134** processor **138** couple to sensors **108** to store water-level **118** data **134** collected at sensors **108** for times t_0 to t_n , where t_0 represents the water-level **118** prior to a rainfall event. In some embodiments, times t_1 to t_n are measured in minute increments (e.g., every 5 min, 10 min, 15 min, 30 min, 45 min, or 60 min) or hour increments (e.g., every 1 hr, 2 hrs, 3 hrs, etc). The water-level data **134** is used to generate a change rate r_1 to r_n for a first sensor **108a** (e.g., where r_1 represents the change between t_0 and t_1 and r_n represents the change between r_{n-1} to r_n). Similarly, water-levels **118** are measured at one or more additional sensors **108** to compare the rates of change (e.g., rr_1 to rr_n) at each time t_1 to t_n for the water-level **118** at each sensor **108** location S_1 , S_2 , S_3 , and/or other locations.

The rates of change r_1 to r_n and rr_1 to rr_n , etc for each sensor are used to compute comparison data **134** c_1 to c_n for each sensor **108**. Data **134** c_1 to c_n compares the rate of change r_1 to r_n for a first sensor **108a** to rate of change data **134** rr_1 to rr_n for at least one other sensor **108b**. In some embodiments, comparison data **134** c_1 to c_n is computed for all times t_0 to t_n , in other embodiments, a select group of times t_x to t_y is compared that includes a subset of the total set of event times t_0 to t_1 . For example, the comparison data **134** c_1 to c_n is divided into select groups of times t_x to t_y corresponding to comparison data **134** c_x to c_y . In addition, t_n can include any number of times data **134** is sampled, including more than 50, 100, 500, 1000, 10,000, or 100,000 samples. The comparison data **134** c_1 to c_n is stored in electronic memory **136** and/or analyzed with a data **134** processor **138** to determine problematic clog **106** locations and areas, size and shape estimates of the clog, and/or the progression of clog front **144**. Change rates (e.g., r , rr , etc.) of the water-levels **118** are analyzed to determine how the

11

comparison data **134** (e.g., c , cc , etc.) changes over time (e.g., t_0 to t_n), in reference to the water-level **118** change rates (e.g., r , rr , etc.).

In some embodiments, the processor **138** calculates or determines whether the water-level **118** change rate r for each sensor **108** is slowing relative to other sensor(s) **108** with change rate rr , based on changes in the comparison data **134** c , cc , etc. For example, the rate r of water-level **118** change is considered to have slowed relative to other sensors **108** if the rate r is slowed by some predetermined amount. In various embodiments, the threshold predetermined amount of rater change may be a rate that slows more than 5%, 10%, 15%, 20%, 25%, 30%, 40%, 50%, or more or surrounding sensors **108**.

Application 2—Flat Parking Lot Application

FIG. **8** show a plan area **102** for a typical parking lot. The plan area **102** for the parking lot follows a “flat” grade over existing topography. If the entire parking surface **112** is permeable pavement **104** there is no surface **112** runoff over the parking lot plan area **102**. Instead rainwater accumulates directly into the storage system **100** below the plan area **102**.

Sensors **108** are placed in locations S_1 - S_6 that divide the parking surface **112** into various tributary areas **150**. The number of sensors **108** used is assessed based on the tendency for localized “clogging” in the plan area **102** of the permeable pavement **104** surface **112**. In other words, sensors **108** are placed in or near in high clogging areas (e.g., areas with trees, areas adjacent to sediment runoff, etc.). In some embodiments, a grid arrangement **152**, similar to FIG. **8**, is used to develop a maintenance grid of sensors **108** that track clogging along surface **112**. For example, processor **138** can determine locations where sensors **108** with slow water-level rates r relative to rate rr changes of other sensors **108**, based on the placement of sensors **108** in the plan area **102** and the orientation of the permeable and/or impermeable pavement structures.

In some embodiments, a tipping bucket rain gauge **132** is located at the site (similar to FIG. **2**) to record localized rainfall. When the tipping bucket rain gauge **132** tips, it indicates that adequate precipitation to constitute a rainfall event. In other words, once the rain gauge tips, system **100** begins an assessment of rainfall transmission into the storage system **100**. Only one tipping bucket rain gauge is generally used for a large multi-acre plan area **102** such as a campus.

