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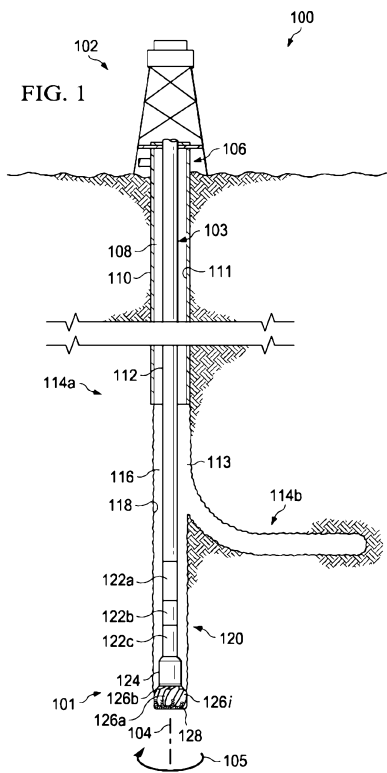
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(54) Title: SYSTEM AND METHOD OF CONSTANT DEPTH OF CUT CONTROL OF DRILLING TOOLS



(57) Abstract: According to some embodiments of the present disclosure, a method of configuring a blade of a drill bit comprises determining a first desired depth of cut for a first radial swath associated with a bit face of a drill bit. The first radial swath is associated with a first area of the bit face. The method further comprises identifying a first plurality of cutting elements located on the bit face. Each of the cutting elements includes at least a portion located within the first radial swath. The method additionally comprises configuring a first blade surface of a blade. The first blade surface is located within the first radial swath and configured based on the first desired depth of cut for the first radial swath. The blade surface is also configured based on each portion of the first plurality of cutting elements located within the first radial swath.

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SYSTEM AND METHOD OF CONSTANT DEPTH OF CUT CONTROL OF DRILLING TOOLS

RELATED APPLICATION

This application claims the benefit of U.S. Provisional Patent Application Serial No. 61/412,173 filed November 10, 2010 and U.S. Provisional Patent Application Serial No. 61/416,160 filed November 22, 2010, which are incorporated herein by reference in
5 their entirety.

TECHNICAL FIELD

The present disclosure relates generally to downhole drilling tools and, more particularly, to a system and method of constant depth of cut control of drilling tools.
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BACKGROUND

Various types of downhole drilling tools including, but not limited to, rotary drill bits, reamers, core bits, and other downhole tools have been used to form wellbores in associated downhole formations. Examples of such rotary drill bits include, but are not
15 limited to, fixed cutter drill bits, drag bits, polycrystalline diamond compact (PDC) drill bits, and matrix drill bits associated with forming oil and gas wells extending through one or more downhole formations. Fixed cutter drill bits such as a PDC bit may include multiple blades that each include multiple cutting elements.

In typical drilling applications, a PDC bit may be used to drill through various
20 levels or types of geological formations with longer bit life than non-PDC bits. Typical formations may generally have a relatively low compressive strength in the upper portions (e.g., lesser drilling depths) of the formation and a relatively high compressive strength in the lower portions (e.g., greater drilling depths) of the formation. Thus, it typically becomes increasingly more difficult to drill at increasingly greater depths. As
25 well, the ideal bit for drilling at any particular depth is typically a function of the compressive strength of the formation at that depth. Accordingly, the ideal bit for drilling typically changes as a function of drilling depth.

A drilling tool may include one or more depth of cut controllers (DOCCs) configured to control the amount that a drilling tool cuts into the side of a geological

formation. However, conventional DOCC configurations may cause an uneven depth of cut control of the cutting elements of the drilling tool. This uneven depth of cut control may allow for portions of the DOCCs to wear unevenly. Also, uneven depth of cut control may cause the drilling tool to vibrate, which may damage parts of the drill string or slow the drilling process.

SUMMARY

According to some embodiments of the present disclosure, a method of configuring a blade of a drill bit comprises determining a first desired depth of cut for a first radial swath associated with a bit face of a drill bit. The first radial swath is associated with a first area of the bit face. The method further comprises identifying a first plurality of cutting elements located on the bit face. Each of the cutting elements includes at least a portion located within the first radial swath. The method additionally comprises configuring a first blade surface of a blade associated with the bit face. The first blade surface is located within the first radial swath and configured based on the first desired depth of cut for the first radial swath. The blade surface is also configured based on each portion of the first plurality of cutting elements located within the first radial swath.

BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of the present disclosure and its features and advantages, reference is now made to the following description, taken in conjunction with the accompanying drawings, in which:

FIGURE 1 illustrates an example embodiment of a drilling system in accordance with some embodiments of the present disclosure;

FIGURE 2 illustrates a bit face profile of a drill bit forming a wellbore, in accordance with some embodiments of the present disclosure;

FIGURE 3 illustrates a blade profile that may represent a cross-sectional view of a blade of a drill bit, in accordance with some embodiments of the present disclosure;

FIGURES 4A-4D illustrate cutting zones of various cutting elements disposed along a blade, in accordance with some embodiments of the present disclosure;

FIGURE 5A illustrates the face of a drill bit that may be designed and manufactured to provide an improved depth of cut control, in accordance with some embodiments of the present disclosure;

FIGURE 5B illustrates the locations of cutting elements of the drill bit of FIGURE 5A along the bit profile of the drill bit, in accordance with some embodiments of the present disclosure;

FIGURE 6A illustrates a graph of the bit face profile of a cutting element having a cutting zone with a depth of cut that may be controlled by a depth of cut controller (DOCC) designed in accordance with some embodiments of the present disclosure;

FIGURE 6B illustrates a graph of the bit face illustrated in the bit face profile of FIGURE 6A, in accordance with some embodiments of the present disclosure;

FIGURE 6C illustrates the DOCC of FIGURE 6A designed according to some embodiments of the present disclosure;

FIGURE 7 illustrates a flow chart of an example method for designing one or more DOCCs according to the cutting zones of one or more cutting elements, in accordance with some embodiments of the present disclosure;

FIGURE 8A illustrates a graph of the bit face profile of a cutting element having a cutting zone with a depth of cut that may be controlled by a blade, in accordance with some embodiments of the present disclosure;

FIGURE 8B illustrates a graph of the bit face illustrated in the bit face profile of FIGURE 8A, in accordance with some embodiments of the present disclosure;

FIGURE 9 illustrates a flow chart of an example method for designing blade surfaces according to the cutting zones of one or more cutting elements, in accordance with some embodiments of the present disclosure;

FIGURE 10A illustrates the face of a drill bit with a DOCC configured in accordance with some embodiments of the present disclosure;

FIGURE 10B, illustrates a graph of a bit face profile of the bit face illustrated in FIGURE 10A, in accordance with some embodiments of the present disclosure;

FIGURE 10C illustrates an example of the axial coordinates and curvature of a cross-sectional line configured such that a DOCC may control the depth of cut of a drill bit to a desired depth of cut, in accordance with some embodiments of the present disclosure;

FIGURE 10D illustrates a critical depth of cut control curve of the drill bit of FIGURES 10A-10C, in accordance with some embodiments of the present disclosure;

FIGURES 11A and 11B illustrate a flow chart of an example method for configuring a DOCC, in accordance with some embodiments of the present disclosure;

FIGURE 12A illustrates a drill bit that includes a plurality of DOCCs configured to control the depth of cut of a drill bit, in accordance with some embodiments of the present disclosure;

FIGURE 12B illustrates a critical depth of cut control curve of the drill bit of
5 FIGURE 12A, in accordance with some embodiments of the present disclosure;

FIGURE 13A illustrates another example of a drill bit that includes a plurality of DOCCs configured to control the depth of cut of the drill bit, in accordance with some embodiments of the present disclosure;

FIGURES 13B-13E illustrate critical depth of cut control curves of the drill bit of
10 FIGURE 13A, in accordance with some embodiments of the present disclosure;

FIGURE 14A illustrates another example of a drill bit that includes a plurality of DOCCs configured to control the depth of cut of the drill bit, in accordance with some embodiments of the present disclosure;

FIGURES 14B-14D illustrate critical depth of cut control curves of the drill bit of
15 FIGURE 14A, in accordance with some embodiments of the present disclosure;

FIGURE 15A illustrates a drill bit that includes a plurality of blades that may include a DOCC configured to control the depth of cut of a drill bit, in accordance with some embodiments of the present disclosure;

FIGURES 15B-15F illustrate example axial and radial coordinates of cross-sectional lines located between a first radial coordinate and a second radial coordinate, in
20 accordance with some embodiments of the present disclosure;

FIGURE 16A illustrates the face of a drill bit with a blade configured to control the depth of cut of the drill bit, in accordance with some embodiments of the present disclosure;

FIGURE 16B, illustrates a graph of a bit face profile of the bit face illustrated in
25 FIGURE 16A, in accordance with some embodiments of the present disclosure;

FIGURE 16C illustrates a critical depth of cut control curve of the drill bit of FIGURES 16A and 16B, in accordance with some embodiments of the present disclosure;

FIGURES 17A and 17B illustrate a flow chart of an example method for
30 configuring the surface of a blade, in accordance with some embodiments of the present disclosure;

FIGURE 18A illustrates an example of a drill bit that includes a plurality of blades configured to control the depth of cut of the drill bit, in accordance with some embodiments of the present disclosure;

FIGURES 18B-18E illustrate critical depth of cut control curves of the drill bit of FIGURE 18A, in accordance with some embodiments of the present disclosure;

FIGURE 19A illustrates another example of a drill bit that includes a plurality of blades configured to control the depth of cut of the drill bit according to different critical depths of cut for different radial swaths of the drill bit, in accordance with some embodiments of the present disclosure;

FIGURES 19B-19D illustrate critical depth of cut control curves of the drill bit of FIGURE 19A, in accordance with some embodiments of the present disclosure;

FIGURE 20A illustrates the face of a drill bit for which a critical depth of cut control curve (CDCCC) may be determined, in accordance with some embodiments of the present disclosure;

FIGURE 20B illustrates a bit face profile of the drill bit depicted in FIGURE 20A, in accordance with some embodiments of the present disclosure;

FIGURE 20C illustrates a critical depth of cut control curve for a drill bit, in accordance with some embodiments of the present disclosure; and

FIGURE 21 illustrates an example method of determining and generating a critical depth of cut control curve, in accordance with some embodiments of the present disclosure.

DETAILED DESCRIPTION

Embodiments of the present disclosure and its advantages are best understood by referring to FIGURES 1 through 21, where like numbers are used to indicate like and corresponding parts.

FIGURE 1 illustrates an example embodiment of a drilling system 100 configured to drill into one or more geological formations, in accordance with some embodiments of the present disclosure. While drilling into different types of geological formations it may be advantageous to control the amount that a downhole drilling tool cuts into the side of a geological formation in order to reduce wear on the cutting elements of the drilling tool, prevent uneven cutting into the formation, increase control of penetration rate, reduce tool vibration, etc. As disclosed in further detail below, drilling system 100 may include downhole drilling tools (e.g., a drill bit, a reamer, a hole opener, etc.) that may include

one or more cutting elements with a depth of cut that may be controlled by one or more depth of cut controllers (DOCC).

As disclosed in further detail below and according to some embodiments of the present disclosure, a DOCC may be configured to control the depth of cut of a cutting element (sometimes referred to as a “cutter”) according to the location of a cutting zone and cutting edge of the cutting element. Additionally, according to some embodiments of the present disclosure, a DOCC may be configured according to a plurality of cutting elements that may overlap a radial swath of the drill bit associated with a rotational path of the DOCC, as disclosed in further detail below. In the same or alternative
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embodiments, the DOCC may be configured to control the depth of cut of the plurality of cutting elements according to the locations of the cutting zones of the cutting elements. In contrast, a DOCC configured according to traditional methods may not be configured according to a plurality of cutting elements that overlap the rotational path of the DOCC, the locations of the cutting zones of the cutting elements or any combination thereof. Accordingly, a DOCC designed according to the present disclosure may provide a more constant and even depth of cut control of the drilling tool than those designed using conventional methods.

Drilling system 100 may include a rotary drill bit (“drill bit”) 101. Drill bit 101 may be any of various types of fixed cutter drill bits, including PDC bits, drag bits, matrix
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drill bits, and/or steel body drill bits operable to form a wellbore 114 extending through one or more downhole formations. Drill bit 101 may be designed and formed in accordance with teachings of the present disclosure and may have many different designs, configurations, and/or dimensions according to the particular application of drill bit 101.

Drill bit 101 may include one or more blades 126 (e.g., blades 126a-126i) that
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may be disposed outwardly from exterior portions of a rotary bit body 124 of drill bit 101. Rotary bit body 124 may have a generally cylindrical body and blades 126 may be any suitable type of projections extending outwardly from rotary bit body 124. For example, a portion of a blade 126 may be directly or indirectly coupled to an exterior portion of bit body 124, while another portion of the blade 126 is projected away from the exterior portion of bit body 124. Blades 126 formed in accordance with teachings of the present disclosure may have a wide variety of configurations including, but not limited to, substantially arched, helical, spiraling, tapered, converging, diverging, symmetrical, and/or asymmetrical. Various configurations of blades 126 may be used and designed to

form cutting structures for drill bit 101 that may provide a more constant depth of cut control incorporating teachings of the present disclosure, as explained further below. For example, in some embodiments one or more blades 126 may be configured to control the depth of cut of cutting elements 128 that may overlap the rotational path of at least a portion of blades 126, as explained in detail below.

In some cases, blades 126 may have substantially arched configurations, generally helical configurations, spiral shaped configurations, or any other configuration satisfactory for use with each downhole drilling tool. One or more blades 126 may have a substantially arched configuration extending from proximate a rotational axis 104 of bit 101. The arched configuration may be defined in part by a generally concave, recessed shaped portion extending from proximate bit rotational axis 104. The arched configuration may also be defined in part by a generally convex, outwardly curved portion disposed between the concave, recessed portion and exterior portions of each blade which correspond generally with the outside diameter of the rotary drill bit.

In an embodiment of drill bit 101, blades 126 may include primary blades disposed generally symmetrically about the bit rotational axis. For example, one embodiment may include three primary blades oriented approximately 120 degrees relative to each other with respect to bit rotational axis 104 in order to provide stability for drill bit 101. In some embodiments, blades 126 may also include at least one secondary blade disposed between the primary blades. The number and location of secondary blades and primary blades may vary substantially. Blades 126 may be disposed symmetrically or asymmetrically with regard to each other and bit rotational axis 104 where the disposition may be based on the downhole drilling conditions of the drilling environment.

Each of blades 126 may include a first end disposed proximate or toward bit rotational axis 104 and a second end disposed proximate or toward exterior portions of drill bit 101 (*i.e.*, disposed generally away from bit rotational axis 104 and toward uphole portions of drill bit 101). The terms “downhole” and “uphole” may be used in this application to describe the location of various components of drilling system 100 relative to the bottom or end of a wellbore. For example, a first component described as “uphole” from a second component may be further away from the end of the wellbore than the second component. Similarly, a first component described as being “downhole” from a

second component may be located closer to the end of the wellbore than the second component.

Each blade may have a leading (or front) surface disposed on one side of the blade in the direction of rotation of drill bit 101 and a trailing (or back) surface disposed on an opposite side of the blade away from the direction of rotation of drill bit 101. Blades 126 may be positioned along bit body 124 such that they have a spiral configuration relative to rotational axis 104. In other embodiments, blades 126 may be positioned along bit body 124 in a generally parallel configuration with respect to each other and bit rotational axis 104.

Blades 126 may have a general arcuate configuration extending radially from rotational axis 104. The arcuate configurations of blades 126 may cooperate with each other to define, in part, a generally cone shaped or recessed portion disposed adjacent to and extending radially outward from the bit rotational axis. Exterior portions of blades 126, cutting elements 128 and DOCCs (not expressly shown) may be described as forming portions of the bit face.

Blades 126 may include one or more cutting elements 128 disposed outwardly from exterior portions of each blade 126. For example, a portion of a cutting element 128 may be directly or indirectly coupled to an exterior portion of a blade 126 while another portion of the cutting element 128 may be projected away from the exterior portion of the blade 126. Cutting elements 128 may be any suitable device configured to cut into a formation, including but not limited to, primary cutting elements, backup cutting elements or any combination thereof. By way of example and not limitation, cutting elements 128 may be various types of cutters, compacts, buttons, inserts, and gage cutters satisfactory for use with a wide variety of drill bits 101.

Cutting elements 128 may include respective substrates with a layer of hard cutting material disposed on one end of each respective substrate. The hard layer of cutting elements 128 may provide a cutting surface that may engage adjacent portions of a downhole formation to form a wellbore 114. The contact of the cutting surface with the formation may form a cutting zone associated with each of cutting elements 128, as described in further detail with respect to FIGURES 4A-4D. The edge of the cutting surface located within the cutting zone may be referred to as the cutting edge of a cutting element 128.

Each substrate of cutting elements 128 may have various configurations and may be formed from tungsten carbide or other materials associated with forming cutting elements for rotary drill bits. Tungsten carbides may include, but are not limited to, monotungsten carbide (WC), ditungsten carbide (W₂C), macrocrystalline tungsten carbide and cemented or sintered tungsten carbide. Substrates may also be formed using other
5 hard materials, which may include various metal alloys and cements such as metal borides, metal carbides, metal oxides and metal nitrides. For some applications, the hard cutting layer may be formed from substantially the same materials as the substrate. In other applications, the hard cutting layer may be formed from different materials than the
10 substrate. Examples of materials used to form hard cutting layers may include polycrystalline diamond materials, including synthetic polycrystalline diamonds.

Blades 126 may also include one or more DOCCs (not expressly shown) configured to control the depth of cut of cutting elements 128. A DOCC may comprise an impact arrestor, a backup cutter and/or an MDR (Modified Diamond Reinforcement). As
15 mentioned above, in the present disclosure, a DOCC may be designed and configured according to the location of a cutting zone associated with the cutting edge of a cutting element. In the same or alternative embodiments, one or more DOCCs may be configured according to a plurality of cutting elements overlapping the rotational paths of the DOCCs. Accordingly, one or more DOCCs of a drill bit may be configured according to
20 the present disclosure to provide a constant depth of cut of cutting elements 128. Additionally, as disclosed in further detail below, one or more of blades 126 may also be similarly configured to control the depth of cut of cutting elements 128.

Blades 126 may further include one or more gage pads (not expressly shown) disposed on blades 126. A gage pad may be a gage, gage segment, or gage portion
25 disposed on exterior portion of a blade 126. Gage pads may often contact adjacent portions of a wellbore 114 formed by drill bit 101. Exterior portions of blades 126 and/or associated gage pads may be disposed at various angles, either positive, negative, and/or parallel, relative to adjacent portions of a straight wellbore (e.g., wellbore 114a). A gage pad may include one or more layers of hardfacing material.

30 Drilling system 100 may also include a well surface or well site 106. Various types of drilling equipment such as a rotary table, mud pumps and mud tanks (not expressly shown) may be located at a well surface or well site 106. For example, well site 106 may include a drilling rig 102 that may have various characteristics and features

associated with a “land drilling rig.” However, downhole drilling tools incorporating teachings of the present disclosure may be satisfactorily used with drilling equipment located on offshore platforms, drill ships, semi-submersibles and drilling barges (not expressly shown).

5 Drilling system 100 may include a drill string 103 associated with drill bit 101 that may be used to form a wide variety of wellbores or bore holes such as generally vertical wellbore 114a or generally horizontal wellbore 114b as shown in FIGURE 1. Various directional drilling techniques and associated components of a bottom hole assembly (BHA) 120 of drill string 103 may be used to form horizontal wellbore 114b. For
10 example, lateral forces may be applied to drill bit 101 proximate kickoff location 113 to form horizontal wellbore 114b extending from generally vertical wellbore 114a.

 BHA 120 may be formed from a wide variety of components configured to form a wellbore 114. For example, components 122a, 122b and 122c of BHA 120 may include, but are not limited to, drill bits (e.g., drill bit 101) drill collars, rotary steering tools,
15 directional drilling tools, downhole drilling motors, reamers, hole enlargers or stabilizers. The number of components such as drill collars and different types of components 122 included in BHA 120 may depend upon anticipated downhole drilling conditions and the type of wellbore that will be formed by drill string 103 and rotary drill bit 100.

 A wellbore 114 may be defined in part by a casing string 110 that may extend
20 from well surface 106 to a selected downhole location. Portions of a wellbore 114, as shown in FIGURE 1, that do not include casing string 110 may be described as “open hole.” Various types of drilling fluid may be pumped from well surface 106 through drill string 103 to attached drill bit 101. Such drilling fluids may be directed to flow from drill string 103 to respective nozzles (not expressly shown) included in rotary drill bit 100. The
25 drilling fluid may be circulated back to well surface 106 through an annulus 108 defined in part by outside diameter 112 of drill string 103 and inside diameter 118 of wellbore 114a. Inside diameter 118 may be referred to as the “sidewall” of wellbore 114a. Annulus 108 may also be defined by outside diameter 112 of drill string 103 and inside diameter 111 of casing string 110.

30 The rate of penetration (ROP) of drill bit 101 is often a function of both weight on bit (WOB) and revolutions per minute (RPM). Drill string 103 may apply weight on drill bit 101 and may also rotate drill bit 101 about rotational axis 104 to form a wellbore 114 (e.g., wellbore 114a or wellbore 114b). For some applications a downhole motor (not

expressly shown) may be provided as part of BHA 120 to also rotate drill bit 101. The depth of cut controlled by DOCCs (not expressly shown) and blades 126 may also be based on the ROP and RPM of a particular bit. Accordingly, as described in further detail below, the configuration of the DOCCs and blades 126 to provide a constant depth of cut of cutting elements 128 may be based in part on the desired ROP and RPM of a particular drill bit 101.

FIGURE 2 illustrates a bit face profile 200 of drill bit 101 configured to form a wellbore through a first formation layer 202 into a second formation layer 204, in accordance with some embodiments of the present disclosure. Exterior portions of blades (not expressly shown), cutting elements 128 and DOCCs (not expressly shown) may be projected rotationally onto a radial plane to form bit face profile 200. In the illustrated embodiment, formation layer 202 may be described as “softer” or “less hard” when compared to downhole formation layer 204. As shown in FIGURE 2, exterior portions of drill bit 101 that contact adjacent portions of a downhole formation may be described as a “bit face.” Bit face profile 200 of drill bit 101 may include various zones or segments. Bit face profile 200 may be substantially symmetric about bit rotational axis 104 due to the rotational projection of bit face profile 200, such that the zones or segments on one side of rotational axis 104 may be substantially similar to the zones or segments on the opposite side of rotational axis 104.

For example, bit face profile 200 may include a gage zone 206a located opposite a gage zone 206b, a shoulder zone 208a located opposite a shoulder zone 208b, a nose zone 210a located opposite a nose zone 210b, and a cone zone 212a located opposite a cone zone 212b. The cutting elements 128 included in each zone may be referred to as cutting elements of that zone. For example, cutting elements 128_g included in gage zones 206 may be referred to as gage cutting elements, cutting elements 128_s included in shoulder zones 208 may be referred to as shoulder cutting elements, cutting elements 128_n included in nose zones 210 may be referred to as nose cutting elements, and cutting elements 128_c included in cone zones 212 may be referred to as cone cutting elements. As discussed in further detail below with respect to FIGURES 3 and 4, each zone or segment along bit face profile 200 may be defined in part by respective portions of associated blades 126.

Cone zones 212 may be generally convex and may be formed on exterior portions of each blade (e.g., blades 126 as illustrated in FIGURE 1) of drill bit 101, adjacent to and extending out from bit rotational axis 104. Nose zones 210 may be generally convex and

may be formed on exterior portions of each blade of drill bit 101, adjacent to and extending from each cone zone 212. Shoulder zones 208 may be formed on exterior portions of each blade 126 extending from respective nose zones 210 and may terminate proximate to a respective gage zone 206.

5 According to the present disclosure, a DOCC (not expressly shown) may be configured along bit face profile 200 to provide a substantially constant depth of cut control for cutting elements 128. Additionally, in the same or alternative embodiments, a blade surface of a blade 126 may be configured at various points on the bit face profile 200 to provide a substantially constant depth of cut control. The design of each DOCC
10 and blade surface configured to control the depth of cut may be based at least partially on the location of each cutting element 128 with respect to a particular zone of the bit face profile 200 (e.g., gage zone 206, shoulder zone 208, nose zone 210 or cone zone 212). Further, as mentioned above, the various zones of bit face profile 200 may be based on the profile of blades 126 of drill bit 101.

15 FIGURE 3 illustrates a blade profile 300 that represents a cross-sectional view of a blade 126 of drill bit 101. Blade profile 300 includes a cone zone 212, nose zone 210, shoulder zone 208 and gage zone 206 as described above with respect to FIGURE 2. Cone zone 212, nose zone 210, shoulder zone 208 and gage zone 206 may be based on their location along blade 126 with respect to rotational axis 104 and a horizontal
20 reference line 301 that may indicate a distance from rotational axis 104 in a plane perpendicular to rotational axis 104. A comparison of FIGURES 2 and 3 shows that blade profile 300 of FIGURE 3 is upside down with respect to bit face profile 200 of FIGURE 2.

Blade profile 300 may include an inner zone 302 and an outer zone 304. Inner
25 zone 302 may extend outward from rotational axis 104 to nose point 311. Outer zone 304 may extend from nose point 311 to the end of blade 126. Nose point 311 may be the location on blade profile 300 within nose zone 210 that has maximum elevation as measured by bit rotational axis 104 (vertical axis) from reference line 301 (horizontal axis). A coordinate on the graph in FIGURE 3 corresponding to rotational axis 104 may
30 be referred to as an axial coordinate or position. A coordinate on the graph in FIGURE 3 corresponding to reference line 301 may be referred to as a radial coordinate or radial position that may indicate a distance extending orthogonally from rotational axis 104 in a radial plane passing through rotational axis 104. For example, in FIGURE 3 rotational

axis 104 may be placed along a z-axis and reference line 301 may indicate the distance (R) extending orthogonally from rotational axis 104 to a point on a radial plane that may be defined as the ZR plane.

FIGURES 2 and 3 are for illustrative purposes only and modifications, additions or omissions may be made to FIGURES 2 and 3 without departing from the scope of the present disclosure. For example, the actual locations of the various zones with respect to the bit face profile may vary and may not be exactly as depicted.

FIGURES 4A-4D illustrate cutting edges 406 (not expressly labeled in FIGURE 4A) and cutting zones 404 of various cutting elements 402 disposed along a blade 400, as modeled by a drilling bit simulator. The location and size of cutting zones 404 (and consequently the location and size of cutting edges 406) may depend on factors including the ROP and RPM of the bit, the size of cutting elements 402, and the location and orientation of cutting elements 402 along the blade profile of blade 400, and accordingly the bit face profile of the drill bit.

FIGURE 4A illustrates a graph of a profile of a blade 400 indicating radial and axial locations of cutting elements 402a-402j along blade 400. The vertical axis depicts the axial position of blade 400 along a bit rotational axis and the horizontal axis depicts the radial position of blade 400 from the bit rotational axis in a radial plane passing through and perpendicular to the bit rotational axis. Blade 400 may be substantially similar to one of blades 126 described with respect to FIGURES 1-3 and cutting elements 402 may be substantially similar to cutting elements 128 described with respect to FIGURES 1-3. In the illustrated embodiment, cutting elements 402a-402d may be located within a cone zone 412 of blade 400 and cutting elements 402e-402g may be located within a nose zone 410 of blade 400. Additionally, cutting elements 402h-402i may be located within a shoulder zone 408 of blade 400 and cutting element 402j may be located within a gage zone 406 of blade 400. Cone zone 412, nose zone 410, shoulder zone 408 and gage zone 406 may be substantially similar to cone zone 212, nose zone 210, shoulder zone 208 and gage zone 206, respectively, described with respect to FIGURES 2 and 3.

FIGURE 4A illustrates cutting zones 404a-404j, with each cutting zone 404 corresponding with a respective cutting element 402. As mentioned above, each cutting element 202 may have a cutting edge (not expressly shown) located within a cutting zone 404. From FIGURE 4A it can be seen that the cutting zone 404 of each cutting element

402 may be based on the axial and radial locations of the cutting element 402 on blade 400, which may be related to the various zones of blade 400.

FIGURE 4B illustrates an exploded graph of cutting element 402b of FIGURE 4A to better illustrate cutting zone 404b and cutting edge 406b associated with cutting element 402b. From FIGURE 4A it can be seen that cutting element 402b may be located in cone zone 412. Cutting zone 404b may be based at least partially on cutting element 402b being located in cone zone 412 and having axial and radial positions corresponding with cone zone 412. As mentioned above, cutting edge 406b may be the edge of the cutting surface of cutting element 402b that is located within cutting zone 404b.

FIGURE 4C illustrates an exploded graph of cutting element 402f of FIGURE 4A to better illustrate cutting zone 404f and cutting edge 406f associated with cutting element 402f. From FIGURE 4A it can be seen that cutting element 402f may be located in nose zone 410. Cutting zone 404f may be based at least partially on cutting element 402f being located in nose zone 410 and having axial and radial positions corresponding with nose zone 410.

FIGURE 4D illustrates an exploded graph of cutting element 402h of FIGURE 4A to better illustrate cutting zone 404h and cutting edge 406h associated with cutting element 402h. From FIGURE 4A it can be seen that cutting element 402h may be located in shoulder zone 408. Cutting zone 404h may be based partially on cutting element 402h being located in shoulder zone 408 and having axial and radial positions corresponding with shoulder zone 408.

An analysis of FIGURE 4A and a comparison of FIGURES 4B-4D reveal that the locations of cutting zones 404 of cutting elements 402 may vary at least in part on the axial and radial positions of cutting elements 402 with respect to rotational axis 104. Accordingly, the location, orientation and configuration of a DOCC (or blade configured to control the depth of cut) for a drill bit may take into consideration the locations of the cutting zones (and their associated cutting edges) of the cutting elements that may overlap the rotational path of a DOCC (or blade configured to control the depth of cut).

FIGURE 5A illustrates the face of a drill bit 101 that may be designed and manufactured according to the present disclosure to provide an improved depth of cut control. FIGURE 5B illustrates the locations of cutting elements 128 and 129 of drill bit 101 along the bit profile of drill bit 101. As discussed in further detail below, drill bit 101 may include a DOCC 502 that may be configured to control the depth of cut of a cutting

element according to the location of a cutting zone and the associated cutting edge of the cutting element. Additionally, DOCC 502 may be configured to control the depth of cut of cutting elements that overlap the rotational path of DOCC 502. In the same or alternative embodiments, DOCC 502 may be configured based on the cutting zones of cutting elements that overlap the rotational path of DOCC 502.

To provide a frame of reference, FIGURE 5A includes an x-axis and a y-axis and FIGURE 5B includes a z-axis that may be associated with rotational axis 104 of drill bit 101 and a radial axis (R) that indicates the orthogonal distance from the center of bit 101 in the xy plane. Accordingly, a coordinate or position corresponding to the z-axis may be referred to as an axial coordinate or axial position of the bit face profile. Additionally, a location along the bit face may be described by x and y coordinates of an xy-plane substantially perpendicular to the z-axis. The distance from the center of bit 101 (e.g., rotational axis 104) to a point in the xy plane of the bit face may indicate the radial coordinate or radial position of the point on the bit face profile of bit 101. For example, the radial coordinate, r , of a point in the xy plane having an x coordinate, x , and a y coordinate, y , may be expressed by the following equation:

$$r = \sqrt{x^2 + y^2}$$

Additionally, a point in the xy plane may have an angular coordinate that may be an angle between a line extending from the center of bit 101 (e.g., rotational axis 104) to the point and the x-axis. For example, the angular coordinate (θ) of a point in the xy plane having an x-coordinate, x , and a y-coordinate, y , may be expressed by the following equation:

$$\theta = \arctan (y/x)$$

As a further example, a point 504 located on the cutting edge of cutting element 128a (as depicted in FIGURES 5A and 5B) may have an x-coordinate (X_{504}) and a y-coordinate (Y_{504}) in the xy plane that may be used to calculate a radial coordinate (R_{504}) of point 504 (e.g., R_{504} may be equal to the square root of X_{504} squared plus Y_{504} squared). R_{504} may accordingly indicate an orthogonal distance of point 504 from rotational axis 104. Additionally, point 504 may have an angular coordinate (θ_{504}) that

may be the angle between the x-axis and the line extending from rotational axis 104 to point 504 (e.g., θ_{504} may be equal to $\arctan(X_{504}/Y_{504})$). Further, as depicted in FIGURE 5B, point 504 may have an axial coordinate (Z_{504}) that may represent a position along the z-axis that may correspond to point 504. It is understood that the coordinates are used for illustrative purposes only, and that any other suitable coordinate system or configuration, may be used to provide a frame of reference of points along the bit face and bit face profile of drill bit 101. Additionally, any suitable units may be used. For example, the angular position may be expressed in degrees or in radians.

Drill bit 101 may include bit body 124 with a plurality of blades 126 positioned along bit body 124. In the illustrated embodiment, drill bit 101 may include blades 126a-126c, however it is understood that in other embodiments, drill bit 101 may include more or fewer blades 126. Blades 126 may include outer cutting elements 128 and inner cutting elements 129 disposed along blades 126. For example, blade 126a may include outer cutting element 128a and inner cutting element 129a, blade 126b may include outer cutting element 128b and inner cutting element 129b and blade 126c may include outer cutting element 128c and inner cutting element 129c.

As mentioned above, drill bit 101 may include one or more DOCCs 502. In the present illustration, only one DOCC 502 is depicted, however drill bit 101 may include more DOCCs 502. Drill bit 101 may rotate about rotational axis 104 in direction 506. Accordingly, DOCC 502 may be placed behind cutting element 128a on blade 126a with respect to the rotational direction 506. However, in alternative embodiments DOCC 502 may be placed in front of cutting element 128a (e.g., on blade 126b) such that DOCC 502 is in front of cutting element 128a with respect to the rotational direction 506.

As drill bit 101 rotates, DOCC 502 may follow a rotational path indicated by radial swath 508 of drill bit 101. Radial swath 508 may be defined by radial coordinates R_1 and R_2 . R_1 may indicate the orthogonal distance from rotational axis 104 to the inside edge of DOCC 502 (with respect to the center of drill bit 101). R_2 may indicate the orthogonal distance from rotational axis 104 to the outside edge of DOCC 502 (with respect to the center of drill bit 101).

As shown in FIGURES 5A and 5B, cutting elements 128 and 129 may each include a cutting zone 505. In the illustrated embodiment, cutting zones 505 of cutting elements 128 and 129 may not overlap at a specific depth of cut. This lack of overlap may occur for some bits with a small number of blades and a small number of cutting elements

at a small depth of cut. The lack of overlap between cutting zones may also occur for cutting elements located within the cone zone of fixed cutter bits because the number of blades within the cone zone is usually small. In such instances, a DOCC 502 or a portion of a blade 126 may be designed and configured according to the location of the cutting zone 505 and cutting edge of a cutting element 128 or 129 with a depth of cut that may be controlled by the DOCC 502 or blade 126.

For example, cutting element 128a may include a cutting zone 505 and associated cutting edge that overlaps the rotational path of DOCC 502 such that DOCC 502 may be configured according to the location of the cutting edge of cutting element 128a, as described in detail with respect to FIGURES 6 and 7. In the same or alternative embodiments, the surface of a blade 126 (e.g., the surface of blade 126b) may also be configured according to the location of the cutting edge of cutting element 128a to control the depth of cut of cutting element 128a, as described in detail with respect to FIGURES 8 and 9.

Therefore, as discussed further below, DOCC 502 may be configured to control the depth of cut of cutting element 128a that may intersect or overlap radial swath 508. Additionally, as described in detail below, in the same or alternative embodiments, the surface of one or more blades 126 within radial swath 508 may be configured to control the depth of cut of cutting element 128a located within radial swath 508. Further, DOCC 502 and the surface of one or more blades 126 may be configured according to the location of the cutting zone and the associated cutting edge of cutting elements 128a that may be located within radial swath 508.