FIG. **9** illustrates a clogged surface, clog front **144**, and infiltration edge for clogging located in the tributary area for Sensor 1. The extent of clogging of the permeable pavement **104** in Application 2 is the same or similar as that in Application 1, with only minor differences. Clogging in the area defined by the sensor in location S_1 is essentially $\frac{1}{6}$ th or 17% of the parking surface **112** plan area **102**. Additional sensors **108** at locations S_2 - S_4 are dispersed (in this case evenly, though other configurations may be desirable, depending on the location of high clogging areas) throughout the parking plan area **102**. The sensors **108** are dispersed and placed to increase the resolution of clogs, particularly in high clogging areas, to measure the extent of a clog **106** in the permeable (or impermeable) surface **112**. In this configuration, each sensor location S_1 through S_6 has an associated area, labeled Area 1 through Area 6, respectively.

When the permeable surface **112** in Area 1 is clogged, sensor **108** at location S_1 measures water accumulation at a much slower rate r_1 than sensors at locations S_2 through S_6 . Sensors **108** at locations S_2 , S_4 , and S_4 may see a slight

12

increase in water accumulation due to sheet flow (e.g., overflow) runoff from Area 1. Therefore, clogging in Area 1 is defined by a slow rate r_1 (e.g., approaching or zero) as water accumulates at the sensor near location S_1 . Water accumulation at sensors **108** near locations S_3 and S_6 are closely correlated with the rainfall intensity measurement, because they are largely unaffected by the clog **106** at location S_1 . Water accumulation at sensors **108** near locations S_2 , S_4 , and S_4 are generally equal to or slightly greater than the accumulation visible at the sensors **108** at locations S_3 and S_6 . Clogging in these areas correlates to sensors **108** data **134** (e.g. Area 1 and the sensor **108a** located at S_1) that is evaluated for the entire surface **112** and presented in Table 1.

A second potential clogging condition for Application 2 originates in locations S_1 and S_2 and between sensor **108** tributary areas **150**, as illustrated in FIG. **10**. In this case, the clogging migrates around the pavement surface **112** in two, or more, areas, specifically Area 1 and Area 2, of FIG. **10**. Table 2 outlines the identification of this clogging scenario using a sensor **108** data **134** array collected from sensors **108** distributed on the parking surface **112** plan area **102**.

A third potential clogging condition for Application 2 occurs at a perimeter of the pavement plan area **102** bounded by series of sensors **108**. Clogging around the perimeter may encompass multiple areas (e.g., one, two, or three tributary areas **150** and their corresponding sensors **108**). FIGS. **11A-B** illustrate some illustrative perimeter clogging scenarios for Application 2. Table 3 presents data **134** collected with a sensor **108** array (e.g., sensors **108** located at multiple locations S_1 , S_2 , S_3 , S_4 , S_4 , S_6 , etc.) to identify this clogging scenario.

A fourth clogging condition for Application 2 occurs when a clog **106** occludes large interior portions of the pavement surface **112** (e.g., between tributary areas **150**). FIGS. **12A-C** illustrate some exemplary clogging scenarios. Table 4 presents data **134** that identifies this clogging scenario using the sensor **108** array on the plan area **102**.

Application 3—Single Permeable Strip Parking Application

A third application (Application 3) includes a parking lot with a single permeable pavement strip located at the low point of the parking surface in a saddle configuration **154**. In this configuration, tributary areas **150** drain into the permeable pavement **104** in the saddle configuration **154** to drain the plan area **102**. FIG. **13** illustrates this arrangement.

At least three clogging conditions occur in this saddle configuration **154**. FIGS. **14A-C** illustrate a Condition 1 clog **106** directly above a sensor **108** on the saddle configuration **154** between two or more tributary areas **150** that are a portion of the plan area **102**. Table 5 presents all clogging variations for this condition and identifies data **134** that is used to identify each condition.

Application 4—Double Permeable Strip Parking Application

The fourth application scenario involves a crowned pavement surface **112** draining to two permeable pavement strips on either side of the crown. This implementation involves a greater number of sensors **108** as compared to Application 3. FIG. **15** illustrates one exemplary sensor **108** array layout or distribution. The clogging progression is shown in FIGS. **16A-D** and sensor **108** data **134** identification of this clogging scenario is presented in Table 6.

13

Cloud-Based Data **134** Transmission and Management Platform

FIG. 17 shows several wireless technologies capable of transmitting sensor **108** data **134**. All connected devices (e.g., sensors **108**, processors **138**, electronic memory **136**) 5 communicate with an aggregation gateway **156** via low power LoRA communications. The aggregation gateway **156** utilizes wireless (WiFi) communications if pick up is near the site or cellular communications if the site is remote. 10 The sensors **108** and LoRA communications system have very low power draw or usage requirements. Thus, sensors **108** can be powered by Lithium-Ion batteries, e.g., included within the sensor **108** housing or perforated pipe **126**. Cellular communications generally use greater power consumption. As such, the aggregation gateway may use alter-

14

native power sources (e.g., solar power generation with a marine battery and/or a direct connection to a power supply). In some embodiments, data **134** processor **138** is remotely coupled to sensors **108** via a wireless data **134** link. In some 5 embodiments, the cellular communication system includes a cloud data **134** service (e.g., Telit).

Information and control process may include dashboarding of sensor **108** data **134** and/or have thresholds for scheduled tasks (e.g., permeable pavement surface **112**, vacuuming, sensory battery replacement, data **134** collection with a tipping bucket rain gauge **132**). Larger installations encompass larger plan area **102** portions of the urban environment to facilitate development of data **134** analytics and predict when/where maintenance is more likely to occur throughout all permeable pavement **104** plan area **102** and/or tributary area **150** installations.

TABLE 1

Potential Clogging Scenarios for Condition 1 for Parking Lot Application 2				
Clogging Area	Sensor(s) with Zero or Slow Accumulation	Sensor(s) with Accumulation Equal to Rainfall Intensity	Sensor(s) with Accumulation Equal To or Exceeding Rainfall Intensity	Clogged Area as Percentage
Area 1	Sensor 1	3, 6	2, 4, 5	17
Area 2	Sensor 2	n.a.	1, 3, 4, 5, 6	17
Area 3	Sensor 3	1, 4	2, 5, 6	17
Area 4	Sensor 4	3, 6	1, 2, 5	17
Area 5	Sensor 5	n.a.	1, 2, 3, 4, 6	17
Area 6	Sensor 6	1, 4	2, 3, 5	17
Areas 1, 2	Sensors 1, 2	n.a.	3, 4, 5, 6	34
Areas 2, 3	Sensors 2, 3	n.a.	1, 4, 5, 6	34
Areas 4, 5	Sensors 4, 5	n.a.	1, 2, 3, 6	34
Areas 5, 6	Sensors 5, 6	n.a.	1, 2, 3, 4	34
Areas 1, 4	Sensors 1, 4	2, 5	3, 6	34
Areas 2, 5	Sensors 2, 5	n.a.	1, 2, 3, 6	34
Areas 3, 6	Sensors 3, 6	1, 4	2, 5	34
Areas 1, 2, 3	Sensors 1, 2, 3	n.a.	4, 5, 6	50
Areas 4, 5, 6	Sensors 4, 5, 6	n.a.	1, 2, 3	50
Areas 1-6	Sensors 1-6	n.a.	n.a.	100

TABLE 2

Potential Clogging Scenarios for Condition 2 for Parking Lot Application 2				
Clogging Area(s) Bounded By	Sensor(s) with Zero or Slow Accumulation	Sensor(s) with Accumulation Equal to Rainfall Intensity	Sensor(s) with Accumulation Equal To or Exceeding Rainfall Intensity	Clogged Area as Percentage
1, 2	n.a.	3, 4, 5, 6	1, 2	17
2, 3	n.a.	1, 4, 5, 6	2, 3	17
4, 5	n.a.	1, 2, 3, 6	4, 5	17
5, 6	n.a.	1, 2, 3, 4	5, 6	17
1, 2, 4, 5	n.a.	3, 6	1, 2, 4, 5	17
2, 3, 5, 6	n.a.	1, 4	2, 3, 5, 6	17

TABLE 3

Potential Clogging Scenarios for Condition 3 for Parking Lot Application 2				
Clogging Area(s) Bounded By	Sensor(s) with Zero or Slow Accumulation	Sensor(s) with Accumulation Equal to Rainfall Intensity	Sensor(s) with Accumulation Equal To or Exceeding Rainfall Intensity	Clogged Area as Percentage
1, 2	n.a.	3, 4, 5, 6	1, 2	8
2, 3	n.a.	1, 4, 5, 6	2, 3	8
4, 5	n.a.	6, 1, 2, 3	4, 5	8
5, 6	n.a.	4, 1, 2, 3	5, 6	8
1, 2, 3	n.a.	4, 5, 6	1, 2, 3	20
4, 5, 6	n.a.	1, 2, 4	4, 5, 6	20