Modifications, additions or omissions may be made to FIGURES 5A and 5B without departing from the scope of the present disclosure. For example, the number of blades 126, cutting elements 128 and DOCCs 502 may vary according to the various design constraints and considerations of drill bit 101. Additionally, radial swath 508 may be larger or smaller than depicted or may be located at a different radial location, or any combination thereof.

Further, in alternative embodiments, the cutting zones 505 of cutting elements 128 and 129 may overlap and a DOCC 502 or a portion of a blade 126 may be designed and configured according to a plurality of cutting elements 128 and/or 129 that may be located within the rotational path of the DOCCs 502 and/or the blades 126 as depicted in FIGURES 10-19. However, the principles and ideas described with respect to FIGURES

6-9 (configuring a DOCC and/or a blade according to cutting zones and cutting edges) may be implemented with respect to the principles and ideas of FIGURES 10-19 (configuring a DOCC and/or a blade according to a plurality of cutting elements that may overlap the rotational path of the DOCC and/or the blade) and vice versa.

5 FIGURES 6A-6C illustrate a DOCC 612 that may be designed according to the location of a cutting zone 602 of a cutting element 600 of a drill bit such as that depicted in FIGURES 5A and 5B. The coordinate system used in FIGURES 6A-6C may be substantially similar to that described with respect to FIGURES 5A and 5B. Therefore, the rotational axis of the drill bit corresponding with FIGURES 6A-6C may be associated
10 with the z-axis of a Cartesian coordinate system to define an axial position with respect to the drill bit. Additionally, an xy plane of the coordinate system may correspond with a plane of the bit face of the drill bit that is substantially perpendicular to the rotational axis. Coordinates on the xy plane may be used to define radial and angular coordinates associated with the drill bit of FIGURES 6A-6C.

15 FIGURE 6A illustrates a graph of a bit face profile of a cutting element 600 that may be controlled by a depth of cut controller (DOCC) 612 located on a blade 604 and designed in accordance with some embodiments of the present disclosure. FIGURE 6A illustrates the axial and radial coordinates of cutting element 600 and DOCC 612 configured to control the depth of cut of cutting element 600 based on the location of a
20 cutting zone 602 (and its associated cutting edge 603) of cutting element 600. In some embodiments, DOCC 612 may be located on the same blade 604 as cutting element 600, and, in other embodiments, DOCC 612 may be located on a different blade 604 as cutting element 600. Cutting edge 603 of cutting element 600 that corresponds with cutting zone 602 may be divided according to cutlets 606a-606e that have radial and axial positions depicted in FIGURE 6A. Additionally, FIGURE 6A illustrates the radial and axial
25 positions of control points 608a-608e that may correspond with a back edge 616 of DOCC 612, as described in further detail with respect to FIGURE 6B.

As depicted in FIGURE 6A, the radial coordinates of control points 608a-608e may be determined based on the radial coordinates of cutlets 606a-606e such that each of
30 control points 608a-608e respectively may have substantially the same radial coordinates as cutlets 606a-606e. By basing the radial coordinates of control points 608a-608e on the radial coordinates of cutlets 606a-606e, DOCC 612 may be configured such that its radial swath substantially overlaps the radial swath of cutting zone 602 to control the depth of

cut of cutting element 600. Additionally, as discussed in further detail below, the axial coordinates of control points 608a-608e may be determined based on a desired depth of cut, Δ , of cutting element 600 and a corresponding desired axial underexposure, δ_{607i} , of control points 608a-608e with respect to cutlets 606a-606e. Therefore, DOCC 612 may be
5 configured according to the location of cutting zone 602 and cutting edge 603.

FIGURE 6B illustrates a graph of the bit face illustrated in the bit face profile of FIGURE 6A. DOCC 612 may be designed according to calculated coordinates of cross-sectional lines 610 that may correspond with cross-sections of DOCC 612. For example, the axial, radial and angular coordinates of a back edge 616 of DOCC 612 may be
10 determined and designed according to determined axial, radial and angular coordinates of cross-sectional line 610a. In the present disclosure, the term "back edge" may refer to the edge of a component that is the trailing edge of the component as a drill bit associated with the drill bit rotates. The term "front edge" may refer to the edge of a component that is the leading edge of the component as the drill bit associated with the component
15 rotates. The axial, radial and angular coordinates of cross-sectional line 610a may be determined according to cutting edge 603 associated with cutting zone 602 of cutting element 600, as described below.

As mentioned above, cutting edge 603 may be divided into cutlets 606a-606e that may have various radial coordinates defining a radial swath of cutting zone 602. A
20 location of cross-sectional line 610a in the xy plane may be selected such that cross-sectional line 610a is associated with a blade 604 where DOCC 612 may be disposed. The location of cross-sectional line 610a may also be selected such that cross-sectional line 610a intersects the radial swath of cutting edge 603. Cross-sectional line 610a may be divided into control points 608a-608e having substantially the same radial coordinates as
25 cutlets 606a-606e, respectively. Therefore, in the illustrated embodiment, the radial swaths of cutlets 606a-606e and control points 608a-608e, respectively, may be substantially the same. With the radial swaths of cutlets 606a-606e and control points 608a-608e being substantially the same, the axial coordinates of control points 608a-608e at back edge 616 of DOCC 612 may be determined for cross-sectional line 610a to better
30 obtain a desired depth of cut control of cutting edge 603 at cutlets 606a-606e, respectively. Accordingly, in some embodiments, the axial, radial and angular coordinates of DOCC 612 at back edge 616 may be designed based on calculated axial, radial and

angular coordinates of cross-sectional line 610a such that DOCC 612 may better control the depth of cut of cutting element 600 at cutting edge 603.

The axial coordinates of each control point 608 of cross-sectional line 610a may be determined based on a desired axial underexposure δ_{607i} between each control point
 5 608 and its respective cutlet 606. The desired axial underexposure δ_{607i} may be based on the angular coordinates of a control point 608 and its respective cutlet 606 and the desired depth of cut Δ of cutting element 600. For example, the desired axial underexposure δ_{607a} of control point 608a with respect to cutlet 606a (depicted in FIGURE 6A) may be based on the angular coordinate (θ_{608a}) of control point 608a, the angular coordinate (θ_{606a}) of
 10 cutlet 606a and the desired depth of cut Δ of cutting element 600. The desired axial underexposure δ_{607a} of control point 608a may be expressed by the following equation:

$$\delta_{607a} = \Delta * (360 - (\theta_{608a} - \theta_{606a})) / 360$$

In this equation, the desired depth of cut Δ may be expressed as a function of rate of penetration (ROP, ft/hr) and bit rotational speed (RPM) by the following equation:

$$\Delta = \text{ROP} / (5 * \text{RPM})$$

The desired depth of cut Δ may have a unit of inches per bit revolution. The desired axial underexposures of control points 608b-608e (δ_{607b} - δ_{607e} , respectively) may be similarly determined. In the above equation, θ_{606a} and θ_{608a} may be expressed in degrees, and “360” may represent one full revolution of approximately 360 degrees.
 20 Accordingly, in instances where θ_{606a} and θ_{608a} may be expressed in radians, “360” may be replaced by “ 2π .” Further, in the above equation, the resultant angle of “($\theta_{608a} - \theta_{606a}$)” (Δ_θ) may be defined as always being positive. Therefore, if resultant angle Δ_θ is negative, then Δ_θ may be made positive by adding 360 degrees (or 2π radians) to Δ_θ .

Additionally, the desired depth of cut (Δ) may be based on the desired ROP for a
 25 given RPM of the drill bit, such that DOCC 612 may be designed to be in contact with the formation at the desired ROP and RPM, and, thus, control the depth of cut of cutting element 600 at the desired ROP and RPM. The desired depth of cut Δ may also be based on the location of cutting element 600 along blade 604. For example, in some embodiments, the desired depth of cut Δ may be different for the cone portion, the nose
 30 portion, the shoulder portion the gage portion, or any combination thereof, of the bit profile portions. In the same or alternative embodiments, the desired depth of cut Δ may also vary for subsets of one or more of the mentioned zones along blade 604.

In some instances, cutting elements within the cone portion of a drill bit may wear much less than cutting elements within the nose and gauge portions. Therefore, the desired depth of cut Δ for a cone portion may be less than that for the nose and gauge portions. Thus, in some embodiments, when the cutting elements within the nose and/or gauge portions wear to some level, then a DOCC 612 located in the nose and/or gauge portions may begin to control the depth of cut of the drill bit.

Once the desired underexposure δ_{607i} of each control point 608 is determined, the axial coordinate (Z_{608i}) of each control point 608 as illustrated in FIGURE 6A may be determined based on the desired underexposure δ_i of the control point 608 with respect to the axial coordinate (Z_{606i}) of its corresponding outlet 606. For example, the axial coordinate of control point 608a (Z_{608a}) may be determined based on the desired underexposure of control point 608a (δ_{607a}) with respect to the axial coordinate of outlet 606 (Z_{606a}), which may be expressed by the following equation:

$$Z_{608a} = Z_{606a} - \delta_{607a}$$

Once the axial, radial and angular coordinates for control points 608 are determined for cross-sectional line 610a, back edge 616 of DOCC 612 may be designed according to these points such that back edge 616 has approximately the same axial, radial and angular coordinates of cross-sectional line 610a. In some embodiments, the axial coordinates of control points 608 of cross-sectional line 610a may be smoothed by curve fitting technologies. For example, if an MDR is designed based on the calculated coordinates of control points 608, then the axial coordinates of control points 608 may be fit by one or more circular lines. Each of the circular lines may have a center and a radius that may be used to design the MDR. The surface of DOCC 612 at intermediate cross-sections 618 and 620 and at front edge 622 may be similarly designed based on determining radial, angular, and axial coordinates of cross-sectional lines 610b, 610c, and 610d, respectively.

Accordingly, the surface of DOCC 612 may be configured at least partially based on the locations of cutting zone 602 and cutting edge 603 of cutting element 600 to improve the depth of cut control of cutting element 600. Additionally, the height and width of DOCC 612 and its placement in the radial plane of the drill bit may be configured based on cross-sectional lines 610, as described in further detail with respect to FIGURE 6C. Therefore, the axial, radial and angular coordinates of DOCC 612 may be such that the desired depth of cut control of cutting element 600 is improved. As shown in

FIGURES 6A and 6B, configuring DOCC 612 based on the locations of cutting zone 602 and cutting edge 603 may cause DOCC 612 to be radially aligned with the radial swath of cutting zone 602 but may also cause DOCC 612 to be radially offset from the center of cutting element 600, which may differ from traditional DOCC placement methods.

5 FIGURE 6C illustrates DOCC 612 designed according to the present disclosure. DOCC 612 may include a surface 614 with back edge 616, a first intermediate cross-section 618, a second intermediate cross-section 620 and a front edge 622. As discussed with respect to FIGURE 6B, back edge 616 may correspond with cross-sectional line 610a. Additionally, first intermediate cross-section 618 may correspond with cross-sectional line 610b, second intermediate cross-section 620 may correspond with cross-sectional line 610c and front edge 622 may correspond with cross-sectional line 610d.

As mentioned above, the curvature of surface 614 may be designed according to the axial curvature made by the determined axial coordinates of cross-sectional lines 610. Accordingly, the curvature of surface 614 along back edge 616 may have a curvature that approximates the axial curvature of cross-sectional line 610a; the curvature of surface 614 along first intermediate cross-section 618 may approximate the axial curvature of cross-sectional line 610b; the curvature of surface 614 along second intermediate cross-section 620 may approximate the axial curvature of cross-sectional line 610c; and the curvature of surface 614 along front edge 622 may approximate the axial curvature of cross-sectional line 610d. In the illustrated embodiment and as depicted in FIGURES 6A and 6C, the axial curvature of cross-sectional line 610a may be approximated by the curvature of a circle with a radius "R," such that the axial curvature of back edge 616 may be substantially the same as the circle with radius "R."

The axial curvature of cross-sectional lines 610a-610d may or may not be the same, and accordingly the curvature of surface 614 along back edge 616, intermediate cross-sections 618 and 620, and front edge 622 may or may not be the same. In some instances where the curvature is not the same, the approximated curvatures of surface 614 along back edge 616, intermediate cross-sections 618 and 620, and front edge 622 may be averaged such that the overall curvature of surface 614 is the calculated average curvature. Therefore, the determined curvature of surface 614 may be substantially constant to facilitate manufacturing of surface 614. Additionally, although shown as being substantially fit by the curvature of a single circle, it is understood that the axial

curvature of one or more cross-sectional lines 610 may be fit by a plurality of circles, depending on the shape of the axial curvature.

DOCC 612 may have a width W that may be large enough to cover the width of cutting zone 602 and may correspond to the length of a cross-sectional line 610. Additionally, the height H of DOCC 612, as shown in FIGURE 6C, may be configured such that when DOCC 612 is placed on blade 604, the axial positions of surface 614 sufficiently correspond with the calculated axial positions of the cross-sectional lines used to design surface 614. The height H may correspond with the peak point of the curvature of surface 614 that corresponds with a cross-sectional line. For example, the height H of DOCC 612 at back edge 616 may correspond with the peak point of the curvature of DOCC 612 at back edge 616. Additionally, the height H at back edge 616 may be configured such that when DOCC 612 is placed at the calculated radial and angular positions on blade 604 (as shown in FIGURE 6B), surface 614 along back edge 616 may have approximately the same axial, angular and radial positions as control points 608a-608e calculated for cross-sectional line 610a.

In some embodiments where the curvature of surface 614 varies according to different curvatures of the cross-sectional lines, the height H of DOCC 612 may vary according to the curvatures associated with the different cross-sectional lines. For example, the height with respect to back edge 616 may be different than the height with respect to front edge 622. In other embodiments where the curvature of the cross-sectional lines is averaged to calculate the curvature of surface 614, the height H of DOCC 612 may correspond with the peak point of the curvature of the entire surface 614.

In some embodiments, the surface of DOCC 612 may be designed using the three dimensional coordinates of the control points of all the cross-sectional lines. The axial coordinates may be smoothed using a two dimensional interpolation method such as a MATLAB[®] function called interp2.

Modifications, additions or omissions may be made to FIGURES 6A-6C without departing from the scope of the present disclosure. Although a specific number of cross-sectional lines, points along the cross-sectional lines and cutlets are described, it is understood that any appropriate number may be used to configure DOCC 612 to acquire the desired depth of cut control. In one embodiment, the number of cross-sectional lines may be determined by the size and the shape of a DOCC. For example, if a hemispherical component is used as a DOCC, (e.g., an MDR) then only one cross sectional

line may be needed. If an impact arrestor (semi-cylinder like) is used, then more cross-sectional lines (e.g., at least two) may be used. Additionally, although the curvature of the surface of DOCC 612 is depicted as being substantially round and uniform, it is understood that the surface may have any suitable shape that may or may not be uniform, depending on the calculated surface curvature for the desired depth of cut. Further, although the above description relates to a DOCC designed according to the cutting zone of one cutting element, a DOCC may be designed according to the cutting zones of a plurality of cutting elements to control the depth of cut of more than one cutting element, as described in further detail below.

10 FIGURE 7 illustrates a flow chart of an example method 700 for designing one or more DOCCs (e.g., DOCC 612 of FIGURES 6A-6C) according to the location of the cutting zone and its associated cutting edge of a cutting element. In the illustrated embodiment the cutting structures of the bit including at least the locations and orientations of all cutting elements may have been previously designed. However in other
15 embodiments, method 700 may include steps for designing the cutting structure of the drill bit.

 The steps of method 700 may be performed by various computer programs, models or any combination thereof, configured to simulate and design drilling systems, apparatuses and devices. The programs and models may include instructions stored on a
20 computer readable medium and operable to perform, when executed, one or more of the steps described below. The computer readable media may include any system, apparatus or device configured to store and retrieve programs or instructions such as a hard disk drive, a compact disc, flash memory or any other suitable device. The programs and models may be configured to direct a processor or other suitable unit to retrieve and
25 execute the instructions from the computer readable media. Collectively, the computer programs and models used to simulate and design drilling systems may be referred to as a “drilling engineering tool” or “engineering tool.”

 Method 700 may start and, at step 702, the engineering tool may determine a desired depth of cut (“ Δ ”) at a selected zone along a bit profile. As mentioned above, the
30 desired depth of cut Δ may be based on the desired ROP for a given RPM, such that the DOCCs within the bit profile zone (e.g., cone zone, shoulder zone, etc.) may be designed

to be in contact with the formation at the desired ROP and RPM, and, thus, control the depth of cut of cutting elements in the cutting zone at the desired ROP and RPM.

At step 704, the locations and orientations of cutting elements within the selected zone may be determined. At step 706, the engineering tool may create a 3D cutter/rock
5 interaction model that may determine the cutting zone for each cutting element in the design based at least in part on the expected depth of cut Δ for each cutting element. As noted above, the cutting zone and cutting edge for each cutting element may be based on the axial and radial coordinates of the cutting element.

At step 708, using the engineering tool, the cutting edge within the cutting zone of
10 each of the cutting elements may be divided into cutting points (“cutlets”) of the bit face profile. For illustrative purposes, the remaining steps are described with respect to designing a DOCC with respect to one of the cutting elements, but it is understood that the steps may be followed for each DOCC of a drill bit, either at the same time or sequentially.

At step 710, the axial and radial coordinates for each cutlet along the cutting edge
15 of a selected cutting element associated with the DOCC may be calculated with respect to the bit face (e.g., the axial and radial coordinates of cutlets 606 of FIGURES 6A and 6B may be determined). Additionally, at step 712, the angular coordinate of each cutlet may be calculated in the radial plane of the bit face.

At step 714, the locations of a number of cross-sectional lines in the radial plane
20 corresponding to the placement and design of a DOCC associated with the cutting element may be determined (e.g., cross-sectional lines 610 associated with DOCC 612 of FIGURES 6A-6C). The cross-sectional lines may be placed within the radial swath of the cutting zone of the cutting element such that they intersect the radial swath of the cutting zone, and, thus have a radial swath that substantially covers the radial swath of the cutting zone. In some embodiments, the length of the cross-sectional lines may be based on the width of the cutting zone and cutting edge such that the radial swath of the cutting zone and cutting edge is substantially intersected by the cross-sectional lines. Therefore, as
25 described above, the cross-sectional lines may be used to model the shape, size and configuration of the DOCC such that the DOCC controls the depth of cut of the cutting
30 element at the cutting edge of the cutting element.

Further, the number of cross-sectional lines may be determined based on the desired size of the DOCC to be designed as well as the desired precision in designing the

DOCC. For example, the larger the DOCC, the more cross-sectional lines may be used to adequately design the DOCC within the radial swath of the cutting zone and thus provide a more consistent depth of cut control for the cutting zone.

At step 716, the locations of the cross-sectional lines disposed on a blade may be
5 determined (e.g., the locations of cross-sectional lines 610 in FIGURE 6B) such that the radial coordinates of the cross-sectional lines substantially intersect the radial swath of the cutting zone of the cutting element. At step 717, each cross-sectional line may be divided into points with radial coordinates that substantially correspond with the radial
10 coordinates of the cutlets determined in step 708 (e.g., cross-sectional line 610a divided into points 608 of FIGURES 6A-6C). At step 718, the engineering tool may be used to determine the angular coordinate for each point of each cross-sectional line in a plane substantially perpendicular to the bit rotational axis (e.g., the xy plane of FIGURES 6A-6C). At step 720, the axial coordinate for each point on each cross-sectional line may also be determined by determining a desired axial underexposure between the cutlets of the
15 cutting element and each respective point of the cross-sectional lines corresponding with the cutlets, as described above with respect to FIGURES 6A-6C. After determining the axial underexposure for each point of each cross-sectional line, the axial coordinate for each point may be determined by applying the underexposure of each point to the axial coordinate of the cutlet associated with the point, also as described above with respect to
20 FIGURES 6A-6C.

After calculating the axial coordinate of each point of each cross-sectional line based on the cutlets of a cutting zone of an associated cutting element, (e.g., the axial coordinates of points 608a-608e of cross-sectional line 610a based on cutlets 606a-606e of FIGURES 6A-6C) at step 720, method 700 may proceed to steps 724 and 726 where a
25 DOCC may be designed according to the axial, angular, and radial coordinates of the cross-sectional lines.

In some embodiments, at step 724, for each cross-sectional line, the curve created by the axial coordinates of the points of the cross-sectional line may be fit to a portion of a circle. Accordingly, the axial curvature of each cross-sectional line may be
30 approximated by the curvature of a circle. Thus, the curvature of each circle associated with each cross-sectional line may be used to design the three-dimensional surface of the DOCC to approximate a curvature for the DOCC that may improve the depth of cut control. In some embodiments, the surface of the DOCC may be approximated by

smoothing the axial coordinates of the surface using a two dimensional interpolation method, such as a MATLAB[®] function called interp2.

In step 726, the width of the DOCC may also be configured. In some embodiments, the width of the DOCC may be configured to be as wide as the radial
5 swath of the cutting zone of a corresponding cutting element. Thus, the cutting zone of the cutting element may be located within the rotational path of the DOCC such that the DOCC may provide the appropriate depth of cut control for the cutting element. Further, at step 726, the height of the DOCC may be designed such that the surface of the DOCC is approximately at the same axial position as the calculated axial coordinates of the
10 points of the cross-sectional lines. Therefore, the engineering tool may be used to design a DOCC according to the location of the cutting zone and cutting edge of a cutting element.

After determining the location, orientation and dimensions of a DOCC at step 726, method 700 may proceed to step 728. At step 728, it may be determined if all the DOCCs have been designed. If all of the DOCCs have not been designed, method 700 may repeat
15 steps 708-726 to design another DOCC based on the cutting zones of one or more other cutting elements.

At step 730, once all of the DOCCs are designed, a critical depth of cut control curve (CDCCC) may be calculated using the engineering tool. The CDCCC may be used to determine how even the depth of cut is throughout the desired zone. At step 732, using
20 the engineering tool, it may be determined whether the CDCCC indicates that the depth of cut control meets design requirements. If the depth of cut control meets design requirements, method 700 may end. Calculation of the CDCCC is described in further detail with respect to FIGURES 20A-20C and FIGURE 21.

If the depth of cut control does not meet design requirements, method 700 may
25 return to step 714, where the design parameters may be changed. For example, the number of cross-sectional lines may be increased to better design the surface of the DOCC according to the location of the cutting zone and cutting edge. Further, the angular coordinates of the cross-sectional line may be changed. In other embodiments, if the depth of cut control does not meet design requirements, method 700 may return to step
30 708 to determine a larger number of cutlets for dividing the cutting edge, and thus better approximate the cutting edge. Additionally, as described further below, the DOCC may be designed according to the locations of the cutting zones and cutting edges of more than one cutting element that may be within the radial swath of the DOCC.

Additionally, method 700 may be repeated for configuring one or more DOCCs to control the depth of cut of cutting elements located within another zone along the bit profile by inputting another expected depth of cut, Δ , at step 702. Therefore, one or more DOCCs may be configured for the drill bit within one or more zones along the bit profile of a drill bit according to the locations of the cutting edges of the cutting elements to improve the depth of cut control of the drill bit.

Modifications, additions or omissions may be made to method 700 without departing from the scope of the disclosure. For example, the order of the steps may be changed. Additionally, in some instances, each step may be performed with respect to an individual DOCC and cutting element until that DOCC is designed for the cutting element and then the steps may be repeated for other DOCCs or cutting elements. In other instances, each step may be performed with respect to each DOCC and cutting element before moving onto the next step. Similarly, steps 716 through 724 may be done for one cross-sectional line and then repeated for another cross-sectional line, or steps 716 through 724 may be performed for each cross-sectional line at the same time, or any combination thereof. Further, the steps of method 700 may be executed simultaneously, or broken into more steps than those described. Additionally, more steps may be added or steps may be removed without departing from the scope of the disclosure.

Once one or more DOCCs are designed using method 700, a drill bit may be manufactured according to the calculated design constraints to provide a more constant and even depth of cut control of the drill bit. The constant depth of cut control may be based on the placement, dimensions and orientation of DOCCs, such as impact arrestors, in both the radial and axial positions with respect to the cutting zones and cutting edges of the cutting elements. In the same or alternative embodiments, the depth of cut of a cutting element may be controlled by a blade.

FIGURE 8A illustrates a graph of the bit face profile of a cutting element with a depth of cut that may be controlled by a blade 804. FIGURE 8A illustrates the axial and radial coordinates of cutting element 800 and blade 804 configured to control the depth of cut of cutting element 800 based on the location of a cutting zone 802 (and its associated cutting edge 803) of cutting element 800. Similar to FIGURE 6A, the axial coordinates of points in FIGURE 8A may correspond to the vertical z-axis and the radial coordinates of points in FIGURE 8A may correspond to the horizontal axis and may be expressed as an orthogonal distance R from the center of the drill bit. Additionally, the radial and angular

coordinates may correspond to a location in an xy plane such that the radial and angular coordinates may be determined using corresponding x and y coordinates as described above. Cutting edge 803 may be divided into cutlets 806a-806e, having axial and radial coordinates as shown in FIGURE 8A, similar to cutting edge 603 divided into cutlets
5 606a-606e in FIGURES 6A and 6B.

Additionally, the cross-sectional view of blade 804 shown in FIGURE 8A may be at a trailing edge 816 of blade 804. Blade points 808a-808e on trailing edge 816 having substantially the same radial coordinates as cutlets 806a-806e (e.g., blade point 808a may have the same radial coordinate as cutlet 806a, blade point 808b may have the same radial
10 coordinate as cutlet 806b, etc.) may be selected to configure blade 804 to control the depth of cut of cutting element 800.

FIGURE 8B illustrates a graph of the bit face illustrated in the bit face profile of FIGURE 8A. Similar to FIGURE 6B, the graph of FIGURE 8B may be based on an xy plane represented by x and y axes. The center of the drill bit in the xy plane may
15 correspond to the intersection of the x and y axes and the rotational axis of the drill bit. Cutlets 806a-806e in the xy plane may be expressed in terms of x and y coordinates that may be used to determine the angular and radial coordinates of cutlets 806a-806e. FIGURE 8B illustrates the angular coordinate of cutlet 806b (θ_{806b}) in the xy plane based on the location of cutlet 806b in the xy plane. FIGURE 8B also illustrates the locations of
20 blade points 808a-808e in the xy plane that have the same radial coordinates as their corresponding cutlets 806. Additionally, as shown in FIGURE 8B, blade points 808a-808e may have angular coordinates that, along with the radial coordinates, may indicate the locations of blade points 808a-808e in the xy plane. Specifically, in FIGURE 8B, the angular and radial coordinates of blade point 808b (θ_{808b} and R_b , respectively) are shown.
25 As with the angular coordinate of cutlet 806b (θ_{806b}), the angular coordinate of blade point 808b may be determined with respect to the depicted x-axis. However, the angular coordinates may be determined with respect to another frame of reference without departing from the scope of the present disclosure.

The desired axial coordinates of each blade point 808 may be determined based on
30 a desired underexposure (δ_{807i}) of the blade point 808 with respect to its associated cutlet 806. The desired underexposure δ_{807i} of a blade point 808 may be determined based on a desired depth of cut Δ in the corresponding blade zone and the angular coordinates of the

blade point 808 and its respective cutlet 806, similar to as described above with respect to the desired underexposure δ_{607i} of points 608 described above with respect to FIGURES 6A-6C. For example, in FIGURE 8A, the axial coordinate of blade point 808b may be calculated such that the difference between the axial position of cutlet 806b and blade point 808b is underexposure δ_{807b} . The axial coordinates of the remaining blade points 806 may be determined in a similar manner.

The surface of blade 804 may be configured such that the axial coordinates of the surface of blade 804 are substantially similar to the calculated axial coordinates of blade points 806. Accordingly, the surface of blade 804 at the trailing edge 816 may be configured according to cutting zone 802 of cutting element 800. The surface of blade 804 at leading edge 822 and at any other intermediate cross sections between trailing edge 816 and leading edge 822 may be similarly designed. In some embodiments, the three-dimensional surface of blade 804 may be configured based on the calculated axial, radial, and angular coordinates of blade points 806 using methods described above with respect to DOCC 612 in FIGURE 6C. For example, the surface of blade 804 may be designed using curve fitting technologies applied to the determined axial coordinates of blade points 806.

FIGURE 9 illustrates a flow chart of an example method 900 for designing blade surfaces according to the cutting zones of one or more cutting elements. In the illustrated embodiment the cutting structures of the bit including at least the locations and orientations of all cutting elements may have been previously designed. However in other embodiments, method 900 may include steps for designing the cutting structure of the drill bit. Similar to method 700, method 900 may be performed by any suitable engineering tool as described above.

Method 900 may start, and at step 902, the engineering tool may determine a desired critical depth of cut control, Δ , at a selected zone along a bit profile in a substantially similar manner as described with respect to step 702 of method 700. At step 904, the locations and orientations of cutting elements within the selected zone may be determined in a substantially similar manner as described with respect to step 704 of method 700. Additionally, step 906 may be substantially similar to step 706 of method 700 where the engineering tool may create a 3D cutter/rock interaction model that may determine the cutting zone and cutting edge associated with each cutting element. At step

908, an initial 3D depiction of the front and trailing edges of the blades and blade surfaces may also be designed using the engineering tool.

At step 910, one of the blades that may control the depth of cut of a cutting element may be selected, and at step 912, the angular and radial coordinates of the trailing edge of the blade may be determined using the engineering tool. At step 914, using the
5 engineering tool, a cutting element with a depth of cut that may be controlled by the trailing edge of the blade may be determined and selected.

At step 916, using the engineering tool, the cutting edge of the cutting element that may be controlled by the trailing edge of the blade may be divided into cutlets in a
10 similar manner as described with respect to step 708 of method 700. At step 918, the axial and radial coordinates for each cutlet may be calculated with respect to the bit face profile. At step 920, the angular coordinate in a plane substantially perpendicular to the rotational axis of the drill bit (e.g., the xy plane of FIGURE 8B) may be calculated.

At step 922, blade points on the trailing edge of the blade having the same radial
15 coordinates as the cutlets may be determined and selected. At step 926, the angular coordinate of each blade point may be determined.

At step 928, the axial underexposure for each blade point such that the blade may provide a constant depth of cut control for the cutting element may be determined. The axial underexposure may be based on the angular coordinate of the blade point and the
20 angular coordinate of the cutlet having the same radial coordinate as the blade point. The axial underexposure may be calculated in a manner substantially similar to the calculation of the axial underexposure described above with respect to FIGURES 6-8.

At step 930, axial coordinates of each blade point may be calculated based on the axial coordinate of each respective cutlet having the same radial coordinate as each
25 respective blade point and based on the calculated axial underexposure of each blade point. In some instances, the curvature of the surface of the blade may be configured to approximate the axial curvature of the cross-sectional line. Therefore, the trailing edge of the blade may be designed to control the depth of cut of a cutting element according to the location of the cutting zone and cutting edge of the cutting element. In some
30 instances, steps 916 through 930 may be repeated for the leading edge of the blade or any other cross-sectional areas of the blade that are associated with the radial swath of the cutting zone of the cutting element such that the surface of the blade within the radial path of the cutting zone may be configured according to the location of the cutting zone of the

cutting element. For example, the surface of blade 804 at leading edge 822 may be configured in a similar manner as trailing edge 816, as described above.

At step 932, it may be determined if there is another cutting element with a depth of cut that may be controlled by the selected blade. If there is another cutting element that may be controlled by the blade, the portion of the surface of the blade corresponding with the cutting zone of the other cutting element may be configured according to steps 916-930. If it is determined that the blade does not control the depth of cut of any more cutting elements, method 900 may proceed from step 932 to step 934.

At step 934, it may be determined if the surfaces of all of the blades have been configured to provide a depth of cut control for cutting elements with depths of cut that may be affected by the blades, if all of the blades have not been configured, method 900 may repeat steps 912-932 with respect to a blade that has not been configured. If all of the blades have been configured, method 900 may proceed to step 936.

At step 936, a critical depth of cut control curve for the blades (CDCCC) may be calculated. At step 938, it may be determined whether or not the CDCCC indicates that the depth of cut control substantially meets design requirements and specifications. The calculation of the CDCCC is described further below with respect to FIGURES 20A-20C and FIGURE 21. If the CDCCC indicates that the depth of cut control does not meet the design requirements, method 900 may return to step 908, where various changes may be made to the design of the blade surface. If the depth of cut control does meet design requirements, method 900 may end.

Additionally, method 900 may be repeated for configuring one or more blade surfaces to control the depth of cut of cutting elements located within another zone along the bit profile by inputting another expected depth of cut, Δ , at step 902. Therefore, one or more blade surfaces may be configured for the drill bit within one or more zones along the bit profile of a drill bit according to the locations of the cutting edges of the cutting elements to improve the depth of cut control of the drill bit.

Modifications, additions or omissions may be made to method 900 and FIGURES 8A and 8B without departing from the scope of the present disclosure. For example, the order of the steps of method 900 may be changed. Additionally, each step may be performed with respect to each blade or each edge of a blade before moving on to the next step, every step may be performed with respect to one blade or edge of one blade and then repeated, or any combination thereof. Further, the steps of method 900 may be

executed simultaneously, or broken into more steps than those described. Additionally, more steps may be added or steps may be removed without departing from the scope of the disclosure.

As mentioned above, methods 700 and 900 (and the associated FIGURES 6-9) are described with respect to an instance where the cutting zone of a cutting element may not overlap with the cutting zone of another cutting element. As previously described, such an instance may occur when the number of blades is small, the number of cutters is small and the depth of cut is also small. Such an instance may also occur with respect to cutting elements within the cone zone of fixed cutter bits because the number of blades within the cone is usually small. Further, methods 700 and 900 (and the associated FIGURES 6-9) may be used when a DOCC (or blade surface configured to control the depth of cut) is located immediately behind a cutting element and the radial length of the DOCC (or blade surface configured to control the depth of cut of the cutting element) is fully within the cutting zone of the cutting element.

However, in other instances, the radial swath associated with a DOCC or blade may intersect a plurality of cutting zones associated with a plurality of cutting elements. Therefore, the DOCC and/or the blade may affect the depth of cut of more than one cutting element, and not merely a single cutting element that may be located closest to the DOCC or portion of the blade configured to act as a DOCC. Therefore, in some embodiments of the present disclosure, a DOCC and/or blade of a drill bit may be configured to control the depth of cut of a drill bit based on the cutting zones of a plurality of cutting elements.

FIGURES 10A-10C illustrate a DOCC 1002 configured to control the depth of cut of cutting elements 1028 and 1029 located within a swath 1008 of drill bit 1001. FIGURE 10A illustrates the face of drill bit 1001 that may include blades 1026, outer cutting elements 1028 and inner cutting elements 1029 disposed on blades 1026. In the illustrated embodiment, DOCC 1002 is located on a blade 1026a and configured to control the depth of cut of all cutting elements 1028 and 1029 located within swath 1008 of drill bit 1001.

A desired critical depth of cut Δ_1 per revolution (shown in FIGURE 10D) may be determined for the cutting elements 1028 and 1029 within radial swath 1008 of drill bit 1001. Radial swath 1008 may be located between a first radial coordinate R_A and a second radial coordinate R_B . R_A and R_B may be determined based on the available sizes that may be used for DOCC 1002. For example, if an MDR is used as DOCC 1002, then

the width of radial swath 1008 (e.g., $R_B - R_A$) may be equal to the diameter of the MDR. As another example, if an impact arrestor is selected as DOCC 1002, then the width of radial swath 1008 may be equal to the width of the impact arrestor. R_A and R_B may also be determined based on the dull conditions of previous bit runs. In some instances radial
5 swath 1008 may substantially include the entire bit face such that R_A is approximately equal to zero and R_B is approximately equal to the radius of drill bit 1008.

Once radial swath 1008 is determined, the angular location of DOCC 1002 within radial swath 1008 may be determined. In the illustrated embodiment where only one DOCC 1002 is depicted, DOCC 1002 may be placed on any blade (e.g., blade 1026a)
10 based on the available space on that blade for placing DOCC 1002. In alternative embodiments, if more than one DOCC is used to provide a depth of cut control for cutting elements 1028 and 1029 located within swath 1008 (e.g., all cutting elements 1028 and 1029 located within the swath 1008), the angular coordinates of the DOCCs may be determined based on a “rotationally symmetric rule” in order to reduce frictional
15 imbalance forces. For example, if two DOCCs are used, then one DOCC may be placed on blade 1026a and another DOCC may be placed on blade 1026d. If three DOCCs are used, then a first DOCC may be placed on blade 1026a, a second DOCC may be placed on blade 1026c and a third DOCC may be placed on blade 1026e. The determination of angular locations of DOCCs is described below with respect to various embodiments.

20 Returning to FIGURE 10A, once the radial and the angular locations of DOCC 1002 are determined, the x and y coordinates of any point on DOCC 1002 may also be determined. For example, the surface of DOCC 1002 in the xy plane of FIGURE 10A may be meshed into small grids. The surface of DOCC 1002 in the xy plane of FIGURE 10A may also be represented by several cross sectional lines. For simplicity, each cross
25 sectional line may be selected to pass through the bit axis or the origin of the coordinate system. Each cross sectional line may be further divided into several points. With the location on blade 1026a for DOCC 1002 selected, the x and y coordinates of any point on any cross sectional line associated with DOCC 1002 may be easily determined and the next step may be to calculate the axial coordinates, z, of any point on a cross sectional
30 line.

In the illustrated embodiment, DOCC 1002 may be placed on blade 1026a and configured to have a width that corresponds to radial swath 1008. Additionally, a cross sectional line 1010 associated with DOCC 1002 may be selected, and in the illustrated

embodiment may be represented by a line "AB." In some embodiments, cross-sectional line 1010 may be selected such that all points along cross-sectional line 1010 have the same angular coordinates. The inner end "A" of cross-sectional line 1010 may have a distance from the center of bit 1001 in the xy plane indicated by radial coordinate R_A and the outer end "B" of cross-sectional line 1010 may have a distance from the center of drill bit 1001 indicated by radial coordinate R_B , such that the radial position of cross-sectional line 1010 may be defined by R_A and R_B . Cross-sectional line 1010 may be divided into a series of points between inner end "A" and outer end "B" and the axial coordinates of each point may be determined based on the radial intersection of each point with one or more cutting edges of cutting elements 1028 and 1029, as described in detail below. In the illustrated embodiment, the determination of the axial coordinate of a control point "f" along cross-sectional line 1010 is described. However, it is understood that the same procedure may be applied to determine the axial coordinates of other points along cross-sectional line 1010 and also to determine the axial coordinates of other points of other cross-sectional lines that may be associated with DOCC 1002.

The axial coordinate of control point "f" may be determined based on the radial and angular coordinates of control point "f" in the xy plane. For example, the radial coordinate of control point "f" may be the distance of control point "f" from the center of drill bit 1001 as indicated by radial coordinate R_f . Once R_f is determined, intersection points 1030 associated with the cutting edges of one or more cutting elements 1028 and/or 1029 having radial coordinate R_f may be determined. Accordingly, intersection points 1030 of the cutting elements may have the same rotational path as control point "f" and, thus, may have a depth of cut that may be affected by control point "f" of DOCC 1002. In the illustrated embodiment, the rotational path of control point "f" may intersect the cutting edge of cutting element 1028a at intersection point 1030a, the cutting edge of cutting element 1028b at intersection point 1030b, the cutting edge of cutting element 1029e at intersection point 1030e and the cutting edge of cutting element 1028f at intersection point 1030f.

The axial coordinate of control point "f" may be determined according to a desired underexposure (δ_{1007i}) of control point "f" with respect to each intersection point 1030. FIGURE 10B depicts the desired underexposure δ_{1007i} of control point "f" with respect to each intersection point 1030. The desired underexposure δ_{1007i} of control point "f" with respect to each intersection point 1030 may be determined based on the desired

critical depth of cut Δ_1 and the angular coordinates of control point “f” (θ_f) and each point 1030 (θ_{1030i}). For example, the desired underexposure of control point “f” with respect to intersection point 1030a may be expressed by the following equation:

$$\delta_{1007a} = \Delta_1 * (360 - (\theta_f - \theta_{1030a})) / 360$$

5 In the above equation, θ_f and θ_{1030a} may be expressed in degrees, and “360” may represent one full revolution of approximately 360 degrees. Accordingly, in instances where θ_f and θ_{1030a} may be expressed in radians, “360” may be replaced by “ 2π .” Further, in the above equation, the resultant angle of “($\theta_f - \theta_{1030a}$)” (Δ_θ) may be defined as always being positive. Therefore, if resultant angle Δ_θ is negative, then Δ_θ may be made positive
10 by adding 360 degrees (or 2π radians) to Δ_θ . The desired underexposure of control point “f” with respect to points 1030b, 1030e and 1030f, (δ_{1007b} , δ_{1007e} , δ_{1007f} , respectively) may be similarly determined.

Once the desired underexposure of control point “f” with respect to each intersection point is determined (δ_{1007i}), the axial coordinate of control point “f” may be
15 determined. The axial coordinate of control point “f” may be determined based on the difference between the axial coordinates of each intersection point 1030 and the desired underexposure with respect to each intersection point 1030. For example, in FIGURE 10B, the axial location of each point 1030 may correspond to a coordinate on the z-axis, and may be expressed as a z-coordinate (Z_{1030i}). To determine the corresponding
20 z-coordinate of control point “f” (Z_f), a difference between the z-coordinate Z_{1030i} and the corresponding desired underexposure δ_{1007i} for each intersection point 1030 may be determined. The maximum value of the differences between Z_{1030i} and δ_{1007i} may be the axial or z-coordinate of control point “f” (Z_f). For the current example, Z_f may be expressed by the following equation:

$$25 \quad Z_f = \max [(Z_{1030a} - \delta_{1007a}), (Z_{1030b} - \delta_{1007b}), (Z_{1030e} - \delta_{1007e}), (Z_{1030f} - \delta_{1007f})]$$

Accordingly, the axial coordinate of control point “f” may be determined based on the cutting edges of cutting elements 1028a, 1028b, 1029e and 1028f. The axial coordinates of other points (not expressly shown) along cross-sectional line 1010 may be similarly determined to determine the axial curvature and coordinates of cross-sectional
30 line 1010. FIGURE 10C illustrates an example of the axial coordinates and curvature of cross-sectional line 1010 such that DOCC 1002 may control the depth of cut of drill bit 1001 to the desired depth of cut Δ_1 within the radial swath defined by R_A and R_B .

The above mentioned process may be repeated to determine the axial coordinates and curvature of other cross-sectional lines associated with DOCC 1002 such that DOCC 1002 may be designed according to the coordinates of the cross-sectional lines. At least one cross sectional line may be used to design a three dimensional surface of DOCC
5 1002. Additionally, in some embodiments, a cross sectional line may be selected such that all the points on the cross sectional line have the same angular coordinate. Accordingly, DOCC 1002 may provide depth of cut control to substantially obtain the desired depth of cut Δ_1 within the radial swath defined by R_A and R_B .

To more easily manufacture DOCC 1002, in some instances, the axial coordinates
10 of cross-sectional line 1010 and any other cross-sectional lines may be smoothed by curve fitting technologies. For example, if DOCC 1002 is designed as an MDR based on calculated cross sectional line 1010, then cross sectional line 1010 may be fit by one or more circular lines. Each of the circular lines may have a center and a radius that are used to design the MDR. As another example, if DOCC 1002 is designed as an impact arrestor,
15 a plurality of cross-sectional lines 1010 may be used. Each of the cross-sectional lines may be fit by one or more circular lines. Two fitted cross-sectional lines may form the two ends of the impact arrestor similar to that shown in FIGURE 6C.

FIGURE 10D illustrates a critical depth of cut control curve (described in further detail below) of drill bit 1001. The critical depth of cut control curve indicates that the
20 critical depth of cut of radial swath 1008 between radial coordinates R_A and R_B may be substantially even and constant. Therefore, FIGURE 10D indicates that the desired depth of cut (Δ_1) of drill bit 1001, as controlled by DOCC 1002, may be substantially constant by taking in account all the cutting elements with depths of cut that may be affected by DOCC 1002 and design DOCC 1002 accordingly.

25 Modifications, additions, or omissions may be made to FIGURES 10A-10D without departing from the scope of the present disclosure. For example, although DOCC 1002 is depicted as having a particular shape, DOCC 1002 may have any appropriate shape. Additionally, it is understood that any number of cross-sectional lines and points along the cross-sectional lines may be selected to determine a desired axial curvature of
30 DOCC 1002. Further, as disclosed below with respect to FIGURES 12-15, although only one DOCC 1002 is depicted on drill bit 1001, drill bit 1001 may include any number of DOCCs configured to control the depth of cut of the cutting elements associated with any

number of radial swaths of drill bit 1001. Further, the desired depth of cut of drill bit 1001 may vary according to the radial coordinate (distance from the center of drill bit 1001 in the radial plane).

FIGURES 11A and 11B illustrate a flow chart of an example method 1100 for
5 designing a DOCC (e.g., DOCC 1002 of FIGURES 10A-10B) according to the cutting zones of one or more cutting elements with depths of cut that may be affected by the DOCC. The steps of method 1100 may be performed by an engineering tool. In the illustrated embodiment the cutting structures of the bit including at least the locations and orientations of all cutting elements may have been previously designed. However in other
10 embodiments, method 1100 may include steps for designing the cutting structure of the drill bit.

Method 1100 may start, and at step 1102, the engineering tool may determine a desired critical depth of cut control (Δ) at a selected zone (e.g., cone zone, nose zone, shoulder zone, gage zone, etc.) along a bit profile. The zone may be associated with a
15 radial swath of the drill bit. At step 1104, the locations and orientations of cutting elements located within the swath may be determined. Additionally, at step 1106 the engineering tool may create a 3D cutter/rock interaction model that may determine the cutting zone and the cutting edge for each cutting element.

At step 1108, the engineering tool may select a cross-sectional line (e.g., cross-
20 sectional line 1010) that may be associated with a DOCC that may be configured to control the depth of cut of a radial swath (e.g., radial swath 1008 of FIGURES 10A-10B) of the drill bit. At step 1110, the location of the cross-sectional line in a plane perpendicular to the rotational axis of the drill bit (e.g., the xy plane of FIGURE 10) may be determined. The location of the cross-sectional line may be selected such that the
25 cross-sectional line intersects the radial swath and is located on a blade (e.g., cross-sectional line 1010 intersects radial swath 1008 and is located on blade 1026a in FIGURE 10A).

At step 1111, a control point “f” along the cross-sectional line may be selected. Control point “f” may be any point that is located along the cross-sectional line and that
30 may be located within the radial swath. At step 1112, the radial coordinate R_f of control point “f” may be determined. R_f may indicate the distance of control point “f” from the center of the drill bit in the radial plane. Intersection points p_i of the cutting edges of one or more cutting elements having radial coordinate R_f may be determined at step 1114. At

step 1116, an angular coordinate of control point “f” (θ_f) may be determined and at step 1118 an angular coordinate of each intersection point p_i (θ_{p_i}) may be determined.

The engineering tool may determine a desired underexposure of each point p_i (δ_{p_i}) with respect to control point “f” at step 1120. As explained above with respect to
5 FIGURE 10, the underexposure δ_{p_i} of each intersection point p_i may be determined based on a desired critical depth of cut Δ of the drill bit in the rotational path of point “f.” The underexposure δ_{p_i} for each intersection point p_i may also be based on the relationship of angular coordinate θ_f with respect to the respective angular coordinate θ_{p_i} .

At step 1122, an axial coordinate for each intersection point p_i (Z_{p_i}) may be
10 determined and a difference between Z_{p_i} and the respective underexposure δ_{p_i} may be determined at step 1124, similar to that described above in FIGURE 10 (e.g., $Z_{p_i} - \delta_{p_i}$). In one embodiment, the engineering tool may determine a maximum of the difference between Z_{p_i} and δ_{p_i} calculated for each intersection point p_i at step 1126. At step 1128, the axial coordinate of control point “f” (Z_f) may be determined based on the maximum
15 calculated difference, similar to that described above in FIGURE 10.

At step 1130, the engineering tool may determine whether the axial coordinates of enough control points of the cross-sectional line (e.g., control point “f”) have been determined to adequately define the axial coordinate of the cross-sectional line. If the axial coordinates of more control points are needed, method 1100 may return to step 1111
20 where the engineering tool may select another control point along the cross-sectional line, otherwise, method 1100 may proceed to step 1132. The number of control points along a cross sectional line may be determined by a desired distance between two neighbor control points, (dr), and the length of the cross sectional line, (L_c). For example, if L_c is 1 inch, and dr is 0.1,” then the number of control points may be $L_c/dr + 1 = 11$. In some
25 embodiments, dr may be between 0.01” to 0.2”.

If the axial coordinates of enough cross-sectional lines have been determined, the engineering tool may proceed to step 1132, otherwise, the engineering tool may return to step 1111. At step 1132, the engineering tool may determine whether the axial, radial and angular coordinates of a sufficient number of cross-sectional lines have been determined
30 for the DOCC to adequately define the DOCC. The number of cross-sectional lines may be determined by the size and the shape of a DOCC. For example, if a hemi-spherical component (e.g., an MDR) is selected as a DOCC, then only one cross sectional line may be used. If an impact arrestor (semi-cylinder like) is selected, then a plurality of cross-

sectional lines may be used. If a sufficient number have been determined, method 1100 may proceed to step 1134, otherwise method 1100 may return to step 1108 to select another cross-sectional line associated with the DOCC.

At step 1134, the engineering tool may use the axial, angular and radial
5 coordinates of the cross-sectional lines to configure the DOCC such that the DOCC has substantially the same axial, angular and radial coordinates as the cross-sectional lines. In some instances, the three dimensional surface of the DOCC that may correspond to the axial curvature of the cross-sectional lines may be designed by smoothing the axial coordinates of the surface using a two dimensional interpolation method such as the
10 MATLAB[®] function called interp2.

At step 1136, the engineering tool may determine whether all of the desired DOCCs for the drill bit have been designed. If no, method 1100 may return to step 1108 to select a cross-sectional line for another DOCC that is to be designed; if yes, method 1100 may proceed to step 1138, where the engineering tool may calculate a critical depth
15 of cut control curve CDCCC for the drill bit, as explained in more detail below.

The engineering tool may determine whether the CDCCC indicates that the drill bit meets the design requirements at step 1140. If no, method 1100 may return to step 1108 and various changes may be made to the design of one or more DOCCs of the drill bit. For example, the number of control points “F” may be increased, the number of cross-
20 sectional lines for a DOCC may be increased, or any combination thereof. The angular locations of cross sectional lines may also be changed. Additionally, more DOCCs may be added to improve the CDCCC. If the CDCCC indicates that the drill bit meets the design requirements, method 1100 may end. Consequently, method 1100 may be used to design and configure a DOCC according to the cutting edges of all cutting elements
25 within a radial swath of a drill bit such that the drill bit may have a substantially constant depth of cut as controlled by the DOCC.

Method 1100 may be repeated for designing and configuring another DOCC within the same radial swath at the same expected depth of cut beginning at step 1108. Method 1100 may also be repeated for designing and configuring another DOCC within
30 another radial swath of a drill bit by inputting another expected depth of cut, Δ , at step 1102. Modifications, additions, or omissions may be made to method 1100 without departing from the scope of the present disclosure. For example, each step may include additional steps. Additionally, the order of the steps as described may be changed. For

example, although the steps have been described in sequential order, it is understood that one or more steps may be performed at the same time.

As mentioned above, a DOCC may be configured to control the depth of cut of a plurality of cutting elements within a certain radial swath of a drill bit (e.g., rotational paths 508 and 1008 of FIGURES 5 and 10 respectively). Additionally, as mentioned above, a drill bit may include more than one DOCC that may be configured to control the depth of cut of the same cutting elements within the radial swath of the drill bit, to control the depth of cut of a plurality of cutting elements located within different radial swaths of the drill bit, or any combination thereof. Multiple DOCCs may also be used to reduce imbalance forces when DOCCs are in contact with formation. FIGURES 12-14 illustrate example configurations of drill bits including multiple DOCCs.

FIGURE 12A illustrates the bit face of a drill bit 1201 that includes DOCCs 1202a, 1202c and 1202e configured to control the depth of cut of drill bit 1201. In the illustrated embodiment, DOCCs 1202 may each be configured such that drill bit 1201 has a critical depth of cut of Δ_1 within a radial swath 1208, as shown in FIGURE 12B. Radial swath 1208 may be defined as being located between a first radial coordinate R_1 and a second radial coordinate R_2 . Each DOCC 1202 may be configured based on the cutting edges of cutting elements 1228 and 1229 that may intersect with radial swath 1208, similarly to as disclosed above with respect to DOCC 1002 of FIGURES 10A-10D.

FIGURE 12B illustrates a critical depth of cut control curve (described in further detail below) of drill bit 1201. The critical depth of cut control curve indicates that the critical depth of cut of radial swath 1208 between radial coordinates R_1 and R_2 may be substantially even and constant. Therefore, FIGURE 12B indicates that DOCCs 1202 may be configured to provide a substantially constant depth of cut control for drill bit 1201 at radial swath 1208.

Additionally, DOCCs 1202 may be disposed on blades 1226 such that the lateral forces created by DOCCs 1202 may be substantially balanced as drill bit 1201 drills at or over critical depth of cut Δ_1 . In the illustrated embodiment, DOCC 1202a may be disposed on a blade 1226a, DOCC 1202c may be disposed on a blade 1226c and DOCC 1202e may be disposed on a blade 1226e. DOCCs 1202 may be placed on the respective blades 1226 such that DOCCs 1202 are spaced approximately 120 degrees apart to more evenly balance the lateral forces created by DOCCs 1202 of drill bit 1201. Therefore, DOCCs 1202 may be configured to provide a substantially constant depth of cut control

for drill bit 1201 at radial swath 1208 and that may improve the force balance conditions of drill bit 1201.

Modifications, additions or omissions may be made to FIGURES 12 without departing from the scope of the present disclosure. For example, although DOCCs 1202 are depicted as being substantially rounded, DOCCs 1202 may be configured to have any suitable shape depending on the design constraints and considerations of DOCCs 1202. Additionally, although each DOCC 1202 is configured to control the depth of cut of drill bit 1208 at radial swath 1208, each DOCC 1202 may be configured to control the depth of cut of drill bit 1208 at different radial swaths, as described below with respect to DOCCs 1302 in FIGURES 13A-13E.

FIGURE 13A illustrates the bit face of a drill bit 1301 that includes DOCCs 1302a, 1302c and 1302e configured to control the depth of cut of drill bit 1301. In the illustrated embodiment, DOCC 1302a may be configured such that drill bit 1301 has a critical depth of cut of Δ_1 within a radial swath 1308 defined as being located between a first radial coordinate R_1 and a second radial coordinate R_2 , as shown in FIGURES 13A and 13B. In the illustrated embodiment, the inner and outer edges of DOCC 1302a may be associated with radial coordinates R_1 and R_2 respectively, as shown in FIGURE 13A. DOCC 1302c may be configured such that drill bit 1301 has a critical depth of cut of Δ_1 within a radial swath (not expressly shown in FIGURE 13A) defined as being located between a third radial coordinate R_3 and a fourth radial coordinate R_4 (not expressly shown in FIGURE 13A), illustrated in FIGURE 13C. In the illustrated embodiment, the inner and outer edges of DOCC 1302b may be associated with radial coordinates R_3 and R_4 respectively. Additionally, DOCC 1302e may be configured such that drill bit 1301 has a critical depth of cut of Δ_1 within a radial swath (not expressly shown in FIGURE 13A) defined as being located between a fifth radial coordinate R_5 and a sixth radial coordinate R_6 (not expressly shown in FIGURE 13A), illustrated in FIGURE 13D. In the illustrated embodiment, the inner and outer edges of DOCC 1302e may be associated with radial coordinates R_5 and R_6 respectively.

Each DOCC 1302 may be configured based on the cutting edges of cutting elements 1328 and 1329 that may intersect with the respective radial swaths associated with each DOCC 1302 as disclosed above with respect to DOCC 1002 of FIGURES 10. FIGURES 13B-13E illustrate critical depth of cut control curves (described in further

detail below) of drill bit 1301. The critical depth of cut control curves indicate that the critical depth of cut of the radial swaths defined by radial coordinates R_1 , R_2 , R_3 , R_4 , R_5 and R_6 may be substantially even and constant. Therefore, FIGURES 13B-13E indicate that DOCCs 1302a, 1302c and 1302e may provide a combined depth of cut control for a radial swath defined by radius R_1 and radius R_6 , as shown in FIGURE 13E.

Additionally, similar to DOCCs 1202 of FIGURE 12A, DOCCs 1302 may be disposed on blades 1326 such that the lateral forces created by DOCCs 1302 may substantially be balanced as drill bit 1301 drills at or over critical depth of cut Δ_1 . In the illustrated embodiment, DOCC 1302a may be disposed on a blade 1326a, DOCC 1302c may be disposed on a blade 1326c and DOCC 1302e may be disposed on a blade 1326e. DOCCs 1302 may be placed on the respective blades 1326 such that DOCCs 1302 are spaced approximately 120 degrees apart to more evenly balance the lateral forces created by DOCCs 1302 of drill bit 1301. Therefore, DOCCs 1302 may be configured to provide a substantially constant depth of cut control for drill bit 1301 at a radial swath defined as being located between radial coordinate R_1 and radial coordinate R_6 and that may improve the force balance conditions of drill bit 1301.

Modifications, additions or omissions may be made to FIGURES 13A-13E without departing from the scope of the present disclosure. For example, although DOCCs 1302 are depicted as being substantially round, DOCCs 1302 may be configured to have any suitable shape depending on the design constraints and considerations of DOCCs 1302. Additionally, although drill bit 1301 includes a specific number of DOCCs 1302, drill bit 1301 may include more or fewer DOCCs 1302. For example, drill bit 1301 may include two DOCCs 1302 spaced 180 degrees apart. Additionally, drill bit 1301 may include other DOCCs configured to provide a different critical depth of cut for a different radial swath of drill bit 1301, as described below with respect to DOCCs 1402 in FIGURES 14A-14D.

FIGURE 14A illustrates the bit face of a drill bit 1401 that includes DOCCs 1402a, 1402b, 1402c, 1402d, 1402e and 1402f configured to control the depth of cut of drill bit 1401. In the illustrated embodiment, DOCCs 1402a, 1402c and 1402e may be configured such that drill bit 1401 has a critical depth of cut of Δ_1 within a radial swath 1408a defined as being located between a first radial coordinate R_1 and a second radial coordinate R_2 , as shown in FIGURES 14A and 14B.

Additionally, DOCCs 1402b, 1402d and 1402f may be configured such that drill bit 1401 has a critical depth of cut of Δ_2 within a radial swath 1408b defined as being located between a third radial coordinate R_3 and a fourth radial coordinate R_4 as shown in FIGURES 14A and 14C. Accordingly, DOCCs 1402 may be configured such that drill bit
5 1401 has a first critical depth of cut Δ_1 for radial swath 1408a and a second critical depth of cut Δ_2 for radial swath 1408b, as illustrated in FIGURES 14A and 14D. Each DOCC 1402 may be configured based on the cutting edges of cutting elements 1428 and 1429 that may intersect with the respective radial swaths 1408 associated with each DOCC 1402, as disclosed above. Additionally, similarly to DOCCs 1202 of FIGURE 12A, and
10 DOCCs 1302 of FIGURE 13A, DOCCs 1402 may be disposed on blades 1426 such that lateral forces created by DOCCs 1402 may substantially be balanced as drill bit 1401 drills at or over critical depth of cut Δ_1 .

Therefore, drill bit 1401 may include DOCCs 1402 configured according to the cutting zones of cutting elements 1428 and 1429. Additionally, as illustrated by critical
15 depth of cut control curves illustrated in FIGURES 14B-14D, DOCCs 1402a, 1402c and 1402e may be configured to provide a substantially constant depth of cut control for drill bit 1401 at radial swath 1408a based on a first desired critical depth of cut for radial swath 1408a. Further DOCCs 1402b, 1402d and 1402f may be configured to provide a substantially constant depth of cut control for drill bit 1401 at radial swath 1408b based
20 on a second desired critical depth of cut for radial swath 1408b. Also, DOCCs 1402 may be located on blades 1426 to improve the force balance conditions of drill bit 1401.

Modifications, additions or omissions may be made to FIGURES 14A-14D without departing from the scope of the present disclosure. For example, although DOCCs 1402 are depicted as being substantially round, DOCCs 1402 may be configured
25 to have any suitable shape depending on the design constraints and considerations of DOCCs 1402. Additionally, although drill bit 1402 includes a specific number of DOCCs 1402, drill bit 1402 may include more or fewer DOCCs 1402.

As shown above, a DOCC may be placed on one of a plurality of blades of a drill bit to provide constant depth of cut control for a particular radial swath of the drill bit.
30 Therefore, selection of one of the plurality of blades for placement of a DOCC may be achieved. FIGURES 15A-15F illustrate a design process that may be used to select a

blade for placement of the DOCC, in accordance with some embodiments of the present disclosure.

FIGURE 15A illustrates the bit face of a drill bit 1501 that includes a plurality of blades 1526 that may include a DOCC configured to control the depth of cut of drill bit 1501 for a radial swath 1508. It can be seen that blades 1526a, 1526c, 1526d, 1526e and 1526f each may intersect radial swath 1508 such that a DOCC may be placed on any one of blades 1526a, 1526c, 1526d, 1526e and 1526f to control the depth of cut of drill bit 1501 at radial swath 1508. However, in some instances not all the blades may include a DOCC, therefore, it may be determined on which of blades 1526a, 1526c, 1526d, 1526e and 1526f to place a DOCC.

To determine on which of blades 1526a, 1526c, 1526d, 1526e and 1526f to place a DOCC, axial, radial and angular coordinates for a cross-sectional line 1510 may be determined for each of blades 1526a, 1526c, 1526d, 1526e and 1526f. The coordinates for each cross-sectional line 1510 may be determined based on the cutting edges of cutting elements (not expressly shown) located within radial swath 1508 and a desired critical depth of cut for radial swath 1508 similar to the determination of the coordinates of cross-sectional lines as describe with respect to FIGURES 10 (e.g., determining the coordinates of cross-sectional lines 1010). For example, axial, radial and angular coordinates may be determined for cross-sectional lines 1510a, 1510c, 1510d, 1510e and 1510f located on blades 1526a, 1526c, 1526d, 1526e and 1526f respectively.

FIGURES 15B-15F illustrate example axial and radial coordinates of cross-sectional lines 1510a, 1510c, 1510d, 1510e and 1510f, respectively between a first radial coordinate R_1 and a second radial coordinate R_2 that define radial swath 1508. FIGURE 15B illustrates that the axial curvature of cross-sectional line 1510a may be approximated using the curvature of three circles. Therefore a DOCC placed on blade 1526a may have a surface with a curvature that may be approximated with the three circular lines fit for cross-sectional line 1510a. Accordingly, three semi-spheres may be used to form this DOCC. FIGURE 15C illustrates that the axial curvature of cross-sectional line 1510b may be approximated using two circles. Therefore a DOCC placed on blade 1526b may have a surface with a curvature that may be approximated with the two circular lines fit for cross-sectional line 1510b. Accordingly, two semi-spheres may be used to form this DOCC. FIGURE 15D illustrates that the axial curvature of cross-sectional line 1510d may be approximated with one circle. Therefore a DOCC placed on blade 1526d may

have a surface with a curvature that may be approximated with the one circular line fit for cross-sectional line 1510d. One semi-sphere may be used to form this DOCC. FIGURE 15E illustrates that the axial curvature of cross-sectional line 1510e may be approximated using two circles. Therefore a DOCC placed on blade 1526e may have a surface with a curvature that may be approximated with the two circles fit for cross-sectional line 1510e. Accordingly, two semi-spheres may be used to form this DOCC. Additionally, FIGURE 15F illustrates that cross-sectional line 1510f may be approximated using three circular lines. Therefore a DOCC placed on blade 1526f may have a surface with a curvature that may be approximated with the three circular lines fit for cross-sectional line 1510f.

As shown by FIGURES 15B-15F, in some instances, it may be advantageous to place a DOCC on blade 1526d because a DOCC placed on blade 1526d may have a simple surface that may be easier to manufacture than DOCCs placed on other blades 1526. Additionally, in some embodiments, cross-sectional line 1510d may be associated with a DOCC (not expressly shown in FIGURE 15A) that may be placed immediately behind a cutting element also located on blade 1526d (not expressly shown in FIGURE 15A). Further, the radial length of cross-sectional line 1510d, (which in the illustrated embodiment may be equal to $R_2 - R_1$), may be fully located within the cutting zone of the cutting element located on blade 1526d. In such an instance, the DOCC associated with cross-sectional line 1526d may be configured based on the cutting edge of the cutting element directly in front of the DOCC using method 700 described above, which may also simplify the design of drill bit 1501.

However, if lateral imbalance force created by DOCCs is a concern, it may be desirable in other instances to place a DOCC on each of blades 1526a, 1526c and 1526e such that the DOCCs are approximately 120 degrees apart. Therefore, FIGURES 15 illustrate how the location of a DOCC within radial swath 1508 may be determined to control the depth of cut of drill bit 1501 along radial swath 1508, depending on various design considerations.

Modifications, additions or omissions may be made to FIGURES 15 without departing from the scope of the present disclosure. For example, the number of blades 1526, the size of swath 1508, the number of blades that may substantially intersect swath 1508, etc., may vary in accordance with other embodiments of the present disclosure. Additionally, the axial curvatures of cross-sectional lines 1510 may vary depending on various design constraints and configurations of drill bit 1501.

As mentioned above, the depth of cut of a drill bit may be controlled by a blade in addition to a DOCC. Therefore, a blade surface may be configured according to the present disclosure such that it may control the depth of cut of a radial swath of a drill bit based on the cutting edges of one or more cutting elements located in the radial swath.

5 FIGURE 16A and 16B illustrate a blade 1626 configured to control the depth of cut of cutting elements 1628 and 1629 of a drill bit 1601. FIGURE 16A illustrates the face of drill bit 1601 that may include blades 1626, outer cutting elements 1628 and inner cutting elements 1629 disposed on blades 1626, similar to drill bit 1001 of FIGURE 10A.

10 In the current example, a portion of blade 1626a may be configured to provide a desired depth of cut Δ_1 (shown in FIGURE 16C) for the cutting elements located within a radial swath 1608 of drill bit 1601. Radial swath 1608 may be defined between a first radial coordinate R_1 and a second radial coordinate R_2 . Similar to DOCC 1002 described with respect to FIGURES 10A-10D, the axial coordinates of blade 1626a may be configured based on one or more cross-sectional lines 1610, which may be configured
15 based on a desired depth of cut Δ_1 of swath 1608. Additionally, the axial, radial and angular coordinates of cross-sectional line 1610 may be determined based on the cutting edges of cutting elements 1628 and/or 1629 that may be intersect radial swath 1608. The axial, radial and angular coordinates of cross-sectional line 1610 may be determined similarly to the axial, radial and angular coordinates of cross-sectional line 1010
20 described with respect to FIGURE 10.

For example, cross-sectional line 1610 may be divided into a series of control points between an inner end and outer end of cross-sectional line 1610 (e.g., a control point "f"). The radial coordinate of control point "f" (R_f , depicted in FIGURE 16B) may be determined. Once R_f is determined, intersection points 1630 of the cutting edges of one
25 or more cutting elements 1628 and/or 1629 having radial coordinate R_f may be determined. Accordingly, intersection points 1630 of the cutting elements may have the same rotational path as control point "f" and, thus, may have a depth of cut that may be affected by the surface of blade 1626 at point "f." In the illustrated embodiment, as depicted in FIGURE 16B, the rotational path of control point "f" may intersect the cutting
30 edge of cutting element 1628a at intersection point 1630a, the cutting edge of cutting element 1628b at intersection point 1630b, the cutting edge of cutting element 1629e at

intersection point 1630e and the cutting edge of cutting element 1628f at intersection point 1630f.

Similarly to that described above with respect to FIGURES 10 and 11, the axial coordinate of blade 1626a at control point “f” may be determined according to a desired underexposure (δ_{1607i}) of control point “f” with respect to each intersection point 1630. FIGURE 16B depicts the desired underexposure δ_{1607i} of control point “f” with respect to each intersection point 1630. The desired underexposure δ_{1607i} of control point “f” with respect to each intersection point 1630 may be determined substantially similarly to that described above with respect to underexposures δ_{607i} , δ_{807i} and δ_{1007i} , described above, and may be based on the desired critical depth of cut Δ_1 and the angular location of control point “f” (θ_f) and each point 1630 (θ_{1630i}). For example, the desired underexposure of control point “f” with respect to intersection point 1630a may be expressed by the following equation:

$$\delta_{1607a} = \Delta_1 * (360 - (\theta_f - \theta_{1630a})) / 360$$

In the above equation, θ_f and θ_{1630a} may be expressed in degrees, and “360” may represent one full revolution of approximately 360 degrees. Accordingly, in instances where θ_f and θ_{1630a} may be expressed in radians, “360” may be replaced by “ 2π .” Further, in the above equation, the resultant angle of “ $(\theta_f - \theta_{1630a})$ ” (Δ_θ) may be defined as always being positive. Therefore, if resultant angle Δ_θ is negative, then Δ_θ may be made positive by adding 360 degrees (or 2π radians) to Δ_θ . The desired underexposure of control point “f” with respect to intersection points 1630b, 1630e and 1630f (δ_{1607b} , δ_{1607e} and δ_{1607f} , respectively) may be similarly determined.

Once the desired underexposure of control point “f” with respect to each intersection point is determined, the axial coordinate of control point “f” may be determined based on the difference between the axial coordinates of each intersection point 1630 and the desired underexposure with respect to each intersection point 1630. For example, in FIGURE 16B, the axial location of each point 1630 may correspond with a coordinate on the z-axis, and may be expressed as a z-coordinate Z_{1630i} . To determine the corresponding z-coordinate of control point “f” (Z_f) a difference between the z-coordinate Z_{1630i} and the corresponding desired underexposure δ_{1607i} for each intersection point 1630 may be determined. The maximum value of the differences between Z_{1630i} and

δ_{1607i} may be the axial or z-coordinate of control point "P" (Z_f). For the current example, Z_f in FIGURES 16 may be expressed by the following equation:

$$Z_f = \max [(Z_{1630a} - \delta_{1607a}), (Z_{1630b} - \delta_{1607b}), (Z_{1630e} - \delta_{1607e}), (Z_{1630f} - \delta_{1607f})]$$

Accordingly, the axial coordinate of control point "P" may be determined based on
5 the cutting edges of cutting elements 1628a, 1628b, 1629e and 1628f. The axial coordinates of other control points along cross-sectional line 1610 may be similarly determined to determine the axial curvature and coordinates of cross-sectional line 1610.

The above mentioned process may be repeated to determine the axial coordinates and curvature of other cross-sectional lines associated with blade 1626a such that blade
10 1626a may provide depth of cut control to substantially obtain the desired depth of cut Δ_1 within the radial swath defined by R_1 and R_2 . The surface of blade 1626a may be manufactured such that the axial coordinates of blade 1626a substantially match the determined axial coordinates of the cross-sectional lines at the same angular and radial locations. The cross-sectional lines may be used to form a three dimensional surface of
15 the blade 1626a. To more easily manufacture the surface of blade 1626a, in some instances, the 3D surface may be smoothed using a two dimensional interpolation method such as the MATLAB[®] function called interp2, similarly to described above with respect to DOCC 1002 in FIGURE 10.

FIGURE 16C illustrates a critical depth of cut control curve (described in further
20 detail below) of drill bit 1601. The critical depth of cut control curve indicates that the critical depth of cut of radial swath 1608 between radial coordinates R_1 and R_2 may be substantially even and constant. Therefore, FIGURE 16C indicates that the desired depth of cut (Δ_1) of drill bit 1601, as controlled by the surface of blade 1626a, may be substantially constant by taking in account all the cutting elements with depths of cut that
25 may be affected by the surface of blade 1626a.