TABLE 4

Potential Clogging Scenarios for Condition 3 for Parking Lot Application 2				
Clogging Area(s) Bounded By	Sensor(s) with Zero or Slow Accumulation	Sensor(s) with Accumulation Equal to Rainfall Intensity	Sensor(s) with Accumulation Equal to or Exceeding Rainfall Intensity	Clogged Area as Percentage
1, 2, 4, 5	n.a.	3, 6	1, 2, 4, 5	20
2, 3, 5, 6	n.a.	1, 4	2, 3, 5, 6	20
1, 2, 3, 4, 5, 6	n.a.	n.a.	1, 2, 3, 4, 5, 6	30
1, 2, 3, 4, 5, 6	2, 5	n.a.	1, 3, 4, 6	>50

TABLE 5

Sensor Tracking of Clogging Scenarios for Parking Lot Application 3				
Clogging Area(s) Bounded By	Sensor(s) with Zero or Slow Accumulation	Sensor(s) with Accumulation Equal to Rainfall Intensity	Sensor(s) with Accumulation Equal to or Exceeding Rainfall Intensity	Clogged Area as Percentage
2	1	3	2	33
1, 3	2	n.a.	1, 3	33
2	3	1	2	33
1, 2	n.a.	3	1, 2	33
2, 3	n.a.	1	2, 3	33
1	2, 3	n.a.	3	66
3	1, 2	n.a.	1	66
n.a.	1, 2, 3	n.a.	n.a.	100

TABLE 6

Sensor Tracking of Clogging Scenarios for Parking Lot Application 4				
Clogging Area(s) Bounded By	Sensor(s) with Zero or Slow Accumulation	Sensor(s) with Accumulation Equal to Rainfall Intensity	Sensor(s) with Accumulation Equal to or Exceeding Rainfall Intensity	Clogged Area as Percentage
2	1	3, 4, 5, 6	2	16
1, 3	2	4, 5, 6	1, 3	16
2	3	4, 5, 6	2	16
5	4	1, 2, 3	5	16
4, 6	5	1, 2, 3	4, 6	16
5	6	1, 2, 3	5	16

TABLE 6-continued

Sensor Tracking of Clogging Scenarios for Parking Lot Application 4				
Clogging Area(s) Bounded By	Sensor(s) with Zero or Slow Accumulation	Sensor(s) with Accumulation Equal to Rainfall Intensity	Sensor(s) with Accumulation Equal to or Exceeding Rainfall Intensity	Clogged Area as Percentage
1, 2	n.a.	3, 4, 5, 6	1, 2	16
2, 3	n.a.	1, 4, 5, 6	2, 3	16
4, 5	n.a.	6, 1, 2, 3	4, 5	16
5, 6	n.a.	4, 1, 2, 3	5, 6	16
3	1, 2	4, 5, 6	3	33
1	2, 3	4, 5, 6	1	33
6	4, 5	1, 2, 3	6	33
4	5, 6	1, 2, 3	4	33
n.a.	1, 2, 3	4, 5, 6	n.a.	50
n.a.	4, 5, 6	1, 2, 3	n.a.	50
n.a.	1, 2, 3, 4, 5, 6	n.a.	n.a.	100

Some embodiments implement a method **200** for determining debris accumulation on a permeable surface **112** supported above a storage system or drainage structure **114** located underneath the permeable surface **112**. Method **200** includes a first step **202** for sensing the water-level **118** at sensors **108** located within the drainage structure **114** at various times (e.g., t_0 to t_n). For example, sensors **108** are located at predetermined locations S_1, S_2, S_3 , etc. within the storage system/drainage structure **114** that are most susceptible to flooding/clogging or otherwise maximize the area of the plan area **102** and/or drainage structure **114** being monitored, e.g., with the least number of sensors **108**. A second step **204** involves determining the rate r of the water-level **118** change at each sensor **108** (e.g., representative for a specific location, e.g., S_1) relative to the total water level **118** change (e.g., representative of a global change and estimated by the water-level **118** change accumulated at all locations e.g., S_2 and S_3). In a third step **206**, the rate r (e.g., r to r_n) of water-level **118** changes is stored by a controller or processor **138** for each location at a particular times (e.g., t_0 to t_n). In a fourth step **208**, the rates r of water-level **118** changes of a first sensor **108** at relative times, e.g., t_1 to t_n to determine locations, e.g., S_1, S_2 , and S_3 at which the relative rate r of water-level **118** change slows for the first sensor **108** in reference to the relative rate r of water-level **118** change of other sensors **108** (e.g., surrounding first sensor **108**). A fifth step **210** involves determining the location, e.g., S_1 of debris accumulation based upon the sensor **108** location (S_1) at which a rate r of water-level **118** change slows.