Modifications, additions, or omissions may be made to FIGURES 16A-16C without departing from the scope of the present disclosure. For example, it is understood that any number of cross-sectional lines and points along the cross-sectional lines may be determined to determine a desired axial curvature of the surface of blade 1626a. Further,
30 as disclosed below with respect to FIGURES 18 and 19, although only one blade 1626 (e.g., blade 1626a) is depicted as controlling the depth of cut of drill bit 1601, any number of blades 1626 may be configured to control the depth of cut of any number of radial

swaths of drill bit 1601. Further, the desired depth of cut of drill bit 1601 may vary according to the radial location (distance from the center of drill bit 1601 in the radial plane) along drill bit 1601. Additionally, the size of radial swath 1608 may be larger or smaller than that specifically depicted in FIGURES 16A-16C. Further, it is understood that any suitable portion of a blade 1626 may be configured to control the depth of cut of drill bit 1601. For example, in some instances the trailing edge and/or the leading edge of blade 1626 may be configured to control the depth of cut of drill bit 1601.

FIGURES 17A and 17B illustrate a flow chart of an example method 1700 for configuring the surface of a blade (e.g., blade 1626a of FIGURES 16A-16B) according to the cutting edges of the cutting elements with depths of cut that may be affected by at least a portion of the blade. In some embodiments, the blade surface may be configured for all the cutting elements with depths of cut that may be affected by at least a portion of the blade. The steps of method 1700 may be performed by an engineering tool, similar to methods 1100 described above. In the illustrated embodiment the cutting structures of the bit including at least the locations and orientations of all cutting elements may have been previously designed. However in other embodiments, method 1700 may include steps for designing the cutting structure of the drill bit.

Method 1700 may start, and at step 1702, the engineering tool may determine desired critical depth of cut control, Δ , at a selected zone (e.g., cone zone, nose zone, shoulder zone, gage zone, etc.) along a bit profile, substantially similar to as done with respect to step 1102 of method 1100. The zone may be associated with a radial swath of the drill bit. At step 1704, the locations and orientations of cutting elements within the swath may be determined. Additionally, at step 1706 the engineering tool may create a 3D cutter/rock interaction model that may determine the cutting zone and the cutting edge for each cutting element.

At step 1708, the engineering tool may select a cross-sectional line (e.g., cross-sectional line 1610 of FIGURE 16A) that may be associated with a blade and may intersect a radial swath (e.g., radial swath 1608) with a desired critical depth of cut. At step 1710, a control point "f" along the cross-sectional line may be selected and at step 1712 the radial coordinate R_f of control point "f" may be determined. R_f may indicate the distance of control point "f" from the center of the drill bit. Intersection points p_i of the cutting edges of one or more cutting elements having the radial coordinate R_f may be determined at step 1714. At step 1716, an angular coordinate of control point "f" (θ_f) may

be determined and at step 1718 an angular coordinate of each intersection point p_i (θ_{p_i}) may be determined.

The engineering tool may determine a desired underexposure of each intersection point p_i (δ_{p_i}) with respect to control point “f” at step 1720. As explained above with respect to FIGURES 10, 11 and 16, the underexposure δ_{p_i} of each intersection point p_i may be determined based on a desired critical depth of cut Δ of the drill bit in the rotational path of control point “f.” The underexposure δ_{p_i} for each intersection point p_i may also be based on the relationship of angular coordinate θ_f with respect to a respective angular coordinate θ_{p_i} .

At step 1722, an axial coordinate for each intersection point p_i (Z_{p_i}) may be determined and a difference between Z_{p_i} and the respective underexposure δ_{p_i} may be determined at step 1724, similar to that described above in FIGURE 16 (e.g., $Z_{p_i} - \delta_{p_i}$). In one embodiment, the engineering tool may determine a maximum of the difference between Z_{p_i} and δ_{p_i} calculated for each point p_i at step 1726. At step 1728, the axial coordinate of control point “f” (Z_f) may be determined based on the maximum calculated difference, similar to that described above in FIGURE 16.

At step 1730, the engineering tool may determine whether the axial coordinates of a sufficient number of control points (e.g., control point “f”) of the cross-sectional line have been determined to adequately define the axial position of the cross-sectional line. If the axial coordinates of more control points are needed, method 1700 may return to step 1710 where the engineering tool may select another control point along the cross-sectional line, otherwise, method 1700 may proceed to step 1732.

At step 1732, the engineering tool may determine whether the axial, radial and angular positions of a sufficient number of cross-sectional lines have been determined for the blade within the radial swath to adequately define the surface of the blade. If yes, method 1700 may proceed to step 1734, otherwise method 1700 may return to step 1708 to select another cross-sectional line associated with the blade and radial swath.

At step 1734, the engineering tool may use the axial, angular and radial coordinates of the cross-sectional lines to configure the blade surface. In some instances, the three dimensional surface of the blade that may correspond with the axial curvature of the cross-sectional lines may be designed by smoothing the surface using a two dimensional interpolation method such as the MATLAB[®] function called interp2.

At step 1736, the engineering tool may determine whether all of the blade surfaces of the drill bit configured to control the depth of cut of the drill bit have been designed. If no, method 1700 may return to step 1708 to select a cross-sectional line for another blade that is to be designed to control the depth of cut of the drill bit for a particular radial swath. In some instances, the other blade may be configured to control the depth of cut for the same radial swath. In other instances the other blade may be configured to control the depth of cut for a different radial swath. If all the blade surfaces of the drill bit are sufficiently designed, method 1700 may proceed to step 1738 where the engineering tool may calculate a critical depth of cut control curve (CDCCC) for the drill bit, as explained in more detail below.

The engineering tool may determine whether the CDCCC indicates that the drill bit meets the design requirements at step 1740. If no, method 1700 may return to step 1708 and various changes may be made to the design of one or more blade surfaces. If yes, method 1700 may end. Consequently, method 1700 may be used to design and configure a blade to control the depth of cut of a drill bit according to the cutting edges of the cutting elements within a swath of the drill bit (e.g., all the cutting elements within the swath).

Method 1700 may be repeated for designing and configuring another blade within the same radial swath at the same expected depth of cut beginning at step 1708. Method 1700 may also be repeated for designing and configuring blades within another radial swath of a drill bit by inputting another expected depth of cut, Δ , at step 1702.

Modifications, additions, or omissions may be made to method 1700 without departing from the scope of the present disclosure. For example, each step may include additional steps. Additionally, the order of the steps as described may be changed. For example, although the steps have been described in sequential order, it is understood that one or more steps may be performed at the same time.

As mentioned above a drill bit may include more than one blade that may be configured to control the depth of cut of the cutting elements within the same swath of the drill bit, to control the depth of cut of different swaths of the drill bit, or any combination thereof. Additionally, different sections of a blade may be configured to control the depth of cut of different radial swaths of a drill bit according to different desired critical depths of cut at the different radial swaths. FIGURES 18 and 19 illustrate example configurations of blades configured to control the depth of cut of drill bits.

FIGURE 18A illustrates an example bit face of a drill bit 1801 that includes blades 1826a, 1826c and 1826e configured to control the depth of cut of drill bit 1801. In the illustrated embodiment, blades 1826a, 1826c and 1826e may be configured to control the depth of cut of drill bit 1801 to have a critical depth of cut Δ_1 for radial swath 1808.

5 Radial swath 1808 may be defined by a first radial coordinate R_1 and a second radial coordinate R_2 , and in the illustrated embodiment may substantially cover the face of drill bit 1801. The surfaces of blades 1826a, 1826c and 1826e may be configured respectively to control the depth of cut of cutting elements 1828 and 1829 located within the swath as described above.

10 FIGURES 18B-18E illustrate critical depth of cut control curves (described in further detail below) of drill bit 1801. The critical depth of cut control curves indicate that the critical depth of cut of radial swath 1808 (Δ_1) defined by radial coordinates R_1 and R_2 may be substantially even and constant. Therefore, FIGURES 18B-18E indicate that the blade surfaces of blades 1826a, 1826c, and 1826e may provide a combined depth of cut

15 control for a radial swath defined by radius R_1 and radius R_2 , as shown in FIGURE 18E.

Additionally, in the illustrated embodiment blades 1826a, 1826c and 1826e may be selected to control the depth of cut of drill bit 1801 based on the spacing of blades 1826a, 1826c and 1826e. Blades 1826a, 1826c and 1826e may be spaced approximately 120 degrees from each other such that the lateral forces created by blades 1826a, 1826c

20 and 1826e may be substantially balanced while drilling. Therefore, blades 1826a, 1826c and 1826e may be configured to control the depth of cut of drill bit 1801 based on cutting elements 1828 and 1829 located within the swath to provide a substantially constant depth of cut control for drill bit 1801 at swath 1608. Additionally, blades 1826a, 1826c and 1826e may be configured such that the lateral forces created by these blades of drill

25 bit 1801 may be substantially balanced.

Modifications, additions or omissions may be made to drill bit 1801 without departing from the scope of the present disclosure. For example, blades 1826 may be configured to control the depth of cut according to different critical depths of cut of different radial swaths as disclosed in more detail below with respect to blades 1926

30 FIGURES 19A-19D.

FIGURE 19A illustrates an example drill bit 1901 that includes blades 1926 configured to control the depth of cut of drill bit 1901 according to different critical

depths of cut for different radial swaths of drill bit 1901. In the illustrated embodiment, blades 1926a, 1926c and 1926e may be configured to control the depth of cut of drill bit 1901 to have a first critical depth of cut Δ_1 for radial swath 1908a, as illustrated by FIGURE 19B. Radial swath 1908a may be defined by a first radial coordinate R_1 and a
5 second radial coordinate R_2 . Blades 1926b, 1926d and 1926f may be configured to control the depth of cut of drill bit 1901 to have a second critical depth of cut Δ_2 as illustrated by FIGURE 19C. In the illustrated embodiment, radial swath 1908b may be defined by a third radial coordinate R_3 and a fourth radial coordinate R_4 . The overall critical depth of cut as controlled by blades 1926a-1926f for drill bit 1901 is illustrated by
10 FIGURE 19D. The surfaces of blades 1926a-1926f may be configured to control the depth of cut based on cutting elements 1928 and 1929 located within the radial swaths according to the present disclosure, as described above.

As shown by the critical depth of cut control curve of FIGURE 19B, the surfaces of blades 1926a, 1926c, and 1926e may be configured according to the present disclosure
15 to provide a substantially constant depth of cut control of radial swath 1908a defined by radial coordinates R_1 and R_2 . FIGURE 19C illustrates another critical depth of cut control curve of drill bit 1901 that indicates that the surfaces of blades 1926b, 1926d, and 1926f may be configured according to the present disclosure to provide a substantially constant depth of cut control of radial swath 1908b defined by radial coordinates R_3 and R_4 .
20 FIGURE 19D illustrates a critical depth of cut control curve indicating the substantially constant depth of cut of radial swaths 1908a and 1908b of drill bit 1901.

Additionally, in the illustrated embodiment, blades 1926a, 1926c and 1926e may be selected to control the depth of cut of drill bit 1901 for radial swath 1908a based on the spacing of blades 1926a, 1926c and 1926e. Blades 1926a, 1926c and 1926e may be
25 spaced approximately 120 degrees from each other such that the lateral forces created by blades 1926a, 1926c and 1926e may be substantially balanced while drilling. Further, in the illustrated embodiment, blades 1926b, 1926d and 1926f may be selected to control the depth of cut of drill bit 1901 for radial swath 1908b based on the spacing of blades 1926b, 1926d and 1926f. Blades 1926b, 1926d and 1926f may also be spaced approximately 120
30 degrees from each other such that the lateral forces created by blades 1926b, 1926d and 1926f may be substantially balanced while drilling.

Modifications, additions or omissions may be made to drill bit 1901 without departing from the scope of the present disclosure. For example, blades 1926a, 1926c and 1926e may be respectively configured according to second critical depth of cut Δ_2 for radial swath 1908b in addition to being configured according to first critical depth of cut Δ_1 for radial swath 1908a. And blades 1926b, 1926d and 1926f may be respectively configured according to first critical depth of cut Δ_1 for radial swath 1908a in addition to being configured according to second critical depth of cut Δ_2 for radial swath 1908b.

As mentioned above, the depth of cut of a drill bit may be analyzed by calculating a critical depth of cut control curve (CDCCC) for a radial swath of the drill bit as provided by the DOCCs, blade, or any combination thereof, located within the radial swath. The CDCCC may be based on a critical depth of cut associated with a plurality of radial coordinates.

FIGURE 20A illustrates the face of a drill bit 2001 for which a critical depth of cut control curve (CDCCC) may be determined, in accordance with some embodiments of the present disclosure. FIGURE 20B illustrates a bit face profile of drill bit 2001 of FIGURE 20A.

Drill bit 2001 may include a plurality of blades 2026 that may include cutting elements 2028 and 2029. Additionally, blades 2026b, 2026d and 2026f may include DOCC 2002b, DOCC 2002d and DOCC 2002f, respectively, that may be configured to control the depth of cut of drill bit 2001. DOCCs 2002b, 2002d and 2002f may be configured and designed according to the desired critical depth of cut of drill bit 2001 within a radial swath intersected by DOCCs 2002b, 2002d and 2002f as described in detail above.

As mentioned above, the critical depth of cut of drill bit 2001 may be determined for a radial location along drill bit 2001. For example, drill bit 2001 may include a radial coordinate R_F that may intersect with DOCC 2002b at a control point P_{2002b} , DOCC 2002d at a control point P_{2002d} , and DOCC 2002f at a control point P_{2002f} . Additionally, radial coordinate R_F may intersect cutting elements 2028a, 2028b, 2028c, and 2029f at outlet points 2030a, 2030b, 2030c, and 2030f, respectively, of the cutting edges of cutting elements 2028a, 2028b, 2028c, and 2029f, respectively.

The angular coordinates of control points P_{2002b} , P_{2002d} and P_{2002f} ($\theta_{P_{2002b}}$, $\theta_{P_{2002d}}$ and $\theta_{P_{2002f}}$, respectively) may be determined along with the angular coordinates of outlet

points 2030a, 2030b, 2030c and 2030f (θ_{2030a} , θ_{2030b} , θ_{2030c} and θ_{2030f} , respectively). A depth of cut control provided by each of control points P_{2002b} , P_{2002d} and P_{2002f} with respect to each of outlet points 2030a, 2030b, 2030c and 2030f may be determined. The depth of cut control provided by each of control points P_{2002b} , P_{2002d} and P_{2002f} may be based on the underexposure (δ_{2007i} depicted in FIGURE 20B) of each of points P_{2002i} with respect to each of outlet points 2030 and the angular coordinates of points P_{2002i} with respect to outlet points 2030.

For example, the depth of cut of cutting element 2028b at outlet point 2030b controlled by point P_{2002b} of DOCC 2002b (Δ_{2030b}) may be determined using the angular coordinates of point P_{2002b} and outlet point 2030b ($\theta_{P_{2002b}}$ and θ_{2030b} , respectively), which are depicted in FIGURE 20A. Additionally, Δ_{2030b} may be based on the axial underexposure (δ_{2007b}) of the axial coordinate of point P_{2002b} ($Z_{P_{2002b}}$) with respect to the axial coordinate of intersection point 2030b (Z_{2030b}), as depicted in FIGURE 20B. In some embodiments, Δ_{2030b} may be determined using the following equations:

$$\Delta_{2030b} = \delta_{2007b} * 360 / (360 - (\theta_{P_{2002b}} - \theta_{2030b})); \text{ and}$$

$$\delta_{2007b} = Z_{2030b} - Z_{P_{2002b}}.$$

In the first of the above equations, $\theta_{P_{2002b}}$ and θ_{2030b} may be expressed in degrees and “360” may represent a full rotation about the face of drill bit 2001. Therefore, in instances where $\theta_{P_{2002b}}$ and θ_{2030b} are expressed in radians, the numbers “360” in the first of the above equations may be changed to “ 2π .” Further, in the above equation, the resultant angle of “ $(\theta_{P_{2002b}} - \theta_{2030b})$ ” (Δ_{θ}) may be defined as always being positive. Therefore, if resultant angle Δ_{θ} is negative, then Δ_{θ} may be made positive by adding 360 degrees (or 2π radians) to Δ_{θ} . Similar equations may be used to determine the depth of cut of cutting elements 2028a, 2028c, and 2029f as controlled by control point P_{2002b} at outlet points 2030a, 2030c and 2030f, respectively (Δ_{2030a} , Δ_{2030c} and Δ_{2030f} , respectively).

The critical depth of cut provided by point P_{2002b} ($\Delta_{P_{2002b}}$) may be the maximum of Δ_{2030a} , Δ_{2030b} , Δ_{2030c} and Δ_{2030f} and may be expressed by the following equation:

$$\Delta_{P_{2002b}} = \max [\Delta_{2030a}, \Delta_{2030b}, \Delta_{2030c}, \Delta_{2030f}].$$

The critical depth of cut provided by points P_{2002d} and P_{2002f} ($\Delta_{P_{2002d}}$ and $\Delta_{P_{2002f}}$, respectively) at radial coordinate R_F may be similarly determined. The overall critical depth of cut of drill bit 2001 at radial coordinate R_F (Δ_{RF}) may be based on the minimum of $\Delta_{P_{2002b}}$, $\Delta_{P_{2002d}}$ and $\Delta_{P_{2002f}}$ and may be expressed by the following equation:

$$\Delta_{RF} = \min [\Delta_{P2002b}, \Delta_{P2002d}, \Delta_{P2002f}].$$

Accordingly, the overall critical depth of cut of drill bit 2001 at radial coordinate R_F (Δ_{RF}) may be determined based on the points where DOCCs 2002 and cutting elements 2028/2029 intersect R_F . Although not expressly shown here, it is understood that the overall critical depth of cut of drill bit 2001 at radial coordinate R_F (Δ_{RF}) may also be affected by control points P_{2026i} (not expressly shown in FIGURES 20A and 20B) that may be associated with blades 2026 configured to control the depth of cut of drill bit 2001 at radial coordinate R_F . In such instances, a critical depth of cut provided by each control point P_{2026i} (Δ_{P2026i}) may be determined. Each critical depth of cut Δ_{P2026i} for each control point P_{2026i} may be included with critical depth of cuts Δ_{P2002i} in determining the minimum critical depth of cut at R_F to calculate the overall critical depth of cut Δ_{RF} at radial location R_F .

To determine a critical depth of cut control curve of drill bit 2001, the overall critical depth of cut at a series of radial locations R_f (Δ_{Rf}) anywhere from the center of drill bit 2001 to the edge of drill bit 2001 may be determined to generate a curve that represents the critical depth of cut as a function of the radius of drill bit 2001. In the illustrated embodiment, DOCCs 2002b, 2002d, and 2002f may be configured to control the depth of cut of drill bit 2001 for a radial swath 2008 defined as being located between a first radial coordinate R_A and a second radial coordinate R_B . Accordingly, the overall critical depth of cut may be determined for a series of radial coordinates R_f that are within radial swath 2008 and located between R_A and R_B , as disclosed above. Once the overall critical depths of cuts for a sufficient number of radial coordinates R_f are determined, the overall critical depth of cut may be graphed as a function of the radial coordinates R_f .

FIGURE 20C illustrates a critical depth of cut control curve for drill bit 2001, in accordance with some embodiments of the present disclosure. FIGURE 20C illustrates that the critical depth of cut between radial coordinates R_A and R_B may be substantially uniform, indicating that DOCCs 2002b, 2002d and 2002f may be sufficiently configured to provide a substantially even depth of cut control between R_A and R_B .

Modifications, additions or omissions may be made to FIGURES 20A-20C without departing from the scope of the present disclosure. For example, as discussed above, blades 2026, DOCCs 2002 or any combination thereof may affect the critical

depth of cut at one or more radial coordinates and the critical depth of cut may be determined accordingly.

FIGURE 21 illustrates an example method 2100 of determining and generating a CDCCC in accordance with some embodiments of the present disclosure. Similar to methods 700, 900, 1100 and 1700, method 2100 may be performed by any suitable engineering tool. In the illustrated embodiment, the cutting structures of the bit, including at least the locations and orientations of all cutting elements and DOCCs, may have been previously designed. However in other embodiments, method 2100 may include steps for designing the cutting structure of the drill bit. For illustrative purposes, method 2100 is described with respect to drill bit 2001 of FIGURES 20A-20C; however, method 2100 may be used to determine the CDCCC of any suitable drill bit.

Method 2100 may start, and at step 2102, the engineering tool may select a radial swath of drill bit 2001 for analyzing the critical depth of cut within the selected radial swath. In some instances the selected radial swath may include the entire face of drill bit 2001 and in other instances the selected radial swath may be a portion of the face of drill bit 2001. For example, the engineering tool may select radial swath 2008 as defined between radial coordinates R_A and R_B and controlled by DOCCs 2002b, 2002d and 2002f, shown in FIGURES 20A-20C.

At step 2104, the engineering tool may divide the selected radial swath (e.g., radial swath 2008) into a number, N_b , of radial coordinates (R_f) such as radial coordinate R_F described in FIGURES 20A and 20B. For example, radial swath 2008 may be divided into nine radial coordinates such that N_b for radial swath 2008 may be equal to nine. The variable " f " may represent a number from one to N_b for each radial coordinate within the radial swath. For example, " R_1 " may represent the radial coordinate of the inside edge of a radial swath. Accordingly, for radial swath 2008, " R_1 " may be approximately equal to R_A . As a further example, " R_{N_b} " may represent the radial coordinate of the outside edge of a radial swath. Therefore, for radial swath 2008, " R_{N_b} " may be approximately equal to R_B .

At step 2106, the engineering tool may select a radial coordinate R_f and may identify control points (P_i) at may be located at the selected radial coordinate R_f and associated with a DOCC and/or blade. For example, the engineering tool may select radial coordinate R_F and may identify control points P_{2002i} and P_{2026i} associated with

DOCCs 2002 and/or blades 2026 and located at radial coordinate R_F , as described above with respect to FIGURES 20A and 20B.

At step 2108, for the radial coordinate R_f selected in step 2106, the engineering tool may identify outlet points (C_j) each located at the selected radial coordinate R_f and associated with the cutting edges of cutting elements. For example, the engineering tool may identify outlet points 2030a, 2030b, 2030c and 2030f located at radial coordinate R_F and associated with the cutting edges of cutting elements 2028a, 2028b, 2028c, and 2029f, respectively, as described and shown with respect to FIGURES 20A and 20B.

At step 2110, the engineering tool may select a control point P_i and may calculate a depth of cut for each outlet C_j as controlled by the selected control point P_i (Δ_{C_j}), as described above with respect to FIGURES 20A and 20B. For example, the engineering tool may determine the depth of cut of outlets 2030a, 2030b, 2030c, and 2030f as controlled by control point P_{2002b} (Δ_{2030a} , Δ_{2030b} , Δ_{2030c} , and Δ_{2030f} , respectively) by using the following equations:

$$\begin{aligned} \Delta_{2030a} &= \delta_{2007a} * 360 / (360 - (\theta_{P_{2002b}} - \theta_{2030a})); \\ \delta_{2007a} &= Z_{2030a} - Z_{P_{2002b}}; \\ \Delta_{2030b} &= \delta_{2007b} * 360 / (360 - (\theta_{P_{2002b}} - \theta_{2030b})); \\ \delta_{2007b} &= Z_{2030b} - Z_{P_{2002b}}; \\ \Delta_{2030c} &= \delta_{2007c} * 360 / (360 - (\theta_{P_{2002b}} - \theta_{2030c})); \\ \delta_{2007c} &= Z_{2030c} - Z_{P_{2002b}}; \\ \Delta_{2030f} &= \delta_{2007f} * 360 / (360 - (\theta_{P_{2002b}} - \theta_{2030f})); \text{ and} \\ \delta_{2007f} &= Z_{2030f} - Z_{P_{2002b}}. \end{aligned}$$

At step 2112, the engineering tool may calculate the critical depth of cut provided by the selected control point (Δ_{P_i}) by determining the maximum value of the depths of cut of the outlets C_j as controlled by the selected control point P_i (Δ_{C_j}) and calculated in step 2110. This determination may be expressed by the following equation:

$$\Delta_{P_i} = \max \{ \Delta_{C_j} \}.$$

For example, control point P_{2002b} may be selected in step 2110 and the depths of cut for outlets 2030a, 2030b, 2030c, and 2030f as controlled by control point P_{2002b} (Δ_{2030a} , Δ_{2030b} , Δ_{2030c} , and Δ_{2030f} , respectively) may also be determined in step 2110, as shown above. Accordingly, the critical depth of cut provided by control point P_{2002b} ($\Delta_{P_{2002b}}$) may be calculated at step 2112 using the following equation:

$$\Delta_{P2002b} = \max [\Delta_{2030a}, \Delta_{2030b}, \Delta_{2030c}, \Delta_{2030f}].$$

The engineering tool may repeat steps 2110 and 2112 for all of the control points P_i identified in step 2106 to determine the critical depth of cut provided by all control points P_i located at radial coordinate R_f . For example, the engineering tool may perform
 5 steps 2110 and 2112 with respect to control points P_{2002d} and P_{2002f} to determine the critical depth of cut provided by control points P_{2002d} and P_{2002f} with respect to cutlets 2030a, 2030b, 2030c, and 2030f at radial coordinate R_F shown in FIGURES 20A and 20B (e.g., Δ_{P2002d} and Δ_{P2002f} , respectively).

At step 2114, the engineering tool may calculate an overall critical depth of cut at
 10 the radial coordinate R_f (Δ_{Rf}) selected in step 2106. The engineering tool may calculate the overall critical depth of cut at the selected radial coordinate R_f (Δ_{Rf}) by determining a minimum value of the critical depths of cut of control points P_i (Δ_{Pi}) determined in steps 2110 and 2112. This determination may be expressed by the following equation:

$$\Delta_{Rf} = \min \{ \Delta_{Pi} \}.$$

15 For example, the engineering tool may determine the overall critical depth of cut at radial coordinate R_F of FIGURES 20A and 20B by using the following equation:

$$\Delta_{RF} = \min [\Delta_{P2002b}, \Delta_{P2002d}, \Delta_{P2002f}].$$

The engineering tool may repeat steps 2106 through 2114 to determine the overall critical depth of cut at all the radial coordinates R_f generated at step 2104.

20 At step 2116, the engineering tool may plot the overall critical depth of cut (Δ_{Rf}) for each radial coordinate R_f , as a function of each radial coordinate R_f . Accordingly, a critical depth of cut control curve may be calculated and plotted for the radial swath associated with the radial coordinates R_f . For example, the engineering tool may plot the overall critical depth of cut for each radial coordinate R_f located within radial swath 2008,
 25 such that the critical depth of cut control curve for swath 2008 may be determined and plotted, as depicted in FIGURE 20C. Following step 2116, method 2100 may end. Accordingly, method 2100 may be used to calculate and plot a critical depth of cut control curve of a drill bit. The critical depth of cut control curve may be used to determine whether the drill bit provides a substantially even control of the depth of cut of
 30 the drill bit. Therefore, the critical depth of cut control curve may be used to modify the DOCCs and/or blades of the drill bit configured to control the depth of cut of the drill bit.

Modifications, additions, or omissions may be made to method 2100 without departing from the scope of the present disclosure. For example, the order of the steps may be performed in a different manner than that described and some steps may be performed at the same time. Additionally, each individual step may include additional steps without departing from the scope of the present disclosure.

Although the present disclosure has been described with several embodiments, various changes and modifications may be suggested to one skilled in the art. For example, although the present disclosure describes the configurations of blades and DOCCs with respect to drill bits, the same principles may be used to control the depth of cut of any suitable drilling tool according to the present disclosure. It is intended that the present disclosure encompasses such changes and modifications as fall within the scope of the appended claims.

WHAT IS CLAIMED IS:

1. A method of configuring a blade of a drill bit comprising:
determining a first desired depth of cut for a first radial swath associated with a bit face of a drill bit, the first radial swath associated with a first area of the bit face;
5 identifying a first plurality of cutting elements located on the bit face that each include at least a portion located within the first radial swath; and
configuring a first blade surface of a blade associated with the bit face, the first blade surface located within the first radial swath and configured based on the first desired depth of cut for the first radial swath and each portion of the first plurality of
10 cutting elements located within the first radial swath.

2. The method of Claim 1, further comprising:
determining a second desired depth of cut for a second radial swath associated with the bit face of the drill bit, the second radial swath associated with a second area of
15 the bit face;
identifying a second plurality of cutting elements located on the bit face that each include at least a portion located within the second radial swath; and
configuring a second blade surface of the blade, the second blade surface located within the second radial swath and configured based on the second desired depth of cut
20 for the second radial swath and each portion of the second plurality of cutting elements located within the second radial swath.

3. The method of Claim 2, wherein the second radial swath is proximate the first radial swath such that the second radial swath overlaps the first radial swath on the
25 bit face.

4. The method of Claim 2, wherein the second radial swath is proximate the first radial swath such that the second radial swath is located adjacent to the first radial swath on the bit face.
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5. The method of Claim 2, wherein the second radial swath is proximate the first radial swath such that the second radial swath is separated from the first radial swath on the bit face.

6. The method of Claim 1, further comprising configuring a plurality of blade surfaces of a plurality of blades associated with the bit face, the plurality of blade surfaces located within the first radial swath and configured based on the first desired depth of cut for the first radial swath and each portion of the first plurality of cutting elements located within the first radial swath.

7. The method of Claim 6, further comprising configuring the plurality of blade surfaces to balance lateral forces of the drill bit created by the plurality of blade surfaces.

8. The method of Claim 1, further comprising:
calculating a desired axial underexposure between the first blade surface and the portions of the first plurality of cutting elements located within the first radial swath based on the first desired depth of cut; and
calculating an axial coordinate for the first blade surface based on the desired axial underexposure, the axial coordinate associated with a location along a rotational axis of the drill bit.

9. The method of Claim 1, further comprising:
determining an angular coordinate and a radial coordinate for a blade point associated with the first blade surface and located within the first radial swath, the angular coordinate and the radial coordinate being defined in a plane substantially perpendicular to a rotational axis of the drill bit;
determining an intersection point for each of the first plurality of cutting elements, each of the intersection points having approximately the same radial coordinate as the blade point;
determining an angular coordinate and an axial coordinate associated with each of the intersection points;
calculating an axial coordinate for the blade point based on the axial coordinate, the radial coordinate and the angular coordinate of the intersection points, the angular coordinate of the blade point and the first desired depth of cut; and

configuring the first blade surface at the blade point based on the axial coordinate of the blade point such that the first blade surface controls a depth of cut of the drill bit at the radial coordinate according to the first desired depth of cut.

- 5 10. The method of Claim 9, further comprising:
 determining a plurality of radial coordinates associated with the first blade surface, each of the plurality of radial coordinates associated with one of a plurality of blade points located within the first radial swath;
 determining a plurality of intersection points associated with the first plurality of
10 cutting elements, each of the plurality of intersection points having approximately the same radial coordinate as one of the plurality of blade points;
 determining an angular coordinate and an axial coordinate associated with each of the plurality of intersection points;
 calculating a plurality of axial coordinates for each of the plurality of blade points
15 based on the first desired depth of cut and the plurality of axial and angular coordinates of the intersection points having approximately the same radial coordinate as the respective blade point; and
 configuring the first blade surface based on the plurality of axial coordinates of the plurality of blade points such that the first blade surface controls the depth of cut of
20 the drill bit at the plurality of radial coordinates according to the first desired depth of cut.

11. The method of Claim 10, further comprising:
 determining an axial curvature associated with the plurality of blade points; and
 configuring the first blade surface based on the axial curvature associated with the
25 plurality of blade points.

12. The method of Claim 10, further comprising:
 determining an axial curvature associated with the plurality of blade points;
 fitting at least a portion of the axial curvature with a circle having a curvature
30 approximating the axial curvature associated with the plurality of blade points; and
 configuring at least a portion of the first blade surface based on the curvature of the circle.

13. The method of Claim 10, further comprising:
performing a two dimensional interpolation of the plurality of axial coordinates associated with the plurality of blade points to obtain smoothed axial coordinates associated with the plurality of blade points; and
5 configuring the first blade surface based on the smoothed axial coordinates associated with the plurality of blade points.

14. The method of Claim 10, further comprising selecting the plurality of blade points based on the plurality of blade points each being associated with a cross-
10 sectional line that substantially intersects the first radial swath.

15. The method of Claim 1, further comprising:
calculating a critical depth of cut control curve associated with the first radial swath;
15 comparing the critical depth of cut control curve with the first desired depth of cut associated with the first radial swath; and
determining whether the first blade surface adequately controls a depth of cut of the drill bit within the first radial swath based on the critical depth of cut control curve.

20 16. The method of Claim 1, wherein the plurality of cutting elements comprises all the cutting elements located on the bit face that each include at least a portion located within the first radial swath.

25 17. The method of Claim 1, wherein each portion of the plurality of cutting elements includes a cutting edge of its associated cutting element, the cutting edge located within a cutting zone of the cutting element.

18. A method of configuring a blade of a drill bit comprising:
determining a desired depth of cut for a radial swath associated with a bit face of a
30 drill bit, the radial swath associated with an area of the bit face;
identifying all cutting elements located on the bit face that each include at least a portion located within the radial swath; and

configuring a blade surface of a blade associated with the bit face, the blade surface located within the radial swath and configured based on the desired depth of cut for the radial swath and each portion of all the cutting elements located within the radial swath.

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19. The method of Claim 18, further comprising configuring a plurality of blade surfaces associated with the bit face, the plurality of blade surfaces located within the radial swath and configured based on the desired depth of cut for the radial swath and each portion of all the cutting elements located within the radial swath.

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20. The method of Claim 19, further comprising configuring the plurality of blade surfaces to balance lateral forces of the drill bit created by the plurality of blade surfaces.

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21. The method of Claim 18, further comprising:

calculating a desired axial underexposure between the blade surface and the portions of all the cutting elements located within the radial swath based on the desired depth of cut; and

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calculating an axial coordinate for the blade surface based on the desired axial underexposure, the axial coordinate associated with a location along a rotational axis of the drill bit.

25

22. The method of Claim 18, further comprising:

determining an angular coordinate and a radial coordinate for a blade point associated with the blade surface and located within the radial swath, the angular coordinate and the radial coordinate being defined in a plane substantially perpendicular to a rotational axis of the drill bit;

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determining an intersection point for each of the cutting elements that includes at least a portion within the radial swath, each of the intersection points having approximately the same radial coordinate as the blade point;

determining an angular coordinate and an axial coordinate associated with each of the intersection points;

calculating an axial coordinate for the blade point based on the axial coordinate, the radial coordinate and the angular coordinate of the intersection points, the angular coordinate of the blade point and the desired depth of cut; and

5 configuring the blade surface at the blade point based on the axial coordinate of the blade point such that the blade surface controls a depth of cut of the drill bit at the radial coordinate according to the desired depth of cut.

23. The method of Claim 22, further comprising:

10 determining a plurality of radial coordinates associated with the blade surface, each of the plurality of radial coordinates associated with one of a plurality of blade points located within the radial swath;

15 determining a plurality of intersection points associated with each of the cutting elements that includes at least a portion within the radial swath, each of the plurality of intersection points having approximately the same radial coordinate as one of the plurality of blade points;

determining an angular coordinate and an axial coordinate associated with each of the plurality of intersection points;

20 calculating a plurality of axial coordinates for each of the plurality of blade points based on the desired depth of cut and the plurality of axial and angular coordinates of the intersection points having approximately the same radial coordinate as the respective blade point; and

25 configuring the blade surface based on the plurality of axial coordinates of the plurality of blade points such that the blade surface controls the depth of cut of the drill bit at the plurality of radial coordinates according to the desired depth of cut.

24. The method of Claim 23, further comprising:

determining an axial curvature associated with the plurality of blade points; and
30 configuring the blade surface based on the axial curvature associated with the plurality of blade points.

25. The method of Claim 23, further comprising:

determining an axial curvature associated with the plurality of blade points;

fitting at least a portion of the axial curvature with a circle having a curvature approximating the axial curvature associated with the plurality of blade points; and configuring at least a portion of the blade surface based on the curvature of the circle.

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26. The method of Claim 23, further comprising:

performing a two dimensional interpolation of the plurality of axial coordinates associated with the plurality of blade points to obtain smoothed axial coordinates associated with the plurality of blade points; and

10 configuring the blade surface based on the smoothed axial coordinates associated with the plurality of blade points.

27. The method of Claim 18, wherein each portion of the plurality of cutting elements includes a cutting edge of its associated cutting element, the cutting edge located
15 within a cutting zone of the cutting element.

28. A drill bit comprising:

a bit body;

a plurality of blades disposed on the bit body to create a bit face;

20 a rotational axis extending through the bit body;

a first plurality of cutting elements each disposed on one of the plurality of blades and including at least a portion located within a first radial swath of the bit face, the first radial swath associated with a first area of the bit face; and

25 a first blade surface associated with one of the plurality of blades, the first blade surface configured to control a first depth of cut associated with the first plurality of cutting elements based on a first desired depth of cut for the first radial swath and each portion of the first plurality of cutting elements located within the first radial swath.

29. The drill bit of Claim 28, further comprising:

30 a second plurality of cutting elements each disposed on one of the plurality of blades and including at least a portion located within a second radial swath of the bit face, the second radial swath associated with a second area of the bit face; and

a second blade surface associated with one of the plurality of blades, the second blade surface configured to control a second depth of cut associated with the second plurality of cutting elements based on a second desired depth of cut for the second radial swath and each portion of the second plurality of cutting elements located within the
5 second radial swath.

30. The drill bit of Claim 28, further comprising a plurality of blade surfaces each associated with one of the plurality of blades and configured to control the first depth of cut associated with the first plurality of cutting elements at the first radial swath
10 based on the first desired depth of cut for the first radial swath and each portion of the first plurality of cutting elements located within the first radial swath.

31. The drill bit of Claim 30, wherein the plurality of blade surfaces are further configured to balance lateral forces of the drill bit associated with the plurality of blades.
15

32. The drill bit of Claim 28, wherein the first blade surface comprises an axial coordinate calculated based on the first desired depth of cut and a desired axial underexposure between the first blade surface and the portions of the first plurality of cutting elements located within the first radial swath, the axial coordinate associated with
20 a location along the rotational axis of the drill bit.

33. The drill bit of Claim 28, further comprising:
a blade point located within the first radial swath and associated with the first blade surface, the blade point having a radial coordinate and an angular coordinate, the
25 radial coordinate and the angular coordinate of the blade point defined in a plane substantially perpendicular to the rotational axis of the drill bit;

a plurality of intersection points associated with the first plurality of cutting elements, each of the plurality of intersection points having approximately the same radial coordinate as the blade point;

30 a plurality of axial coordinates each associated with one of the intersection points, each axial coordinate associated with a location along the rotational axis;

an axial coordinate associated with the blade point and calculated based on the axial coordinates of the intersection points and the first desired depth of cut; and

wherein the first blade surface is configured at the blade point based on the axial coordinate, the radial coordinate, and the angular coordinate of the blade point such that the first blade surface controls a depth of cut of the drill bit at the radial coordinate according to the first desired depth of cut.

5

34. The drill bit of Claim 28, wherein the first blade surface comprises an axial curvature configured based on the first desired depth of cut for the first radial swath and each portion of the first plurality of cutting elements located within the first radial swath.

10

35. The drill bit of Claim 28, wherein the first blade surface is further configured according to axial coordinates associated with a cross-sectional line that intersects the first radial swath in a plane substantially perpendicular to the rotational axis of the drill bit, the axial coordinates associated with the cross-sectional line determined based on the first desired depth of cut for the first radial swath and each portion of the

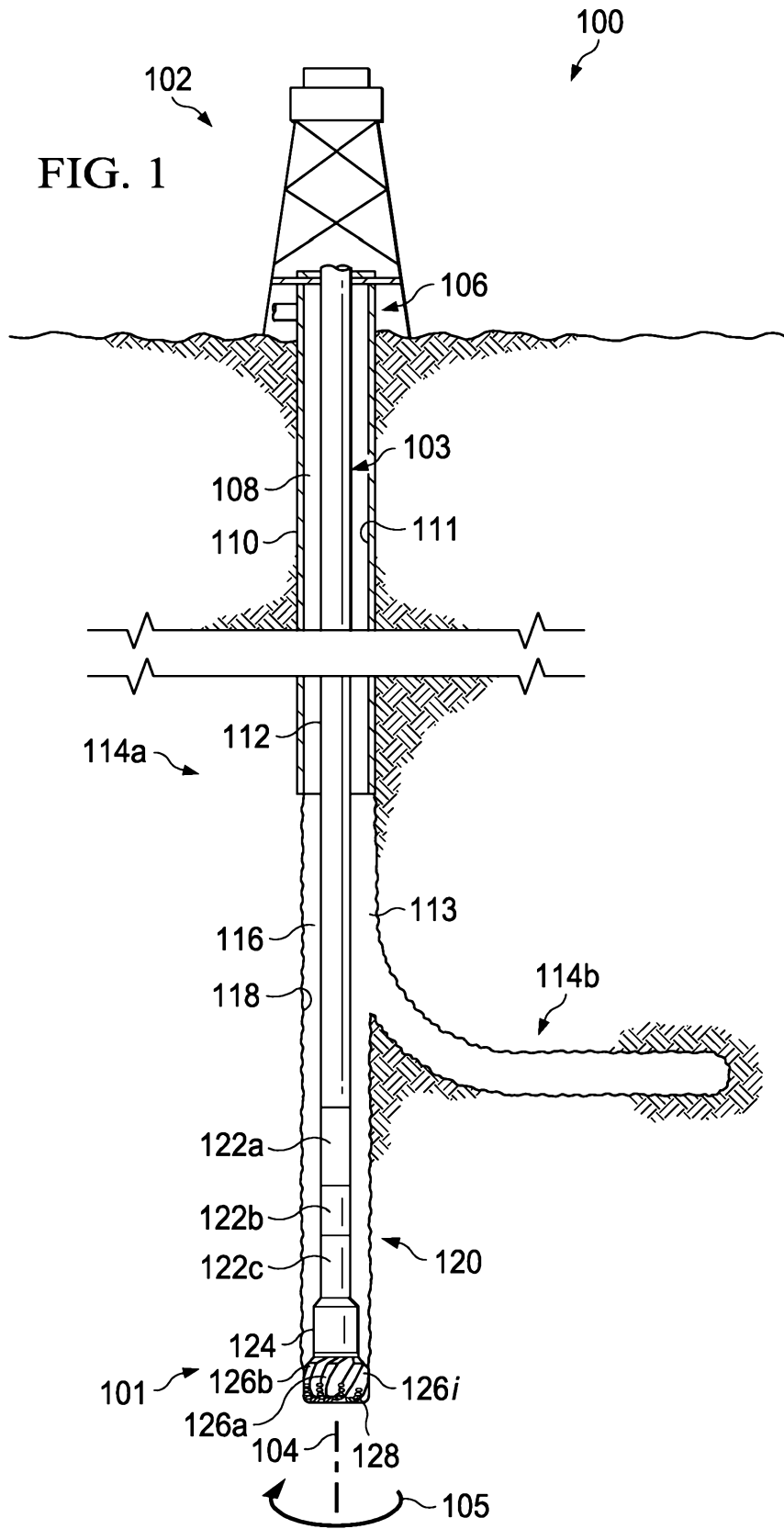
15

36. The drill bit of Claim 28, wherein the plurality of cutting elements comprises all the cutting elements located on the bit face that each include at least a portion located within the first radial swath.

20

37. The drill bit of Claim 28, wherein each portion of the plurality of cutting elements includes a cutting edge of its associated cutting element, the cutting edge located within a cutting zone of the cutting element.

FIG. 1



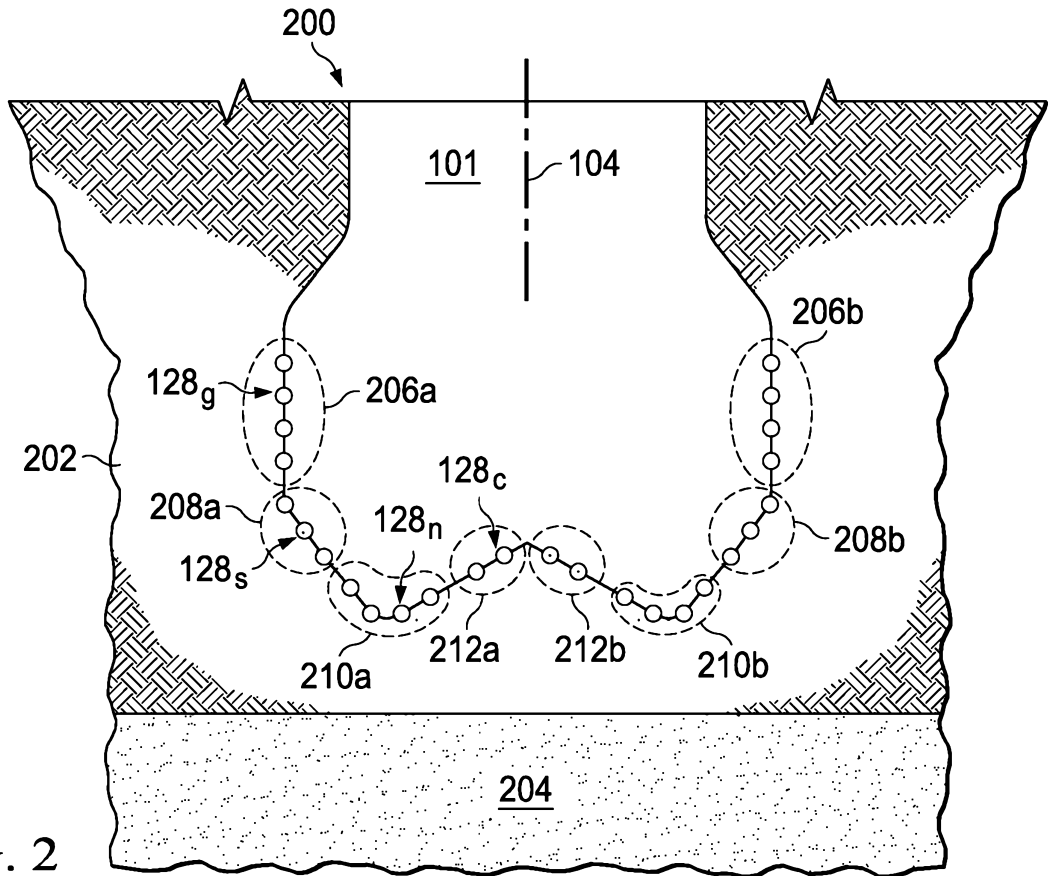


FIG. 2

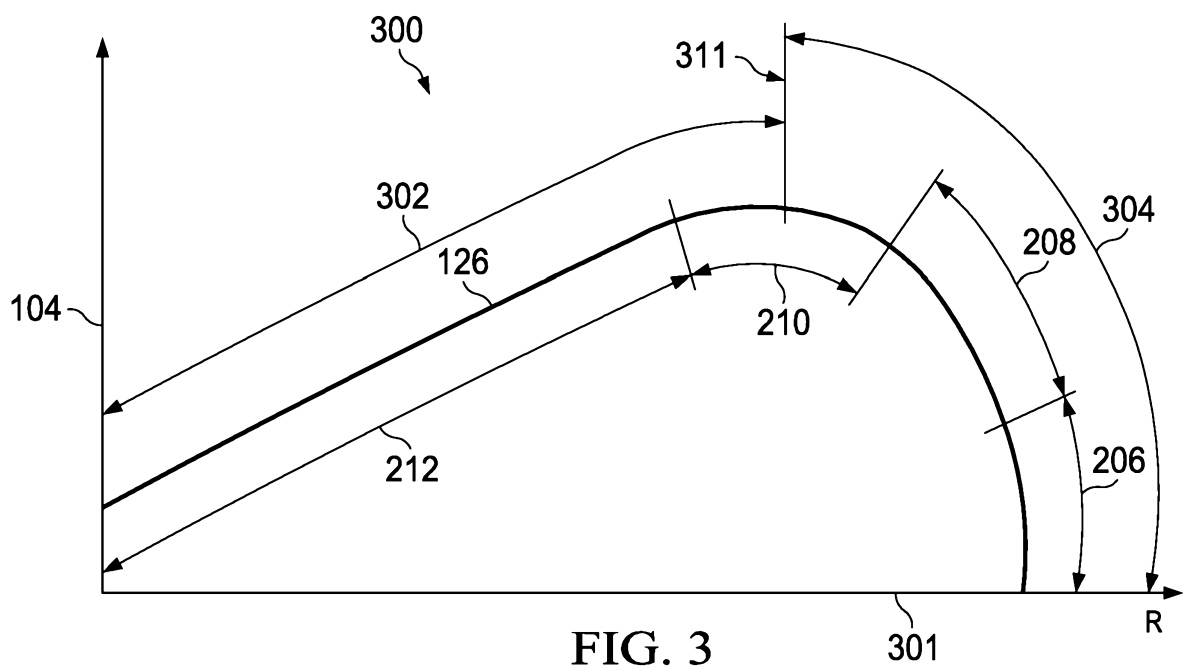
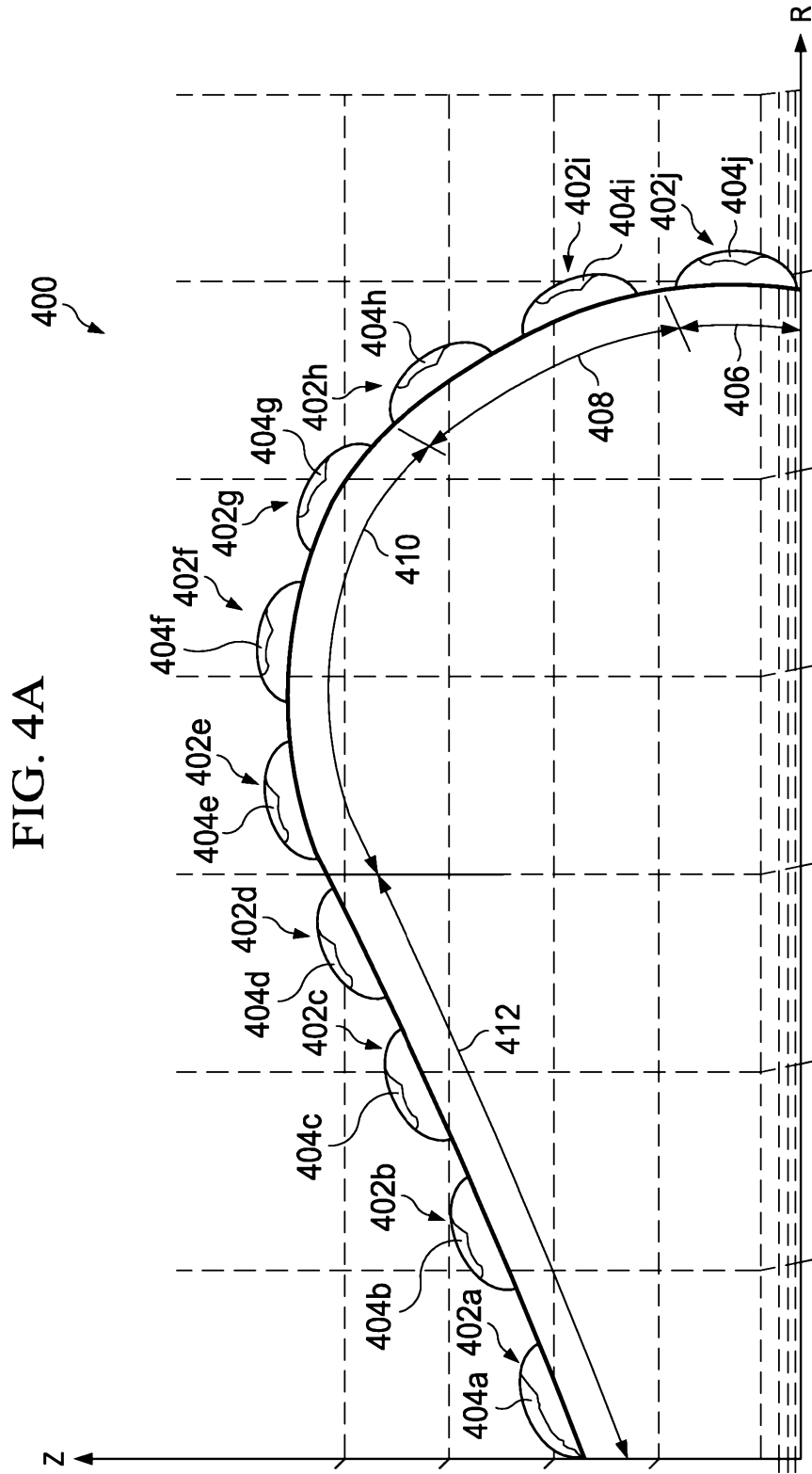


FIG. 3



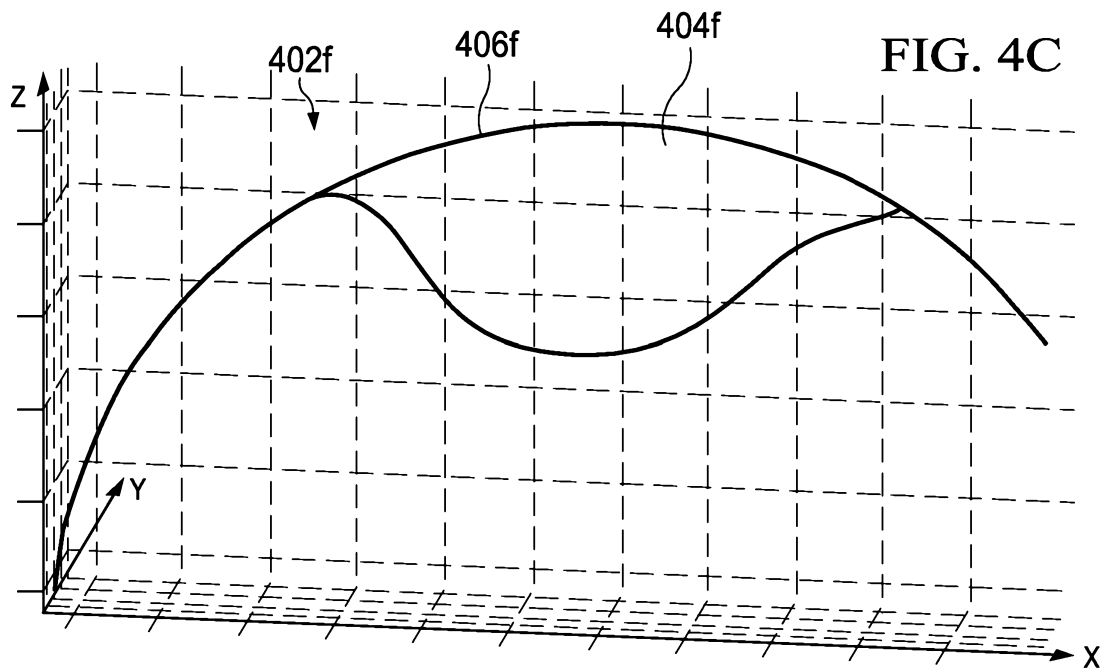
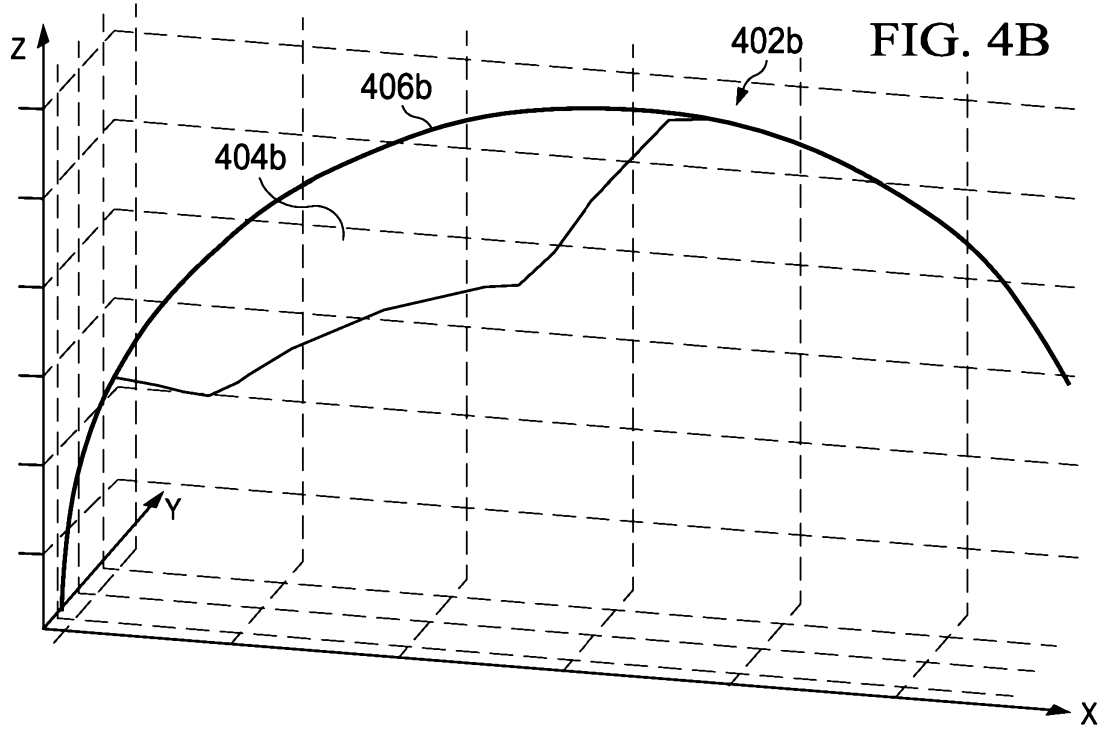


FIG. 4D

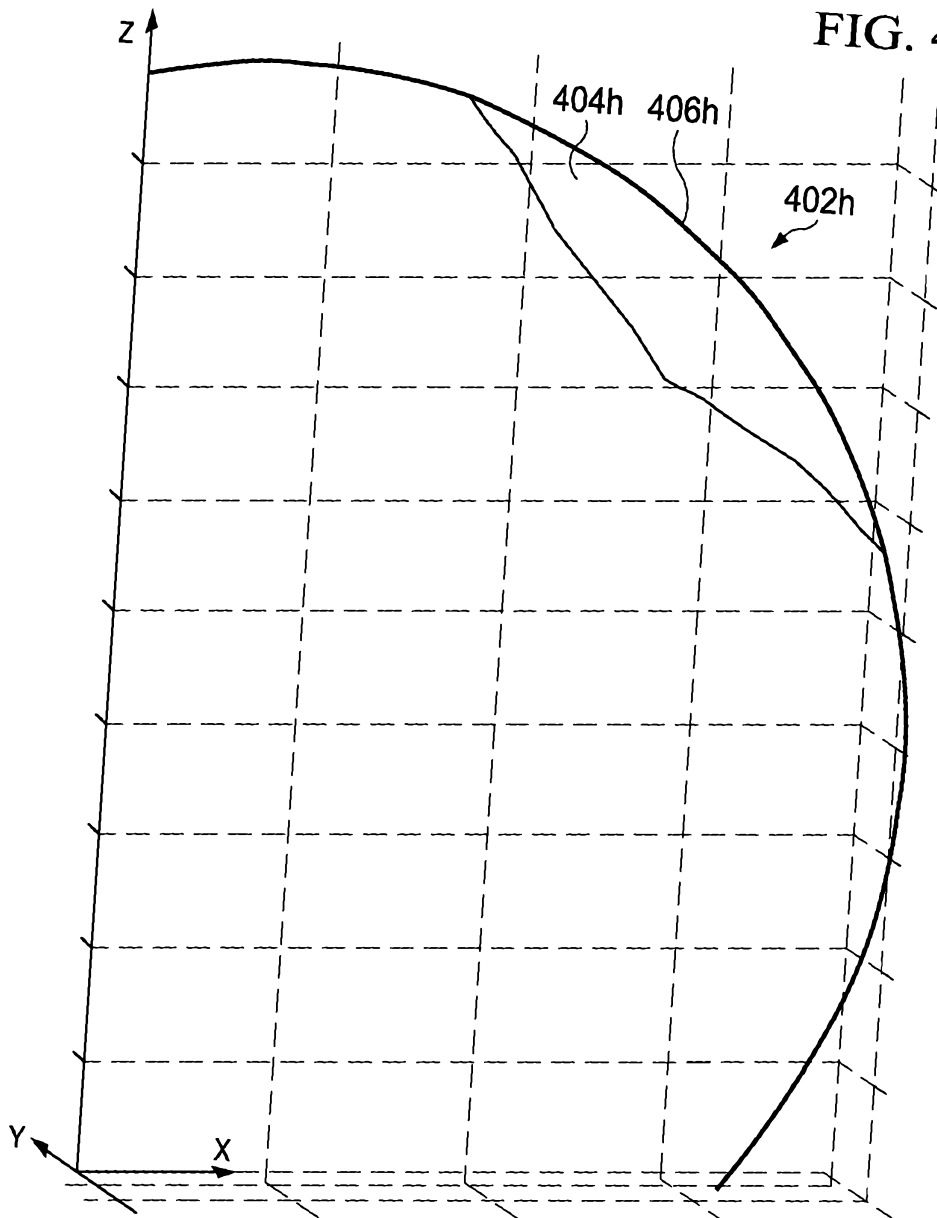


FIG. 5A

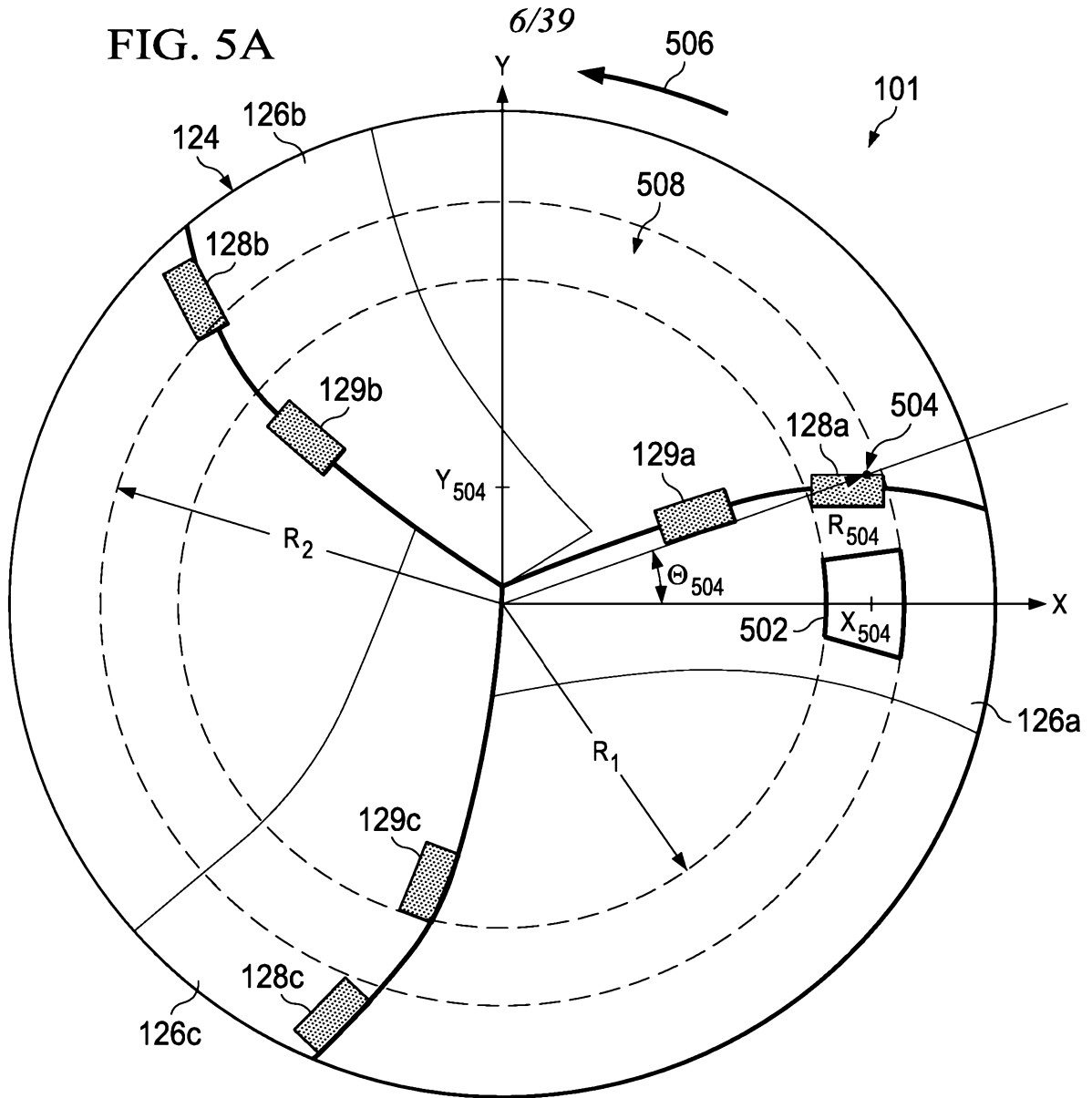
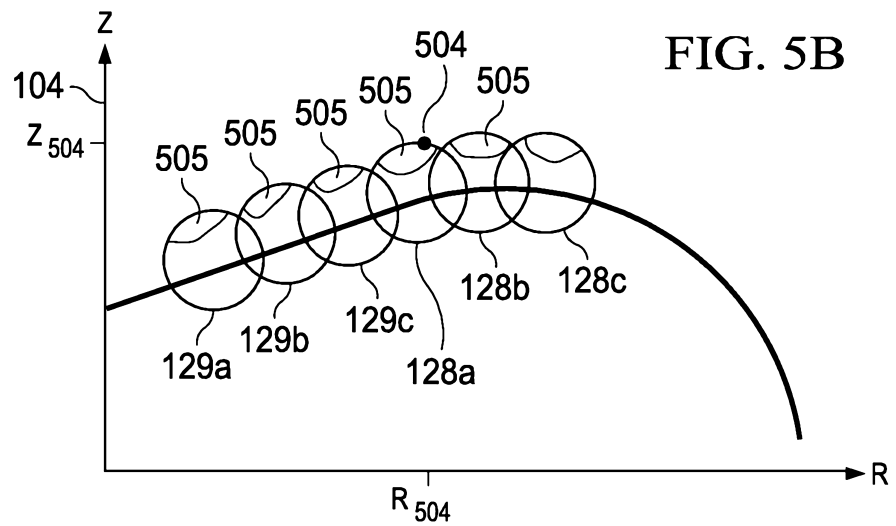
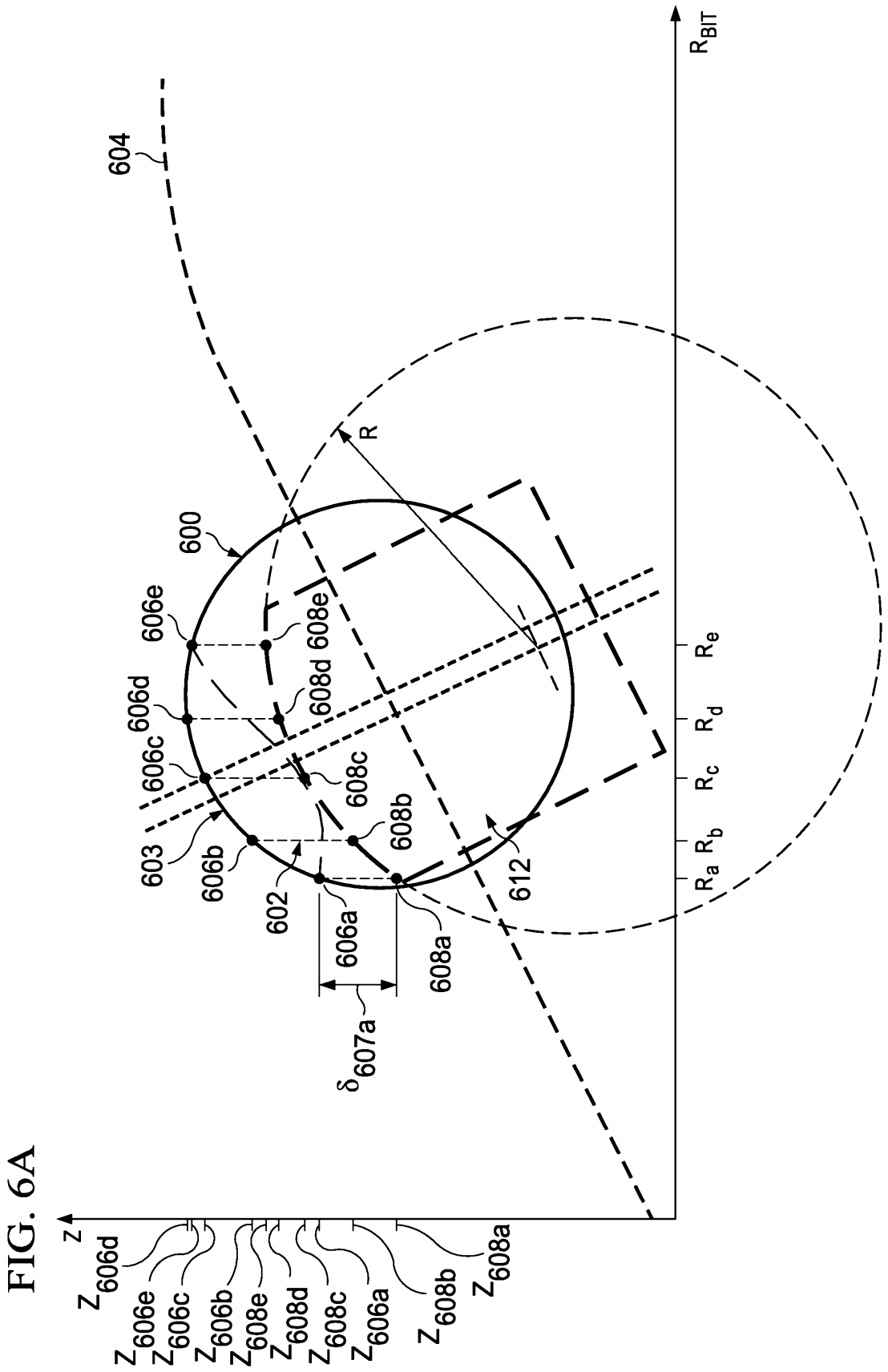