In some embodiments, method **200** further includes a sixth step **212** of identifying characteristics of the debris accumulation based upon the sensor **108** location where the rate r of water-level **118** change slows relative to other sensors **108**. Method **200** includes a seventh step **214** of monitoring a rain gage sensor **108**, e.g., located above the drainage structure **114** in the vicinity of the permeable surface or in another remote location that receives approximately equal rainfall. For example, a remote location may include a local weather station or other WAN connected rainfall measurement. The fifth step **210**, involves determining locations (e.g., S_1, S_2 , and/or S_3 , etc.) at which the relative rate of water-level **118** change slows relative to the water-level **118** change of other sensors **108** at other (e.g., adjacent) locations (e.g., S_1, S_2 , and/or S_3 , etc.), includes determining rain volume from the rain gage sensor **108**.

In some embodiments, the first step **202** of sensing the water-level **118** at sensors **108** located at predetermined locations (e.g., S_1, S_2 , and/or S_3 , etc.) further includes generating and storing data **134** representative of the water-levels **118** at the predetermined locations (e.g., S_1, S_2 , and/or S_3 , etc.) in reference to times t_0 to t_n . For example, a water-level change is considered to have slowed relative to the rate r of water-level **118** change of other sensors **108**, if the water-level **118** sensor detects that the rate r has slowed by more than a predetermined amount or threshold. In various embodiments, the predetermined threshold is a rate that has declined more than 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 50%, or more. In some embodiments, the third step **206** involves storing data **134** off site via wireless transmission of the data **134** to a remote system that stores and/or analyzes the data **134**.

Unless otherwise expressly stated, it is in no way intended that any method set forth herein be construed as requiring that its steps be performed in a specific order. Accordingly, where a method claim does not actually recite an order to be followed by its steps or it is not otherwise specifically stated in the claims or descriptions that the steps are to be limited to a specific order, it is in no way intended that any particular order be inferred. In addition, as used herein, the article "a" is intended to include one or more than one component or element, and is not intended to be construed as meaning only one.

It should be understood that the figures illustrate the exemplary embodiments in detail, and it should be understood that the present application is not limited to the details or methodology set forth in the description or illustrated in the figures. It should also be understood that the terminology is for the purpose of description only and should not be regarded as limiting.

Further modifications and alternative embodiments of various aspects of the invention will be apparent to those skilled in the art in view of this description. Accordingly, this description is to be construed as illustrative only. The construction and arrangements, shown in the various exemplary embodiments, are illustrative only. Although only a few embodiments have been described in detail in this disclosure, many modifications are possible (e.g., variations in sizes, dimensions, structures, shapes and proportions of the various elements, values of parameters, mounting arrangements, use of materials, colors, orientations, etc.) without materially departing from the novel teachings and advantages of the subject matter described herein. Some

19

elements shown as integrally formed may be constructed of multiple parts or elements, the position of elements may be reversed or otherwise varied, and the nature or number of discrete elements or positions may be altered or varied. The order or sequence of any process, logical algorithm, or method steps may be varied or re-sequenced according to alternative embodiments. Other substitutions, modifications, changes and omissions may also be made in the design, operating conditions and arrangement of the various exemplary embodiments without departing from the scope of the present invention.

What is claimed is:

1. System for monitoring water-levels generated by water flowing through an area of a permeable surface into a water drainage structure situated below the permeable surface, the system comprising:
 - a permeable surface including pavement, the permeable surface including water flow openings through which water flows into the water drainage structure;
 - a first water-level sensor located at a first position in the water drainage structure to generate first water-level data representative of the water-level at the first position, wherein the first water-level sensor is associated with a first location in the permeable surface;
 - a second water-level sensor located at a second position in the water drainage structure to generate second water-level data representative of the water-level at the second position, wherein the second water-level sensor is associated with a second location in the permeable surface different than the first location;
 - a data memory; and
 - a data processor communicatively coupled to the first and second water-level sensors and the memory, the data processor configured to receive first water-level data sampled from the first sensor and second water-level data from the second sensor at a plurality of times t_0 to t_n , generate a plurality of first water-level change rates r_1 to r_n based upon the first water-level data in reference to times t_1 to t_n , generate a plurality of second water-level change rates rr_1 to rr_n based upon the second water-level data in reference to times t_1 to t_n , compare rates r_1 to r_n to changes rates rr_1 to rr_n for a select group of times t_1 to t_n to generate comparison data c_1 to c_n in reference to at least one of the first and second water-level change rates r or rr , determine comparison data changes over time in reference to the at least one of the first and second water-level change rates, and determine one or more locations of reduced permeability in the permeable surface based on analyzing the comparison data, wherein the determining the one or more locations of reduced permeability in the permeable surface is based at least in part on the first water-level sensor being located at the first location and the second water-level sensor being located at the second location.
2. The system of claim 1, the data processor further configured to store the first water-level data and the second water-level data in the data memory.
3. The system of claim 1, the data processor further configured to store the first water-level change rates r_1 to r_n and the second water-level change rates rr_1 to rr_n in the data memory.
4. The system of claim 1, the data processor further configured to store the comparison data c_1 to c_n in the data memory.
5. The system of claim 1, the data processor further configured to store the comparison data changes in the data memory.