FIG. 5B





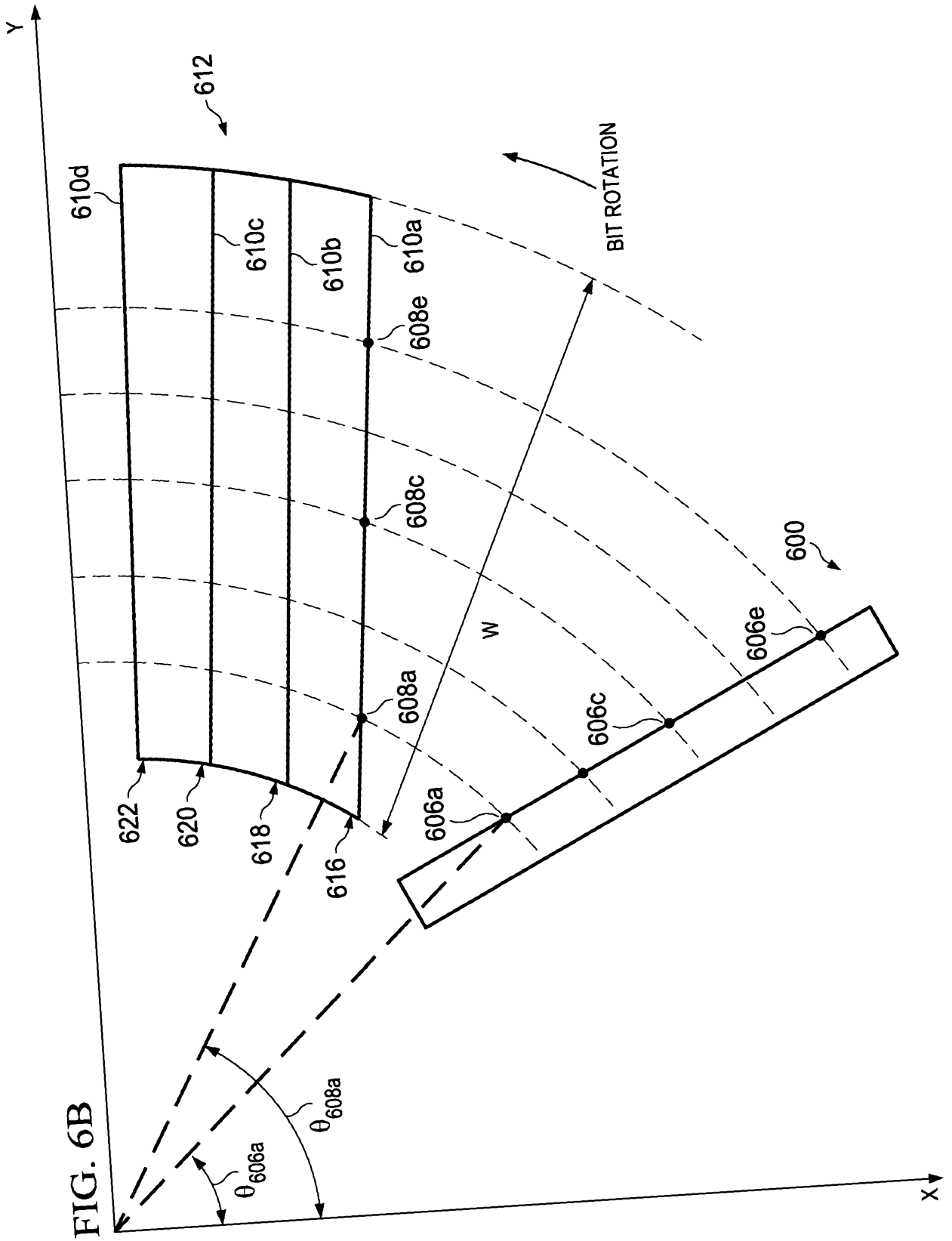


FIG. 6C

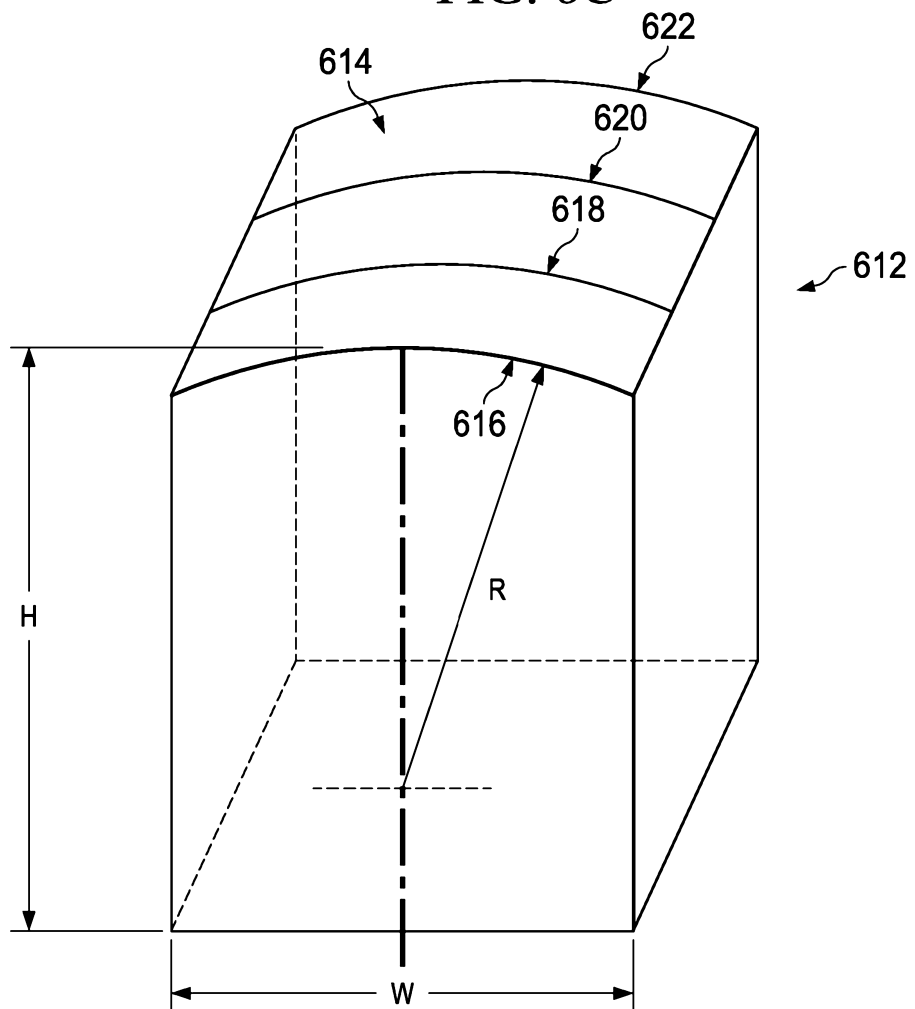
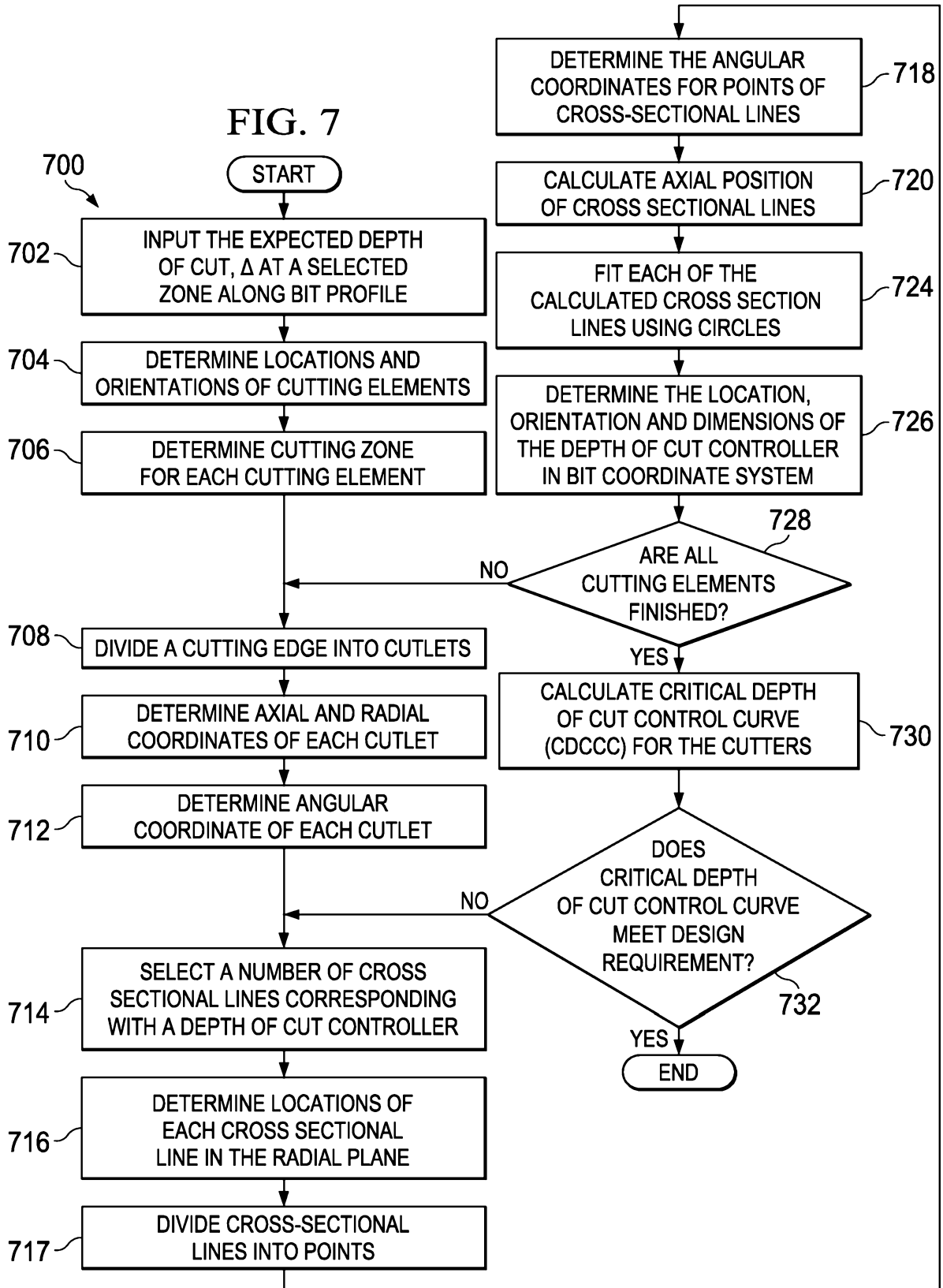
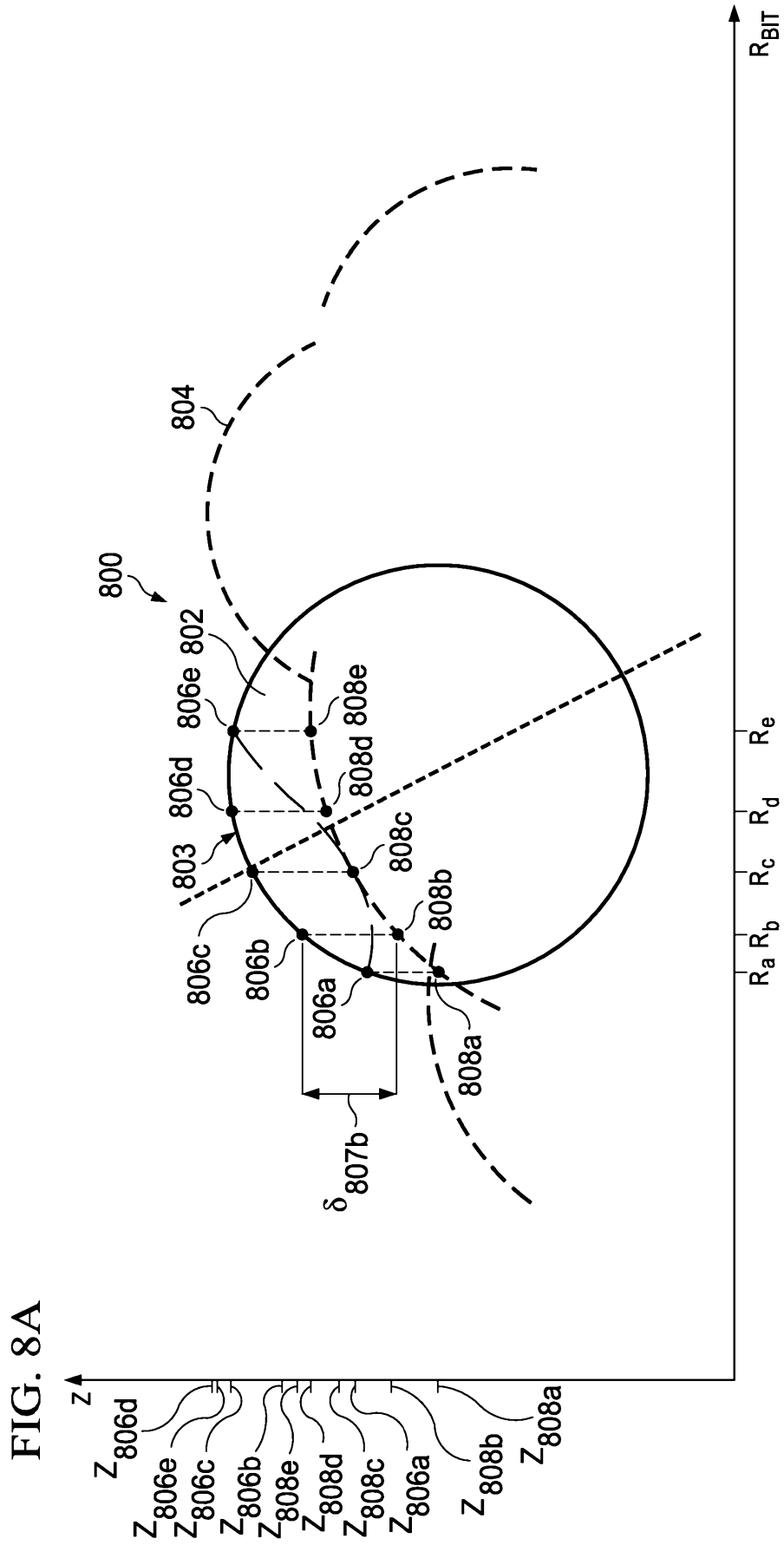


FIG. 7





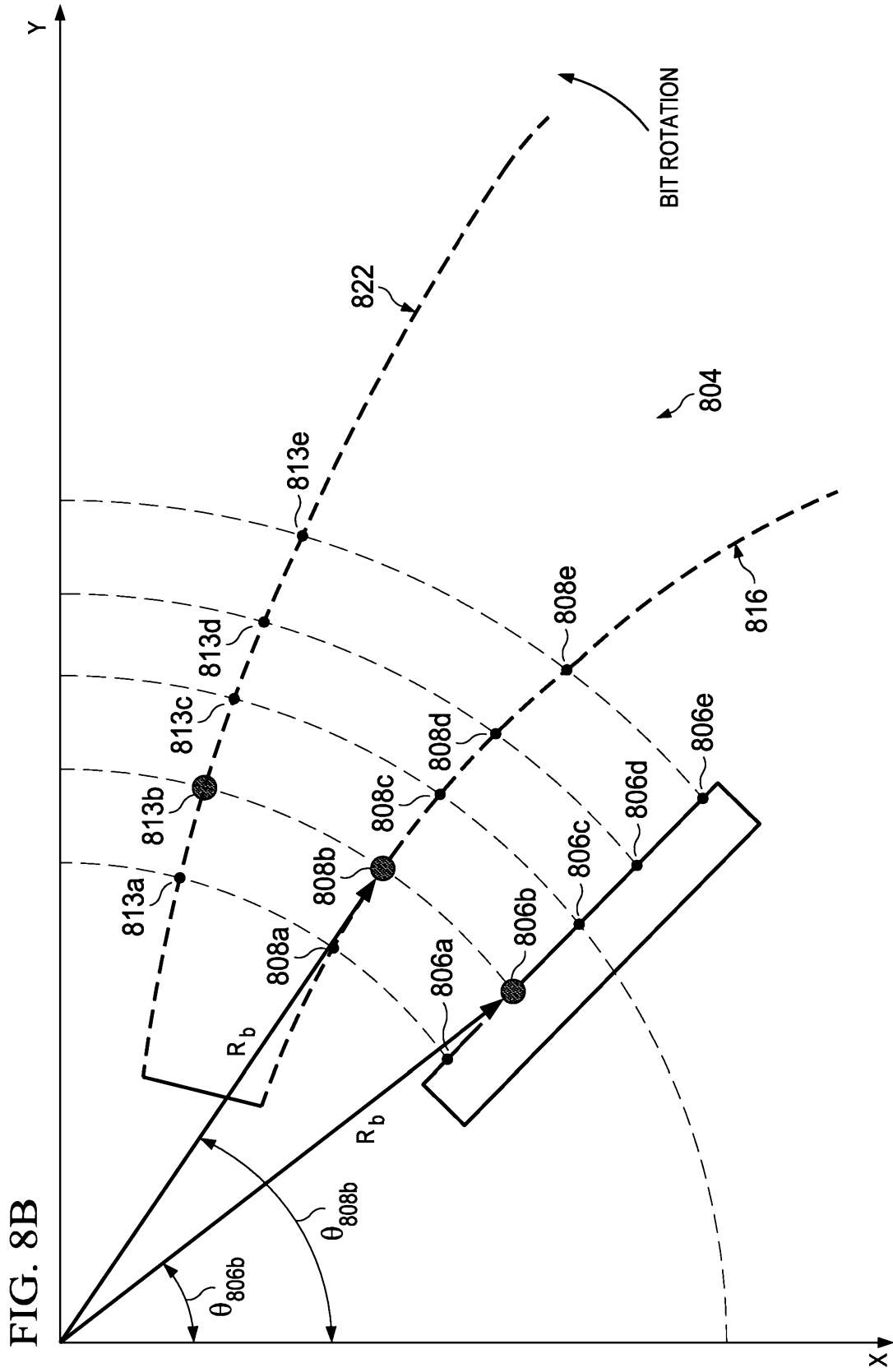


FIG. 9

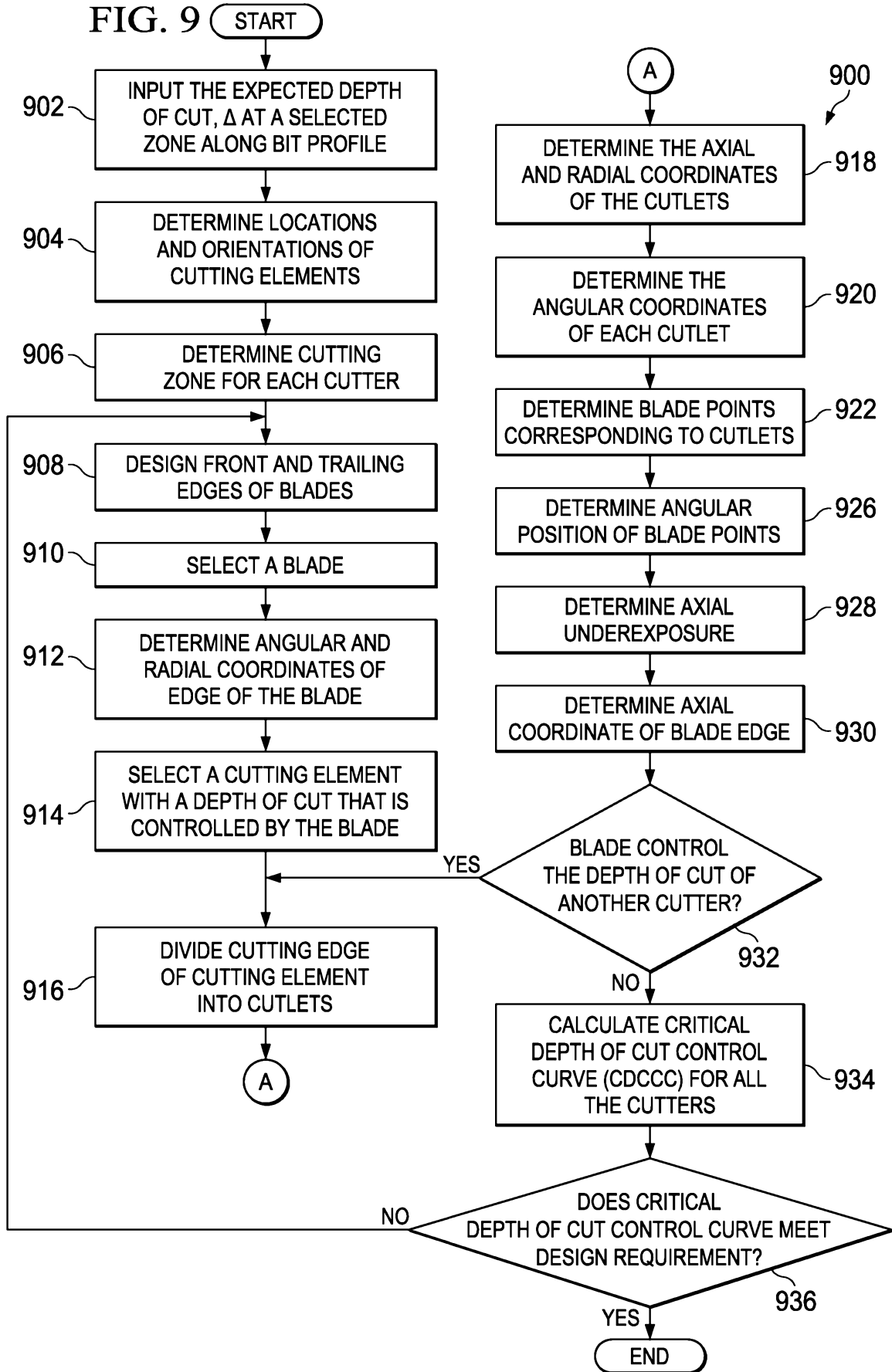
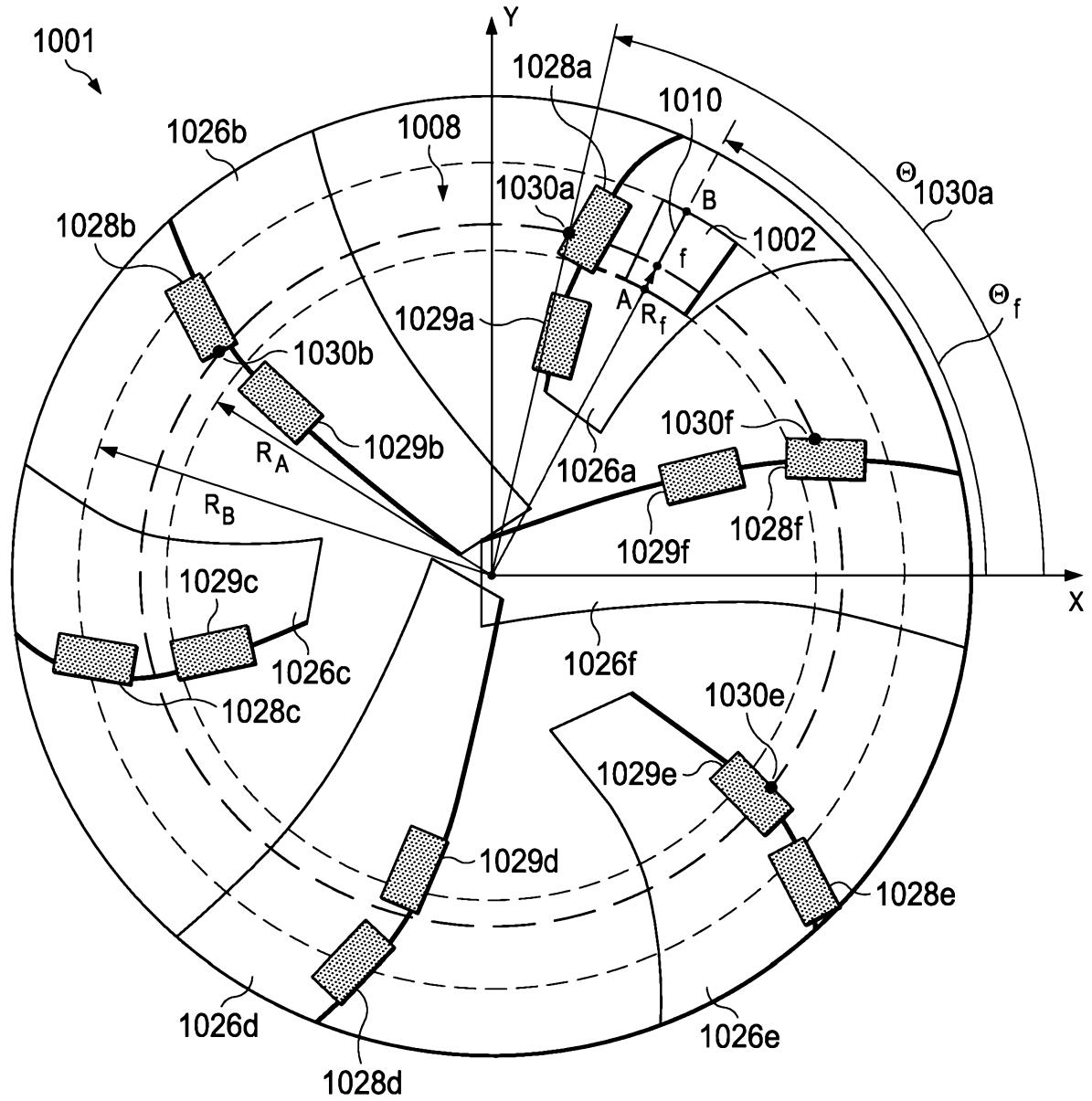


FIG. 10A



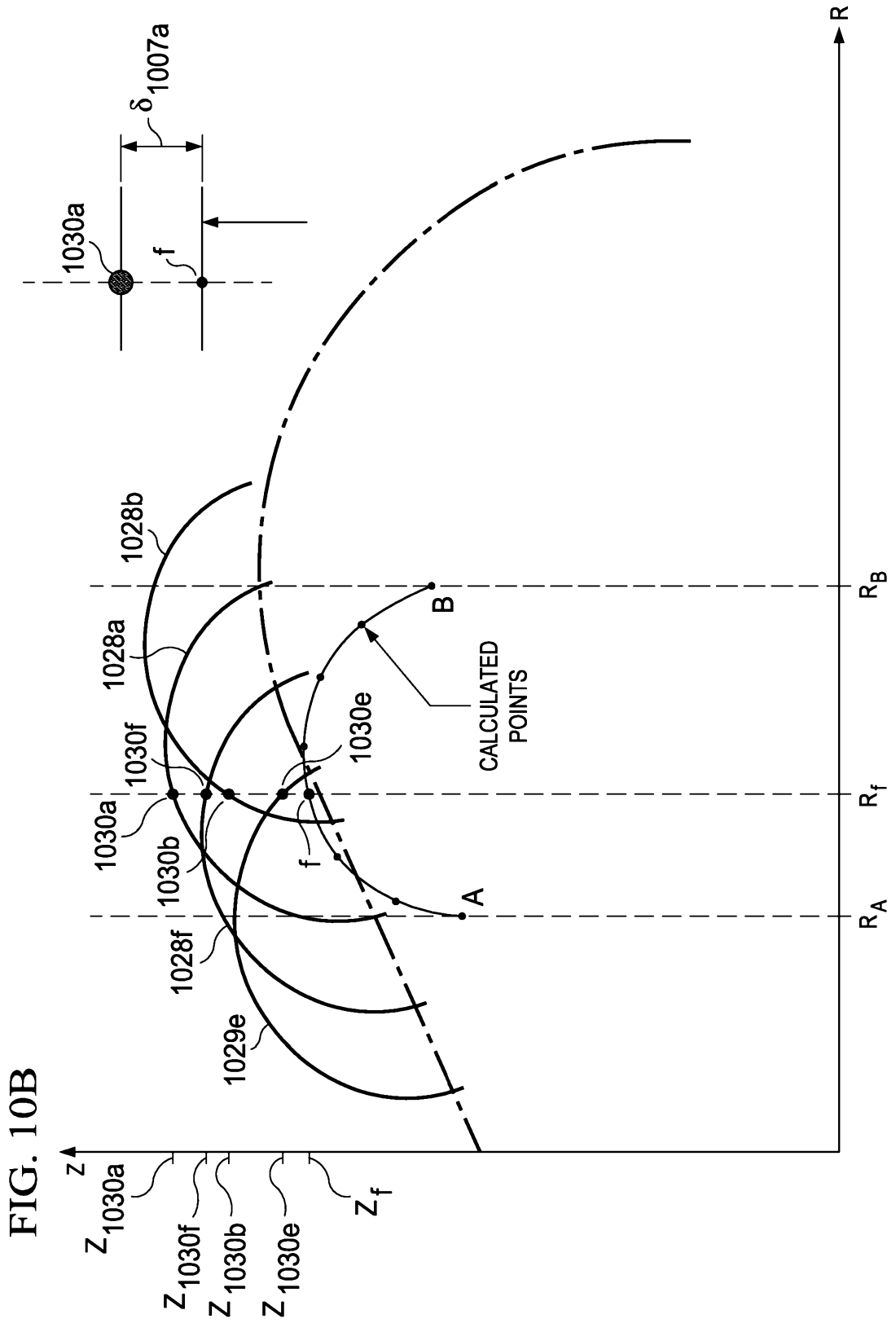


FIG. 10C

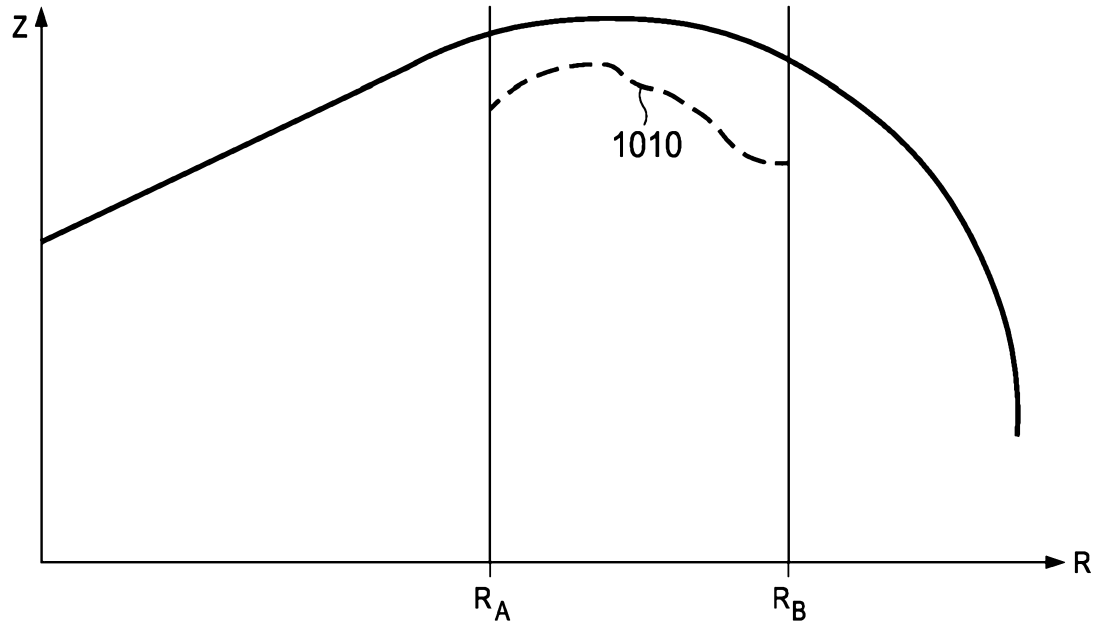
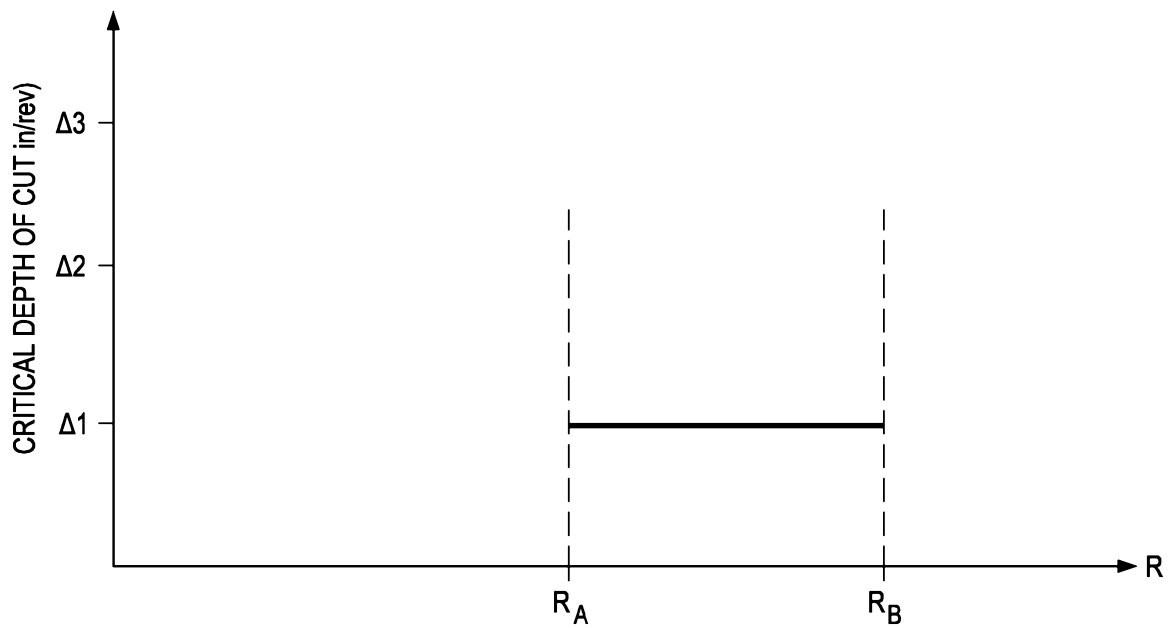
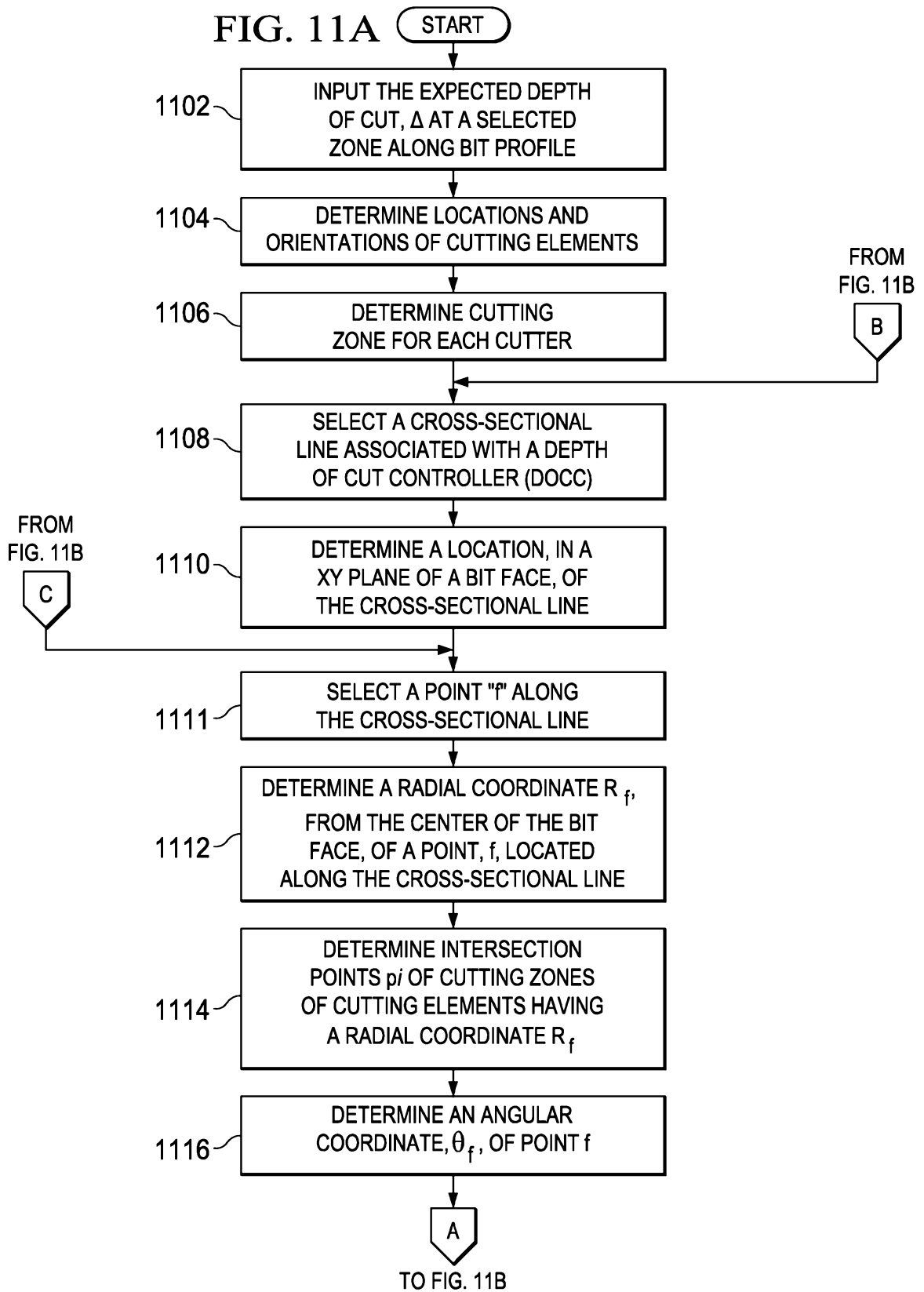


FIG. 10D





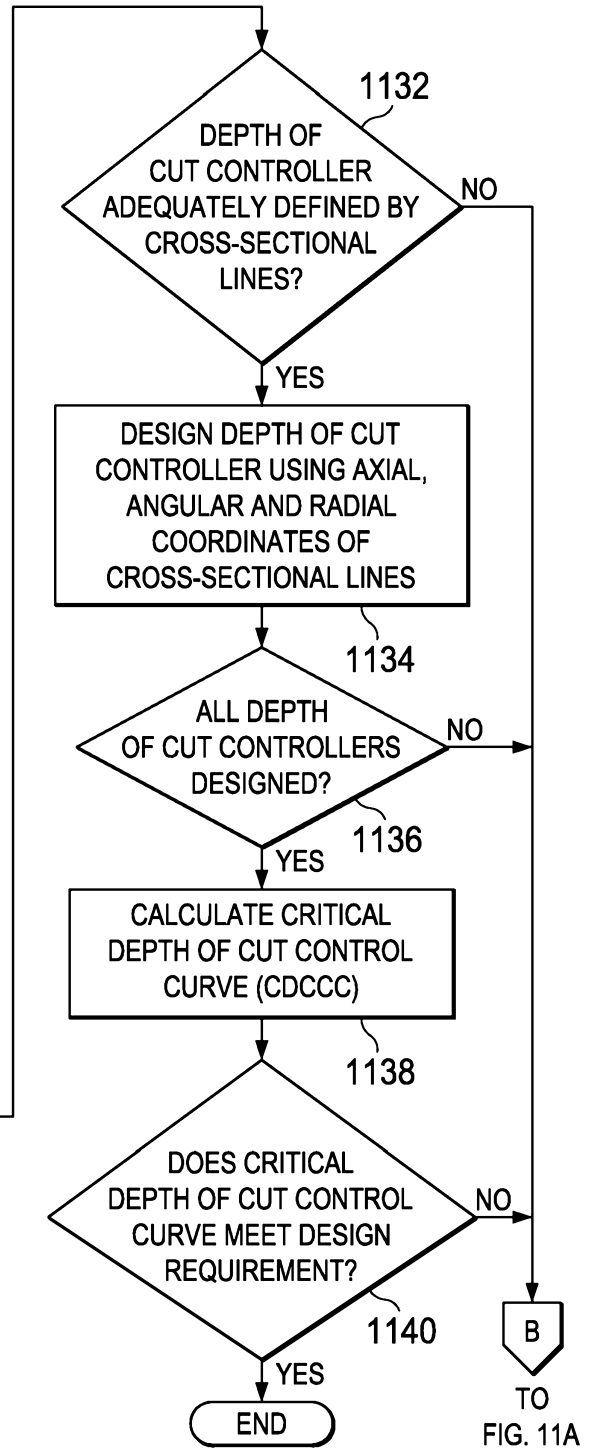
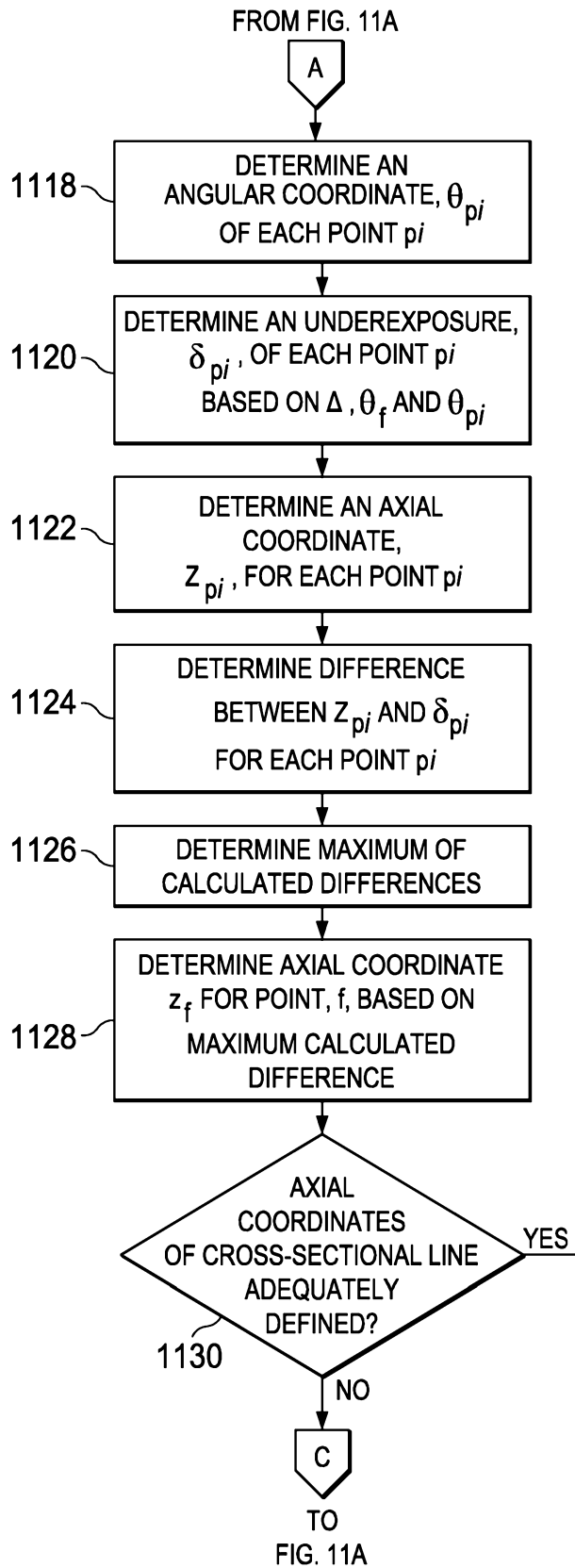


FIG. 11B

1201

FIG. 12A

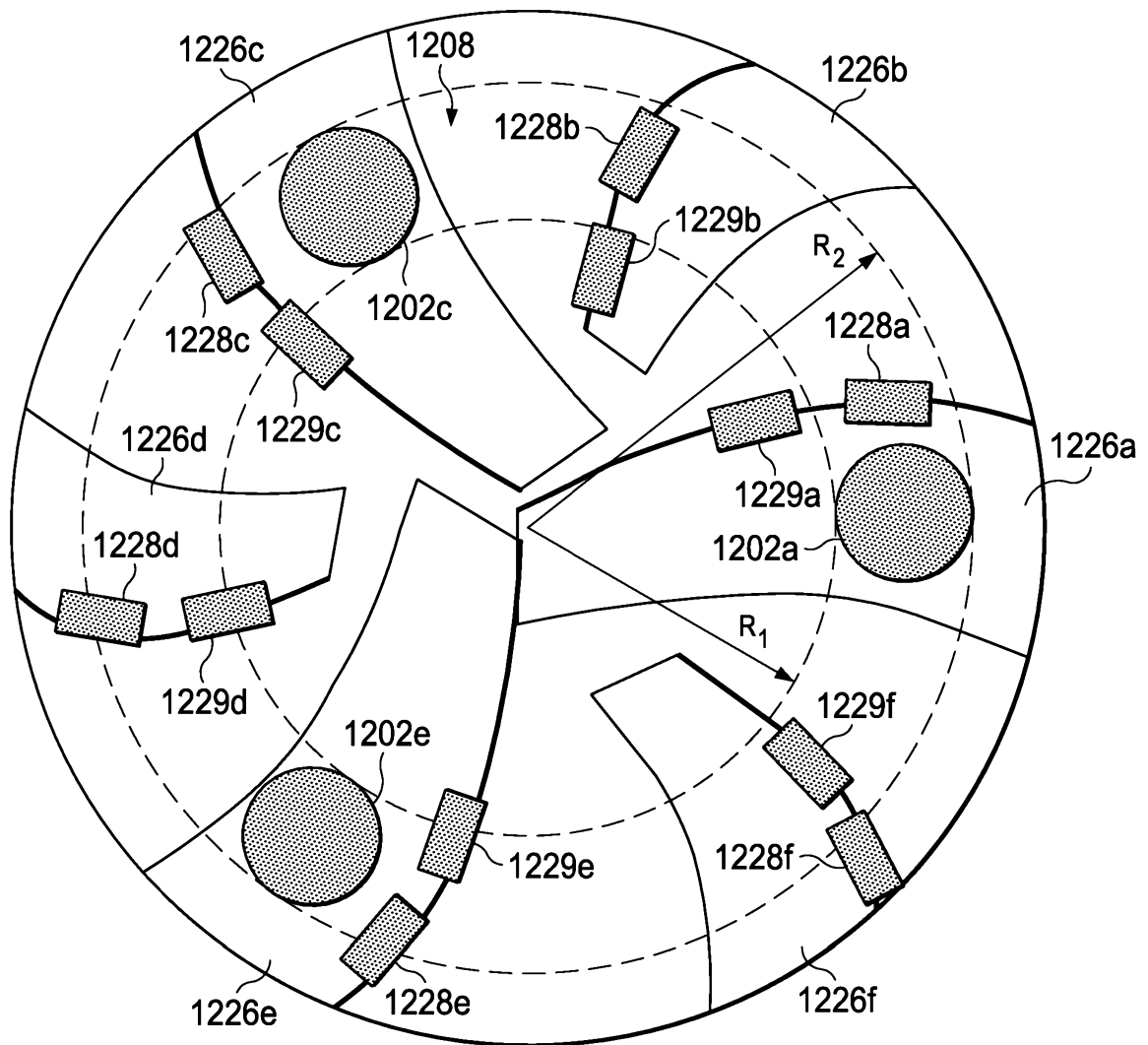
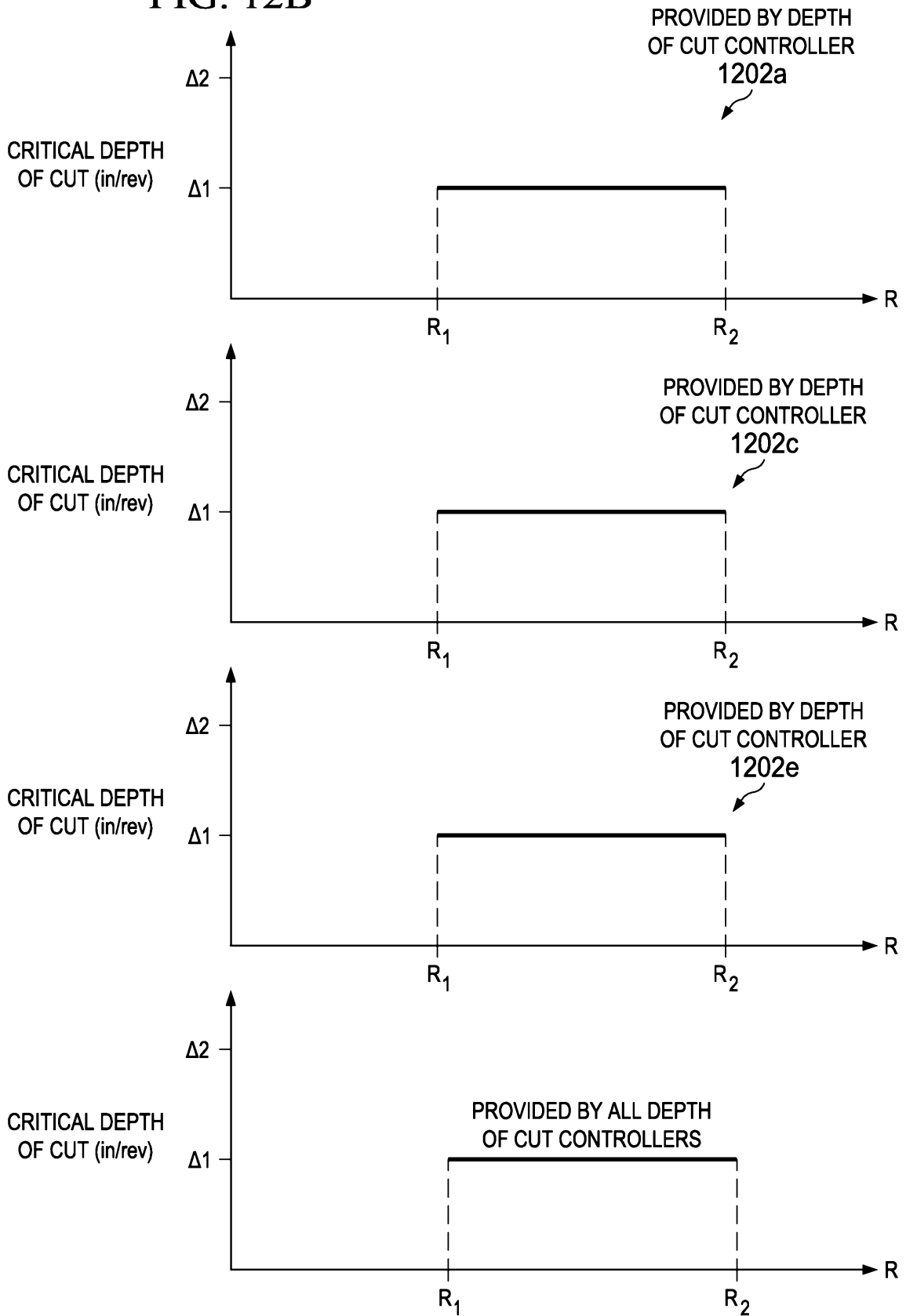
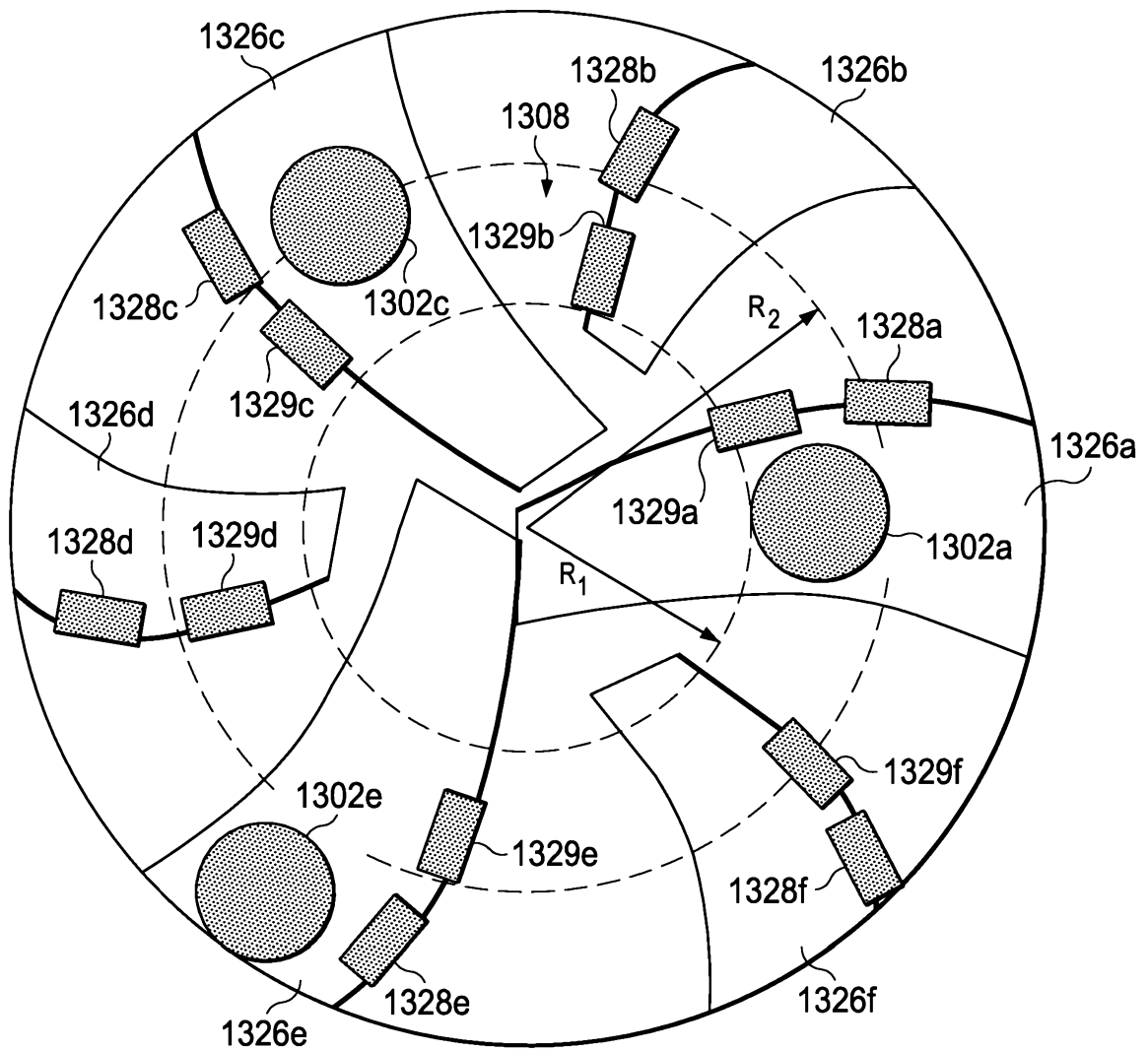


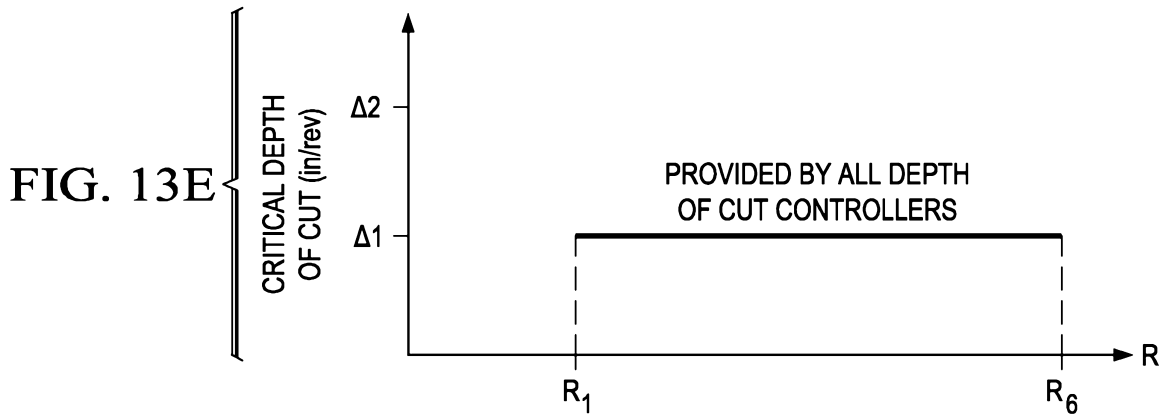
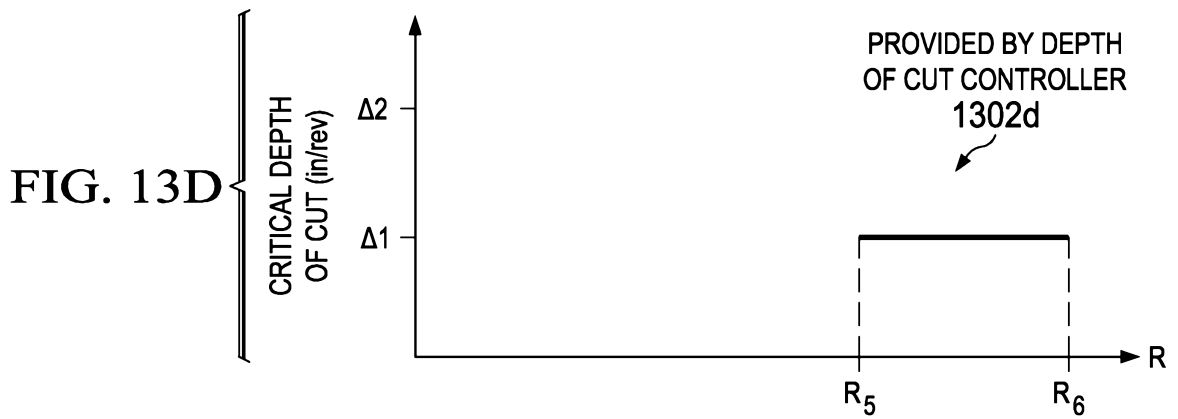
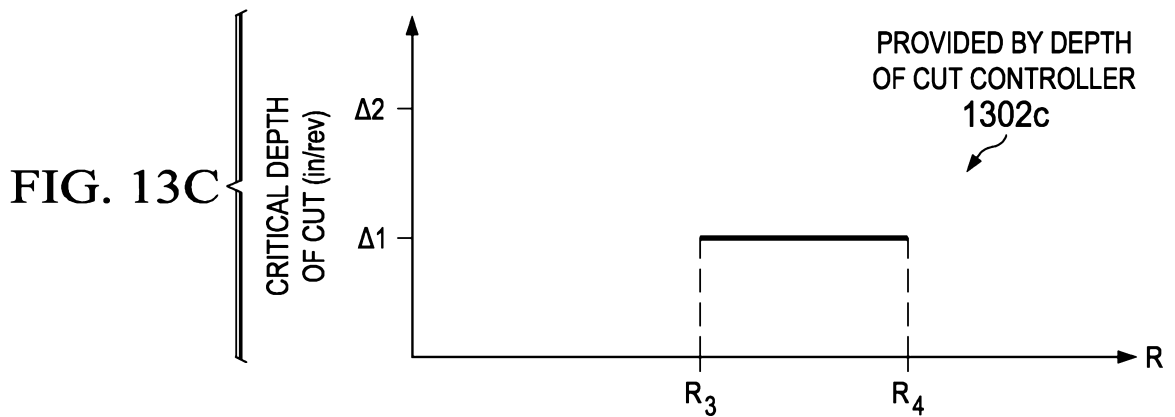
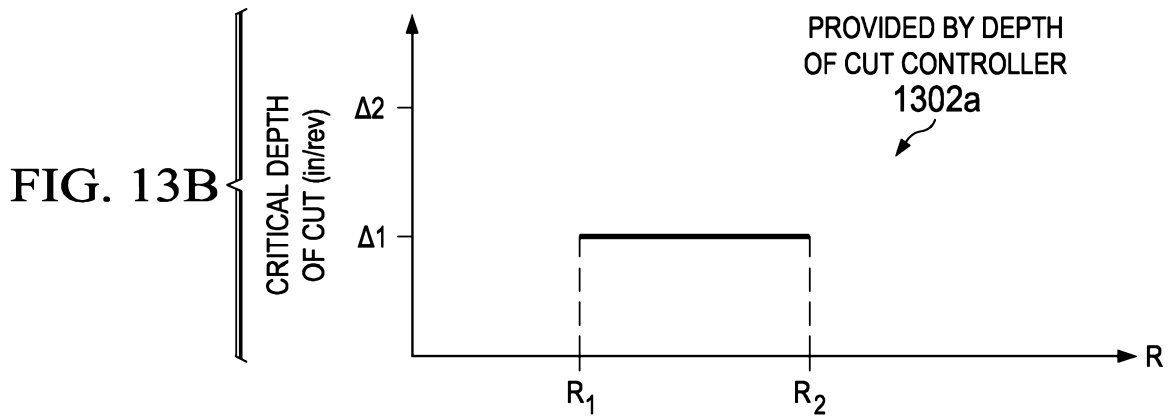
FIG. 12B



1301

FIG. 13A





1401

FIG. 14A

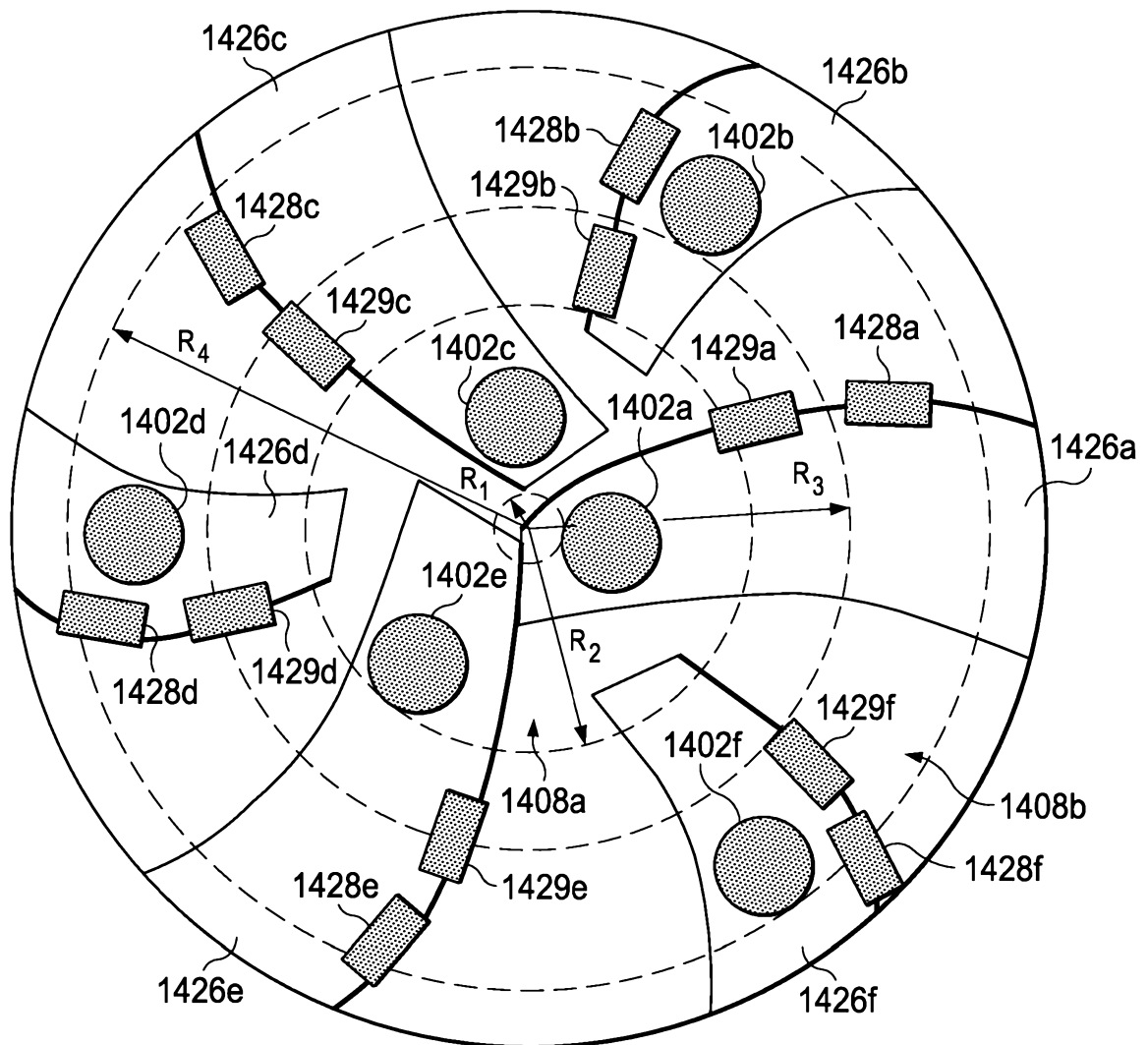


FIG. 14B

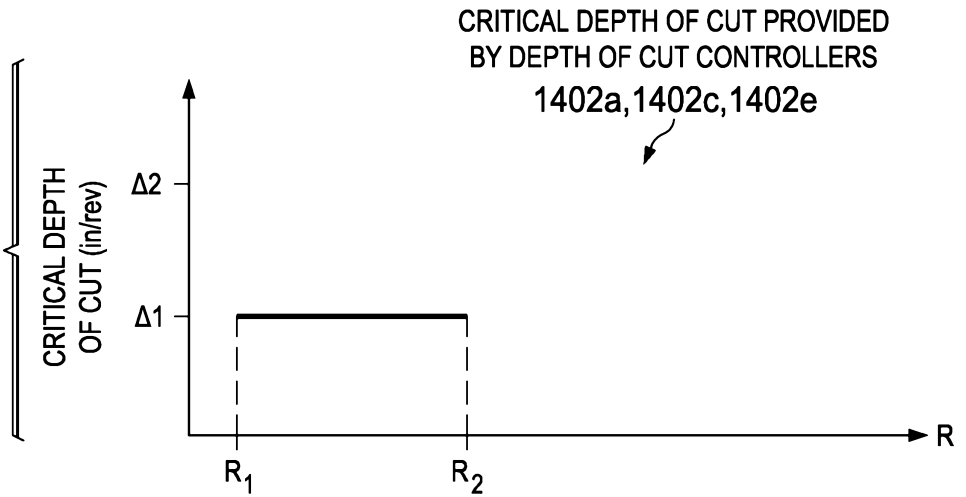


FIG. 14C

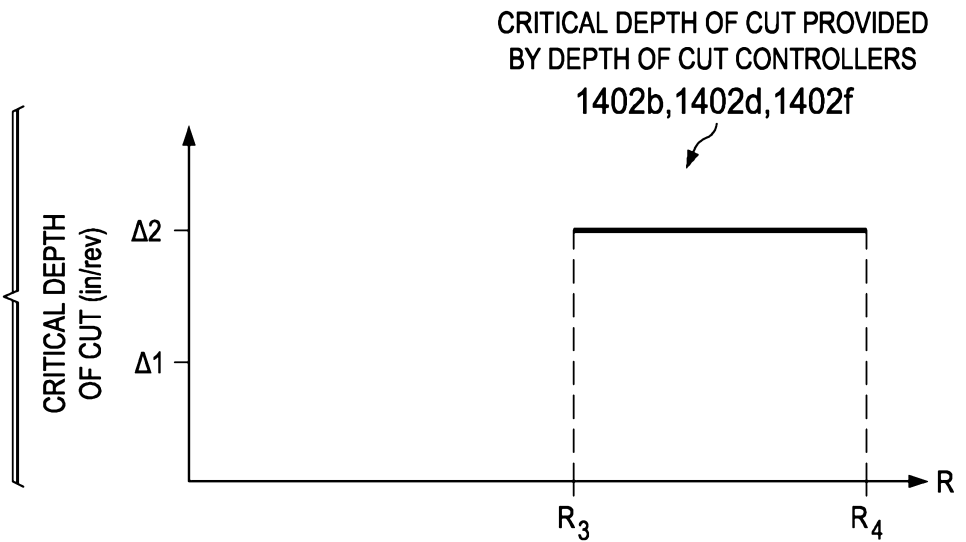
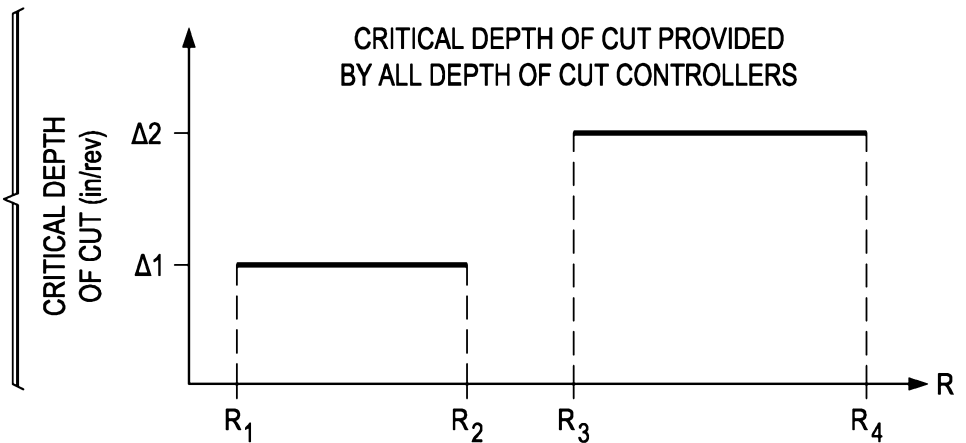


FIG. 14D



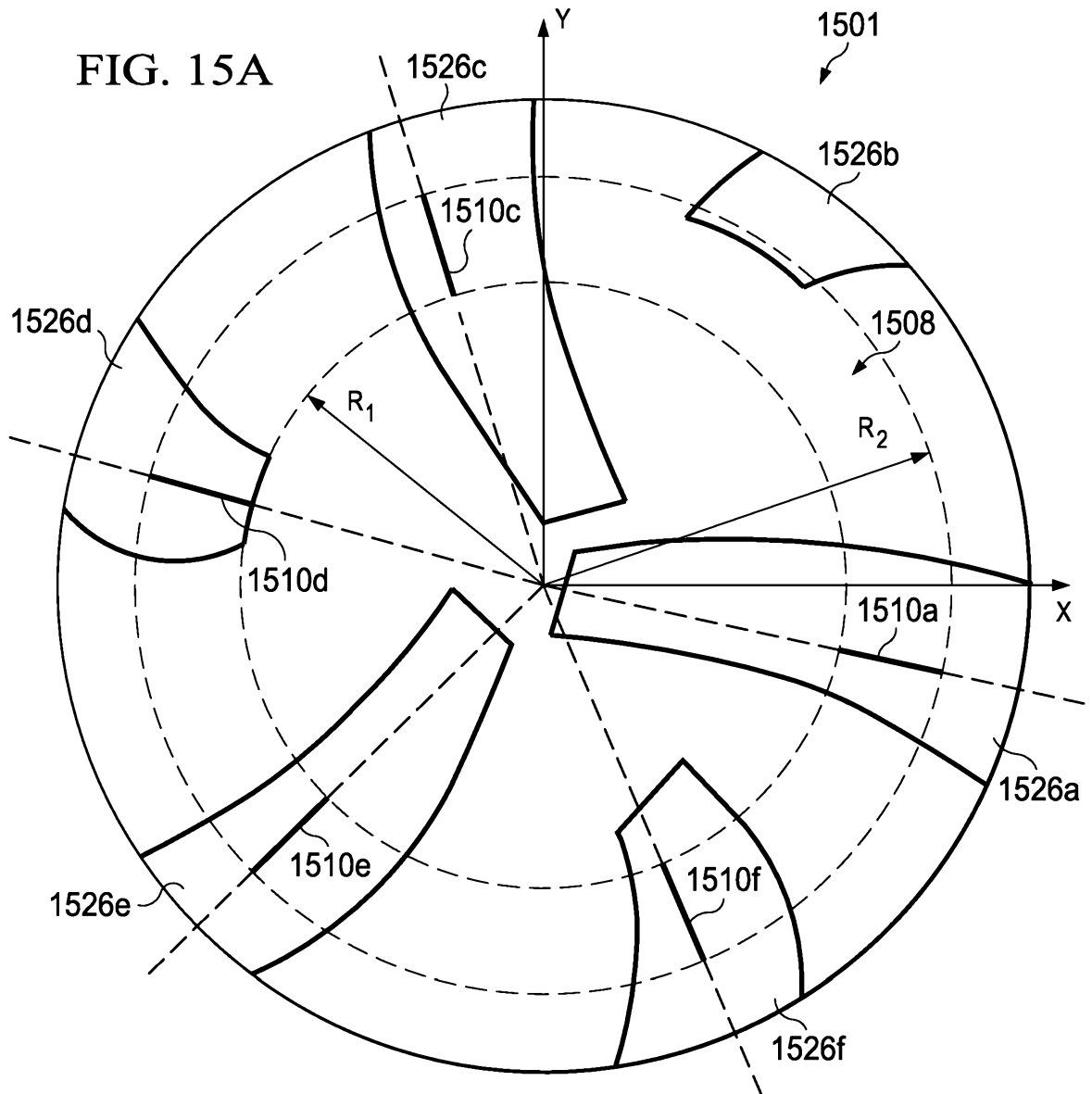


FIG. 15B

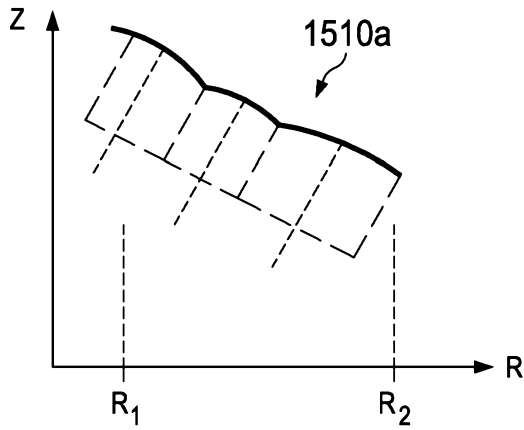


FIG. 15C

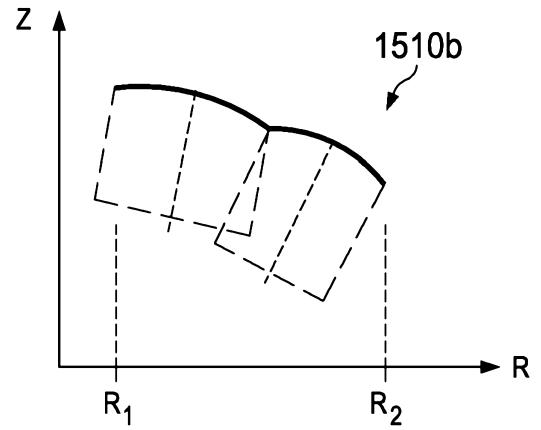


FIG. 15D

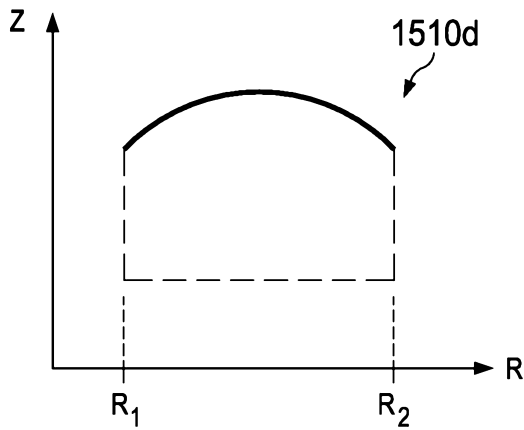


FIG. 15E

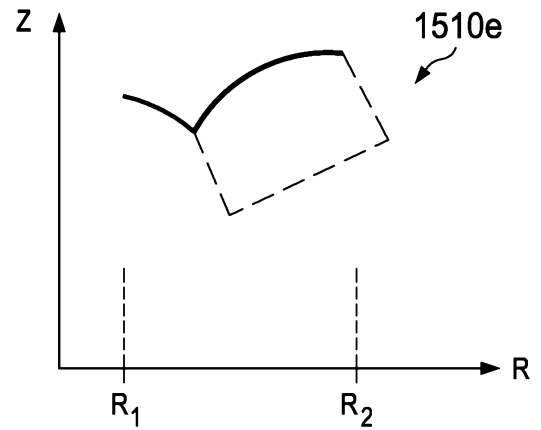


FIG. 15F

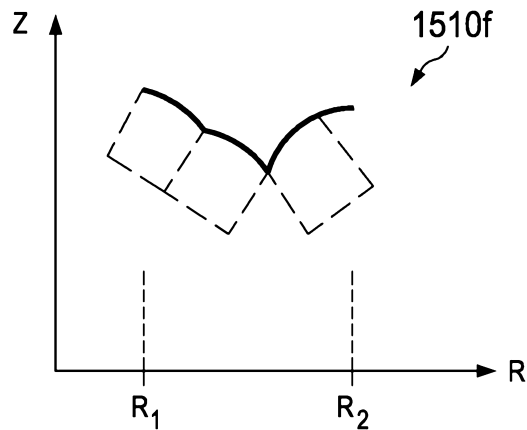


FIG. 16A

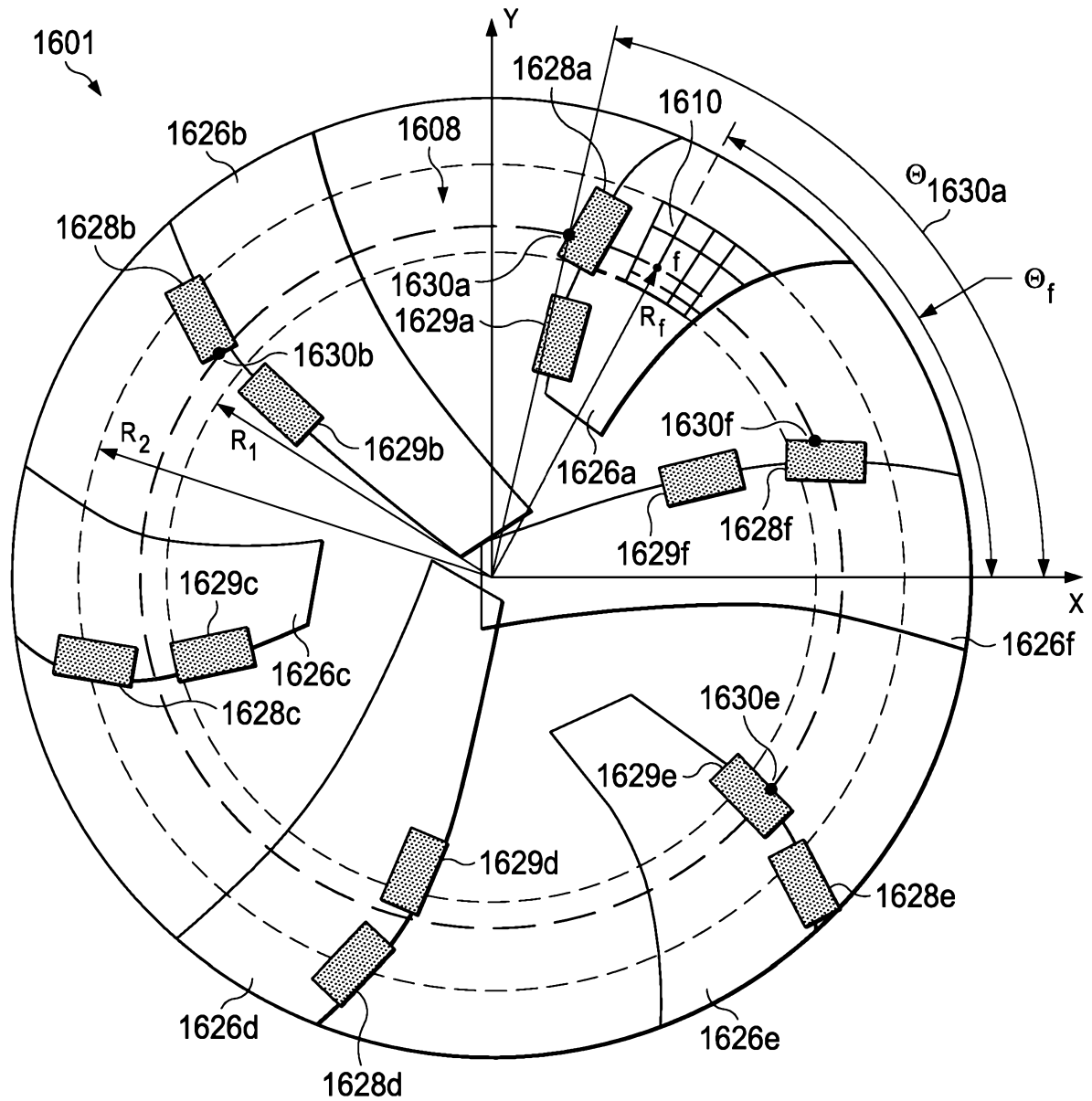


FIG. 16B

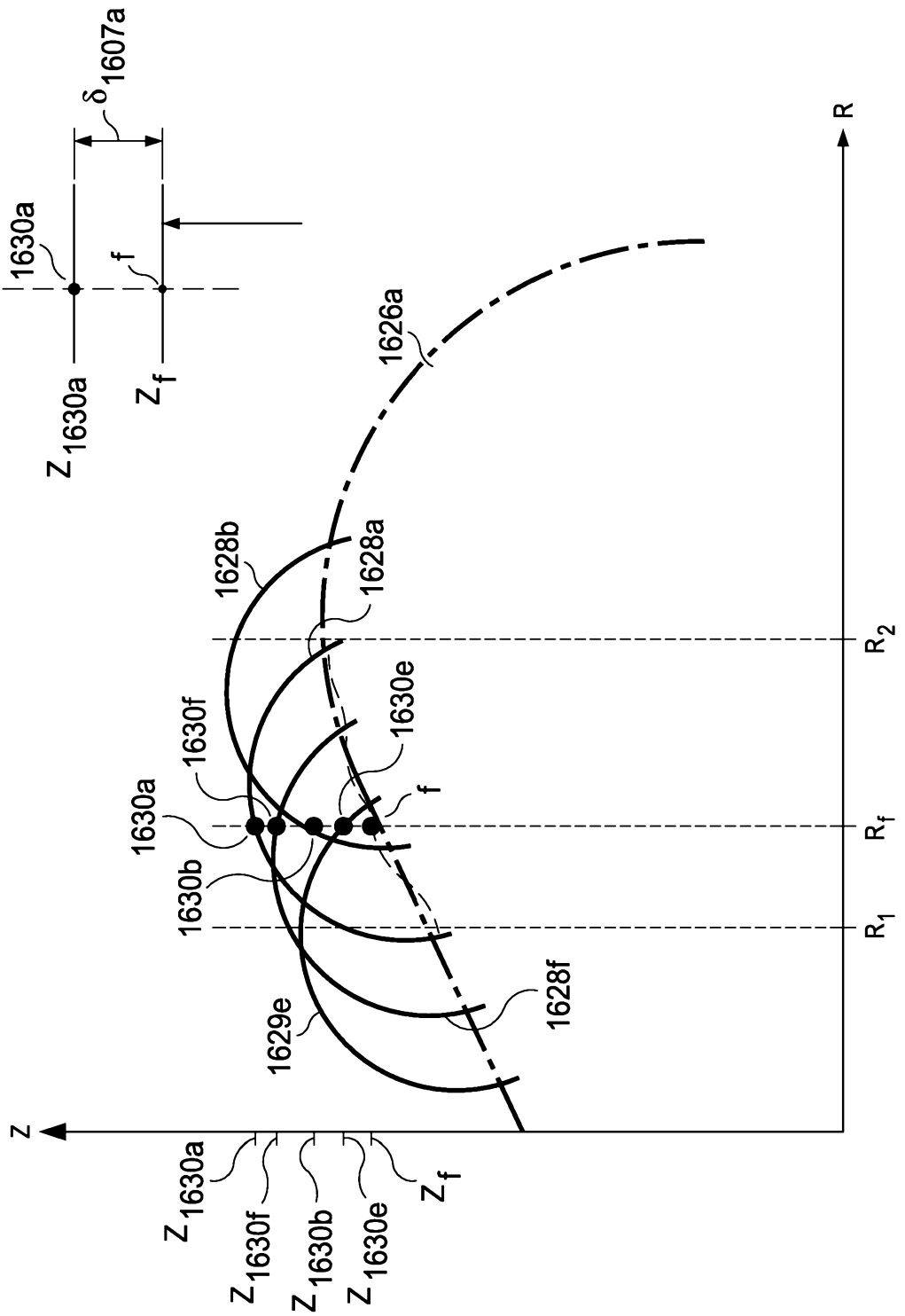
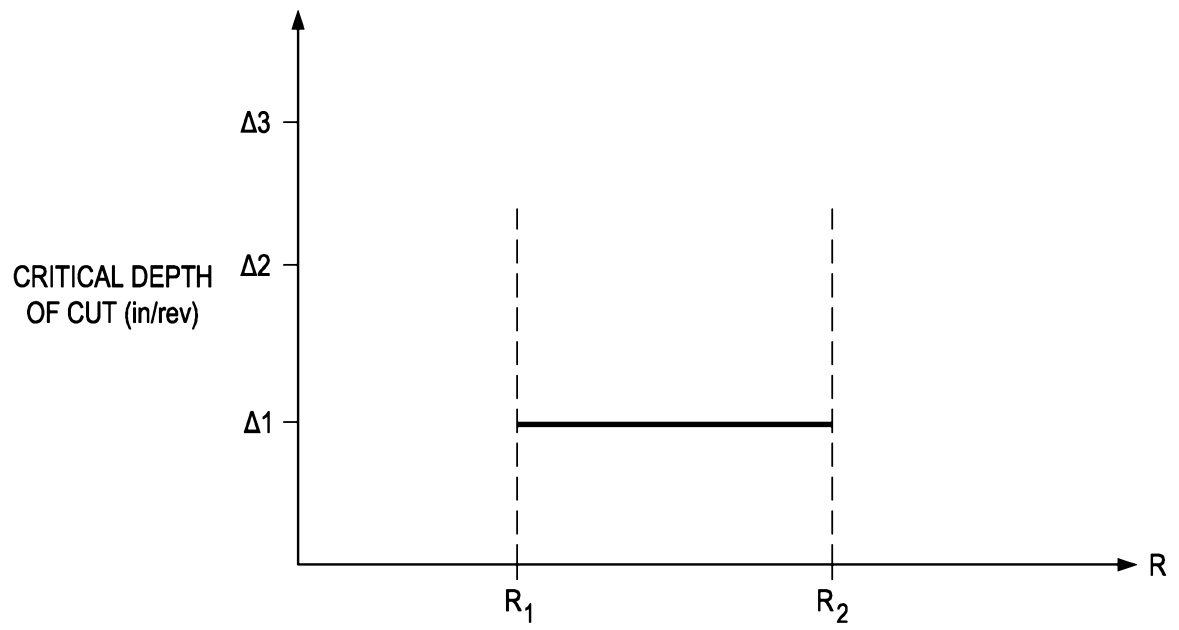
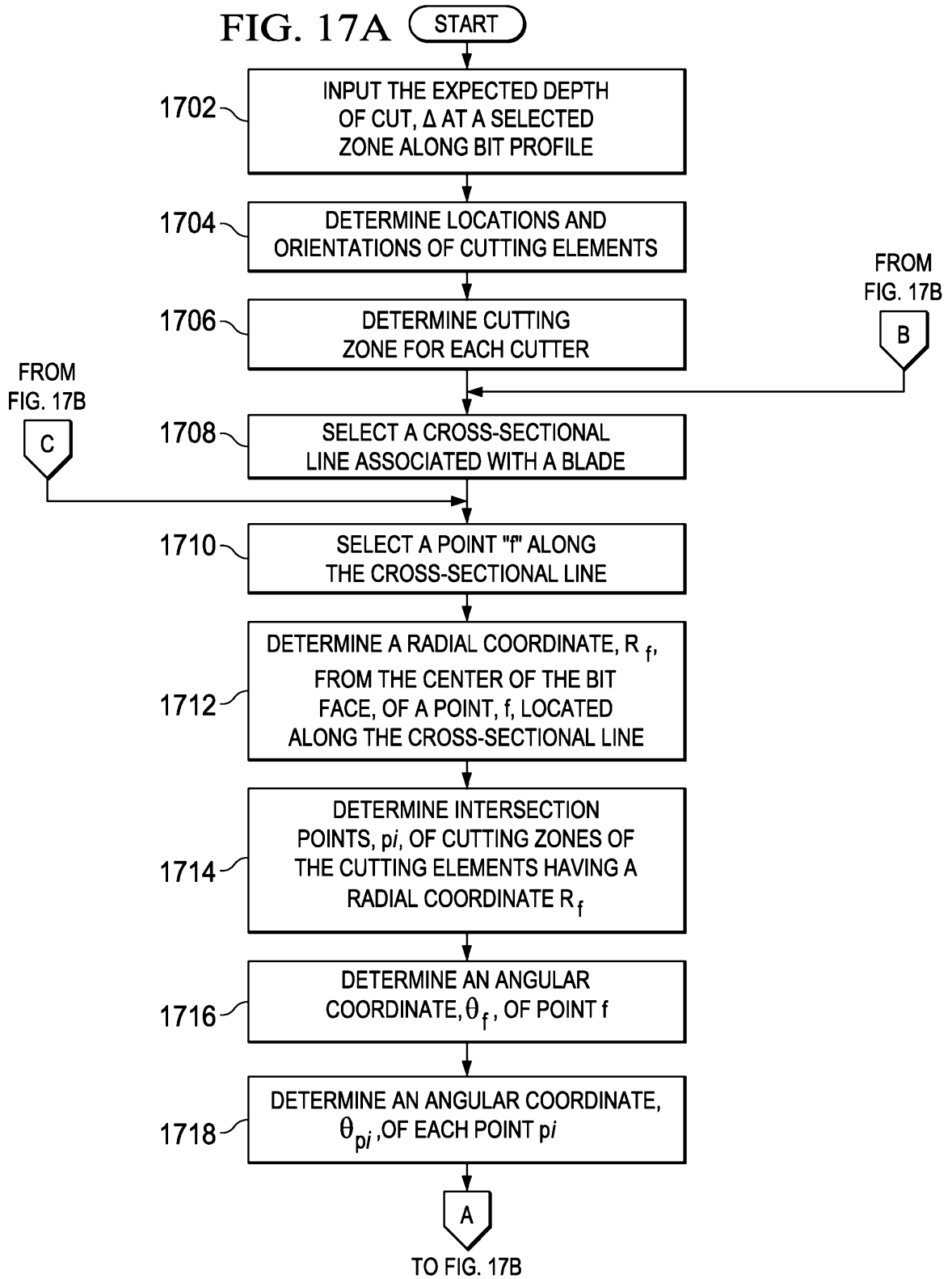


FIG. 16C





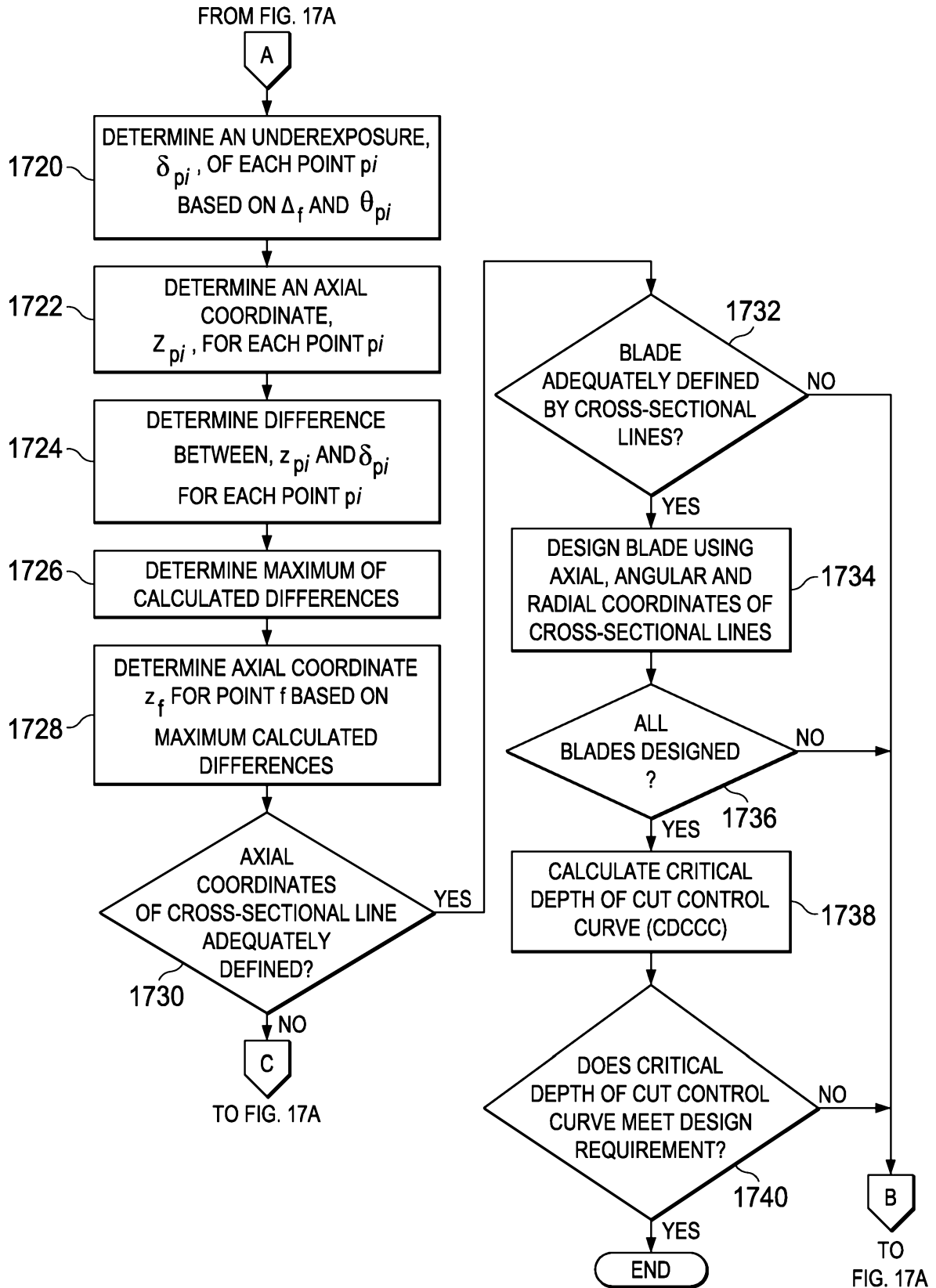
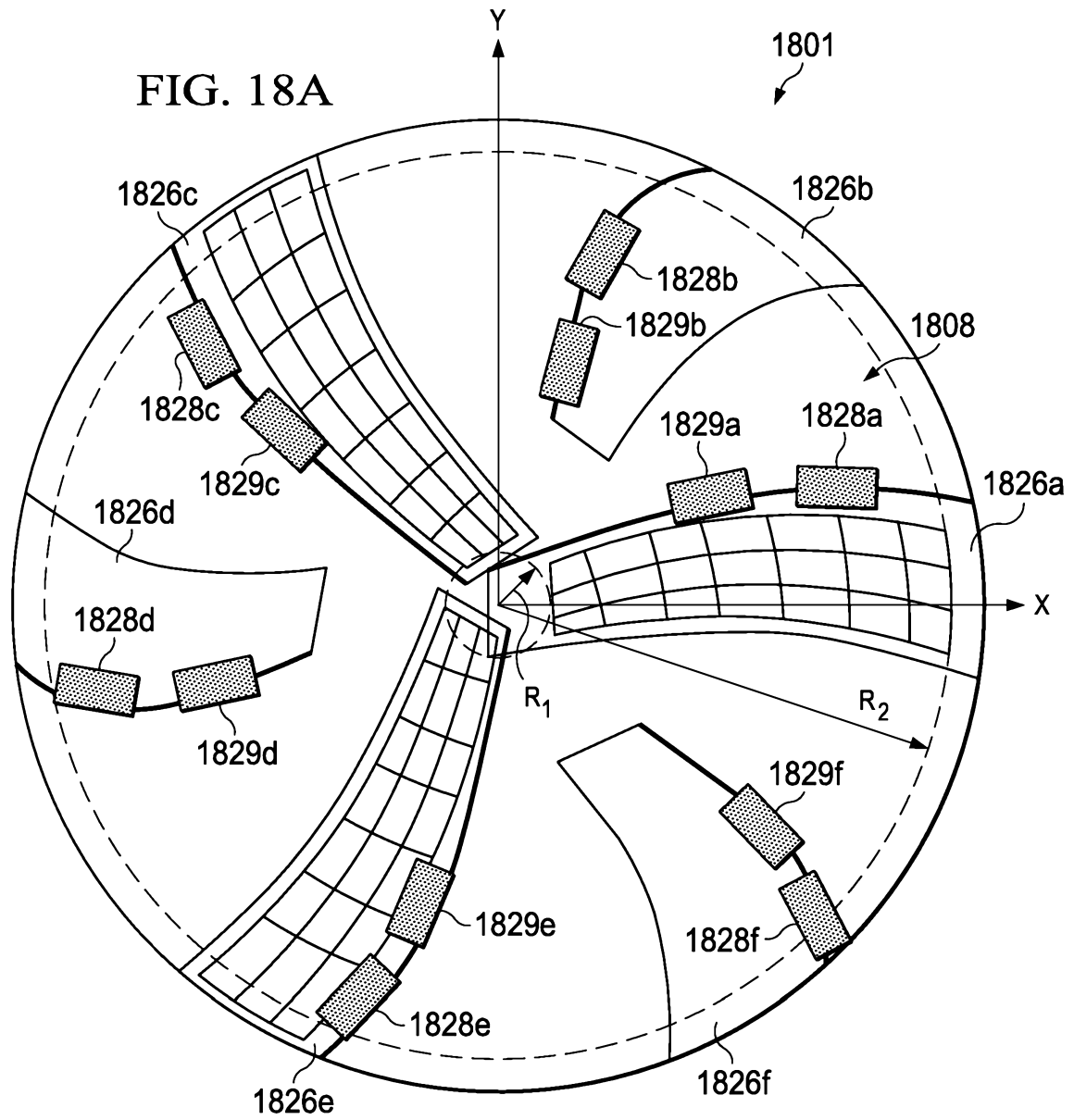


FIG. 17B



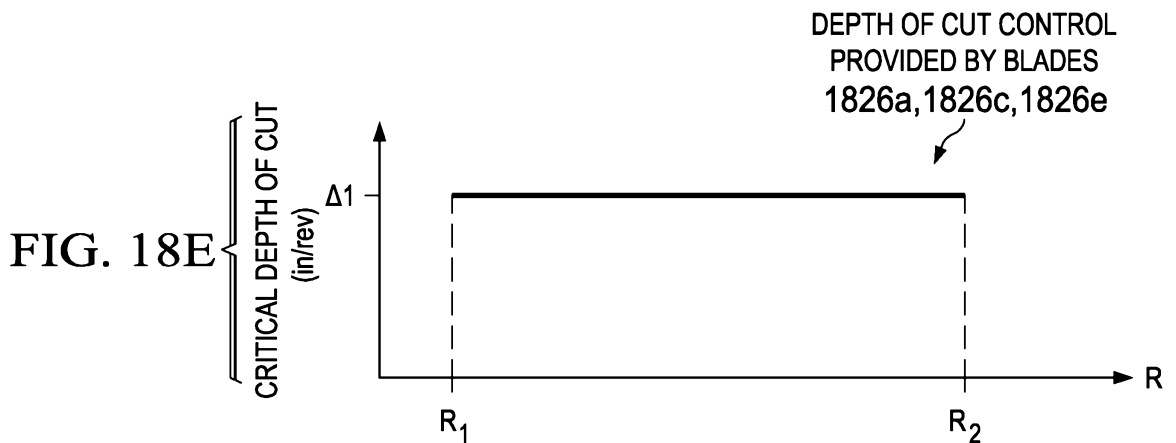
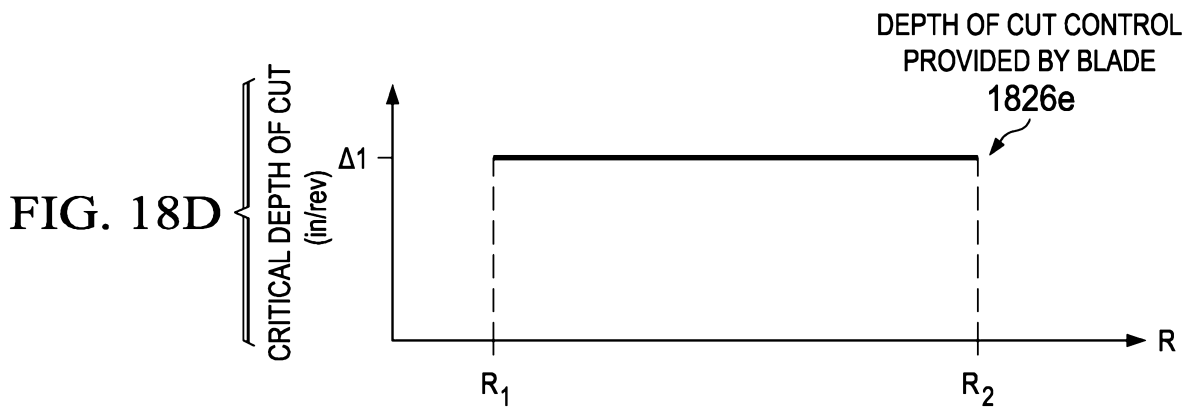
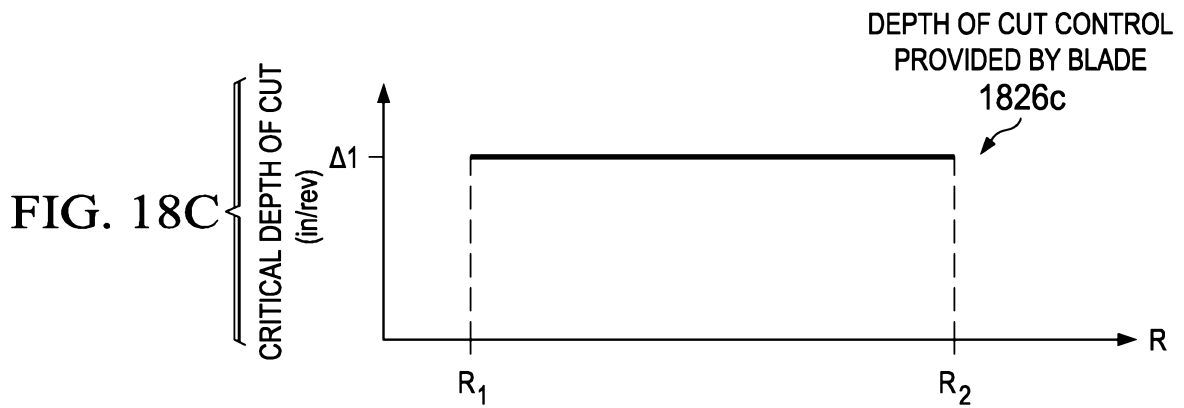
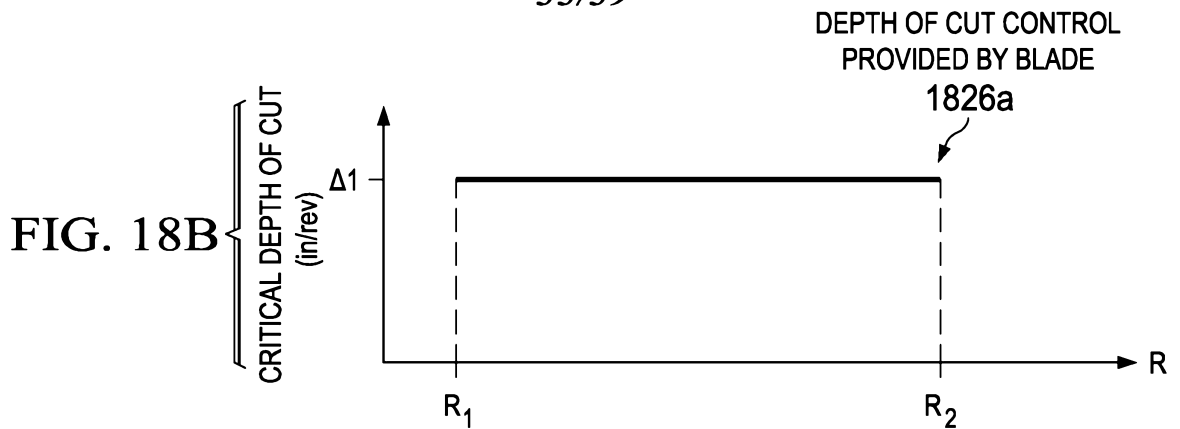
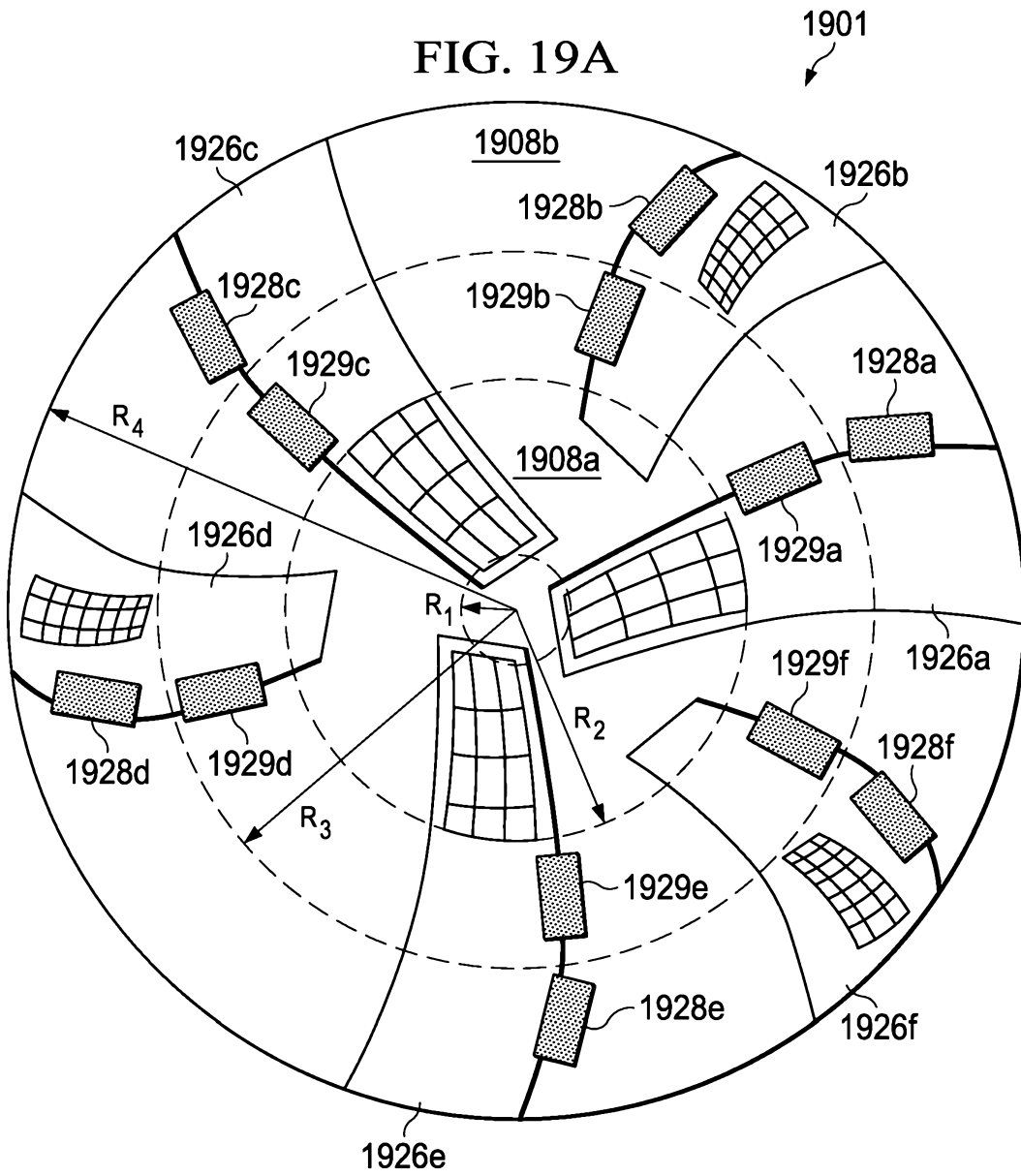
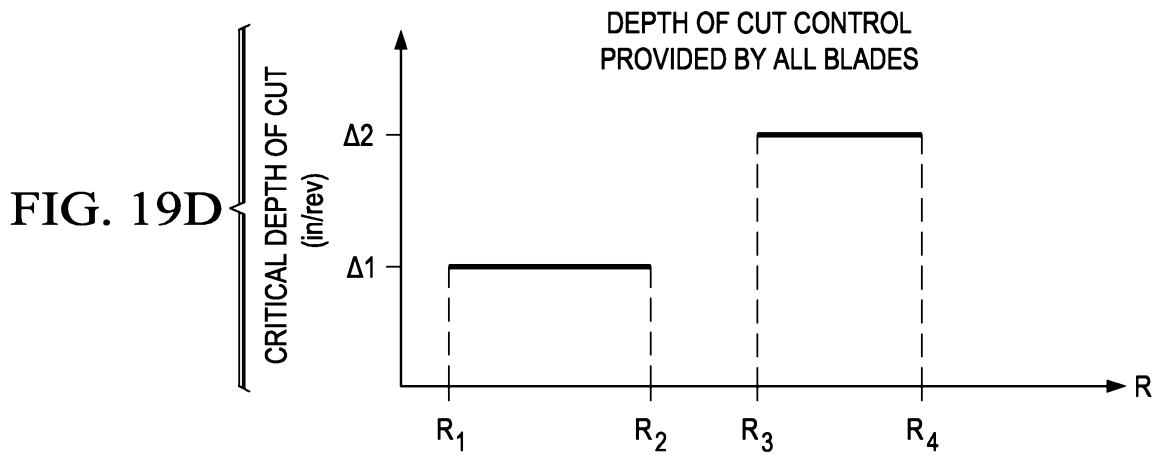