20

6. The system of claim 1, wherein the permeable surface includes a plurality of pavement sections spaced to generate water flow openings through which water flows into the water drainage structure.

7. The system of claim 1, wherein the water drainage structure is porous stone fill.

8. The system of claim 1, wherein the data processor determines if one of the first and second water-level change rates is slowing relative to the other of the first and second water-level change rates based upon the comparison data changes.

9. The system of claim 1, wherein the data processor is communicatively coupled to the water-level sensors via a wireless data link.

10. The system of claim 1, wherein the select group includes all of the times t_1 to t_n .

11. The system of claim 10, wherein t_n is at least 500 samples.

12. A paved system comprising:

- a water drainage structure;
- a rigid permeable surface supported above the drainage structure to permit water to flow from the surface into the structure;
- a plurality of water-level sensors located at respective locations within the drainage structure to generate respective water-level data representative of the water-level at the respective locations, the plurality of water-level sensors including a first water-level sensor associated with a first location, of the respective locations, in the rigid permeable surface and a second water-level sensor associated with a second location, of the respective locations, in the rigid permeable surface different than the first location;
- a memory;
- a data processor communicatively coupled to the first and second water-level sensors and the memory, the data processor receiving first water-level data sampled from the first sensor and second water-level data from the second sensor at a plurality of times t_0 to t_n , the data processor generating water-level rate change data for each water-level sensor in reference to times t_1 to t_n , and comparing water-level rate changes from all sensors from time t_1 to t_n and identifying the water-level sensors which have relative water-level rate changes which slow relative to the water-level rate changes of the other of the sensors from time t_1 to t_n , and the data processor determining one or more locations of reduced permeability in the rigid permeable surface based on analyzing the water-level rate change data, wherein the data processor determining the one or more locations of reduced permeability in the rigid permeable surface is based at least in part on the first water-level sensor being located at the first location and the second water-level sensor being located at the second location.

13. The paved system of claim 12, the data processor storing the water-level rate change data for each water-level sensor in reference to times t_1 to t_n .

14. The paved system of claim 12, the data processor determining the location of the water-level sensors which have water-level rates which slow relative to the water-level rate changes of the other of the sensors.

15. The paved system of claim 12, wherein a water-level change is considered to have slowed for a given sensor relative to the water-level rate change of the other of the sensors if it has slowed by more than a predetermined amount.

21

16. The paved system of claim **12**, wherein the surface is composed of a plurality of pavement sections spaced to produce water flow openings.

17. The paved system of claim **16**, wherein the data processor is communicatively coupled to the water-level sensors via a wireless data link.

18. A method for determining debris accumulation at locations on a permeable surface of the type supported above a drainage structure situated below the permeable surface, the method comprising:

sensing the water-levels at a plurality of predetermined locations within the drainage structure at each of a plurality of times t_0 to t_n , wherein the water-levels are resultant from water flowing through water flow openings in a permeable pavement surface, wherein the sensing the water-levels is performed at least in part by a plurality of water-level sensors;

determining the rate of water-level change at each of the locations based upon the water-level change for the respective locations;

22

comparing the rates of water-level changes and determining the locations at which the relative rate of water-level change slows in reference to the water-level change of the other sensors; and

determining a location of reduced permeability in the permeable pavement surface based upon the location at which relative water-level change slows, and further based at least in part on the first water-level sensor being located at the first location and the second water-level sensor being located at the second location.

19. The method of claim **18**, wherein the step of sensing includes generating and storing data representative of the water-levels at the plurality of predetermined locations in reference to times t_0 to t_n .

20. The method of claim **18**, wherein the step of sensing the water-levels at the plurality of water-level sensors includes the wireless transmission of data.

* * * * *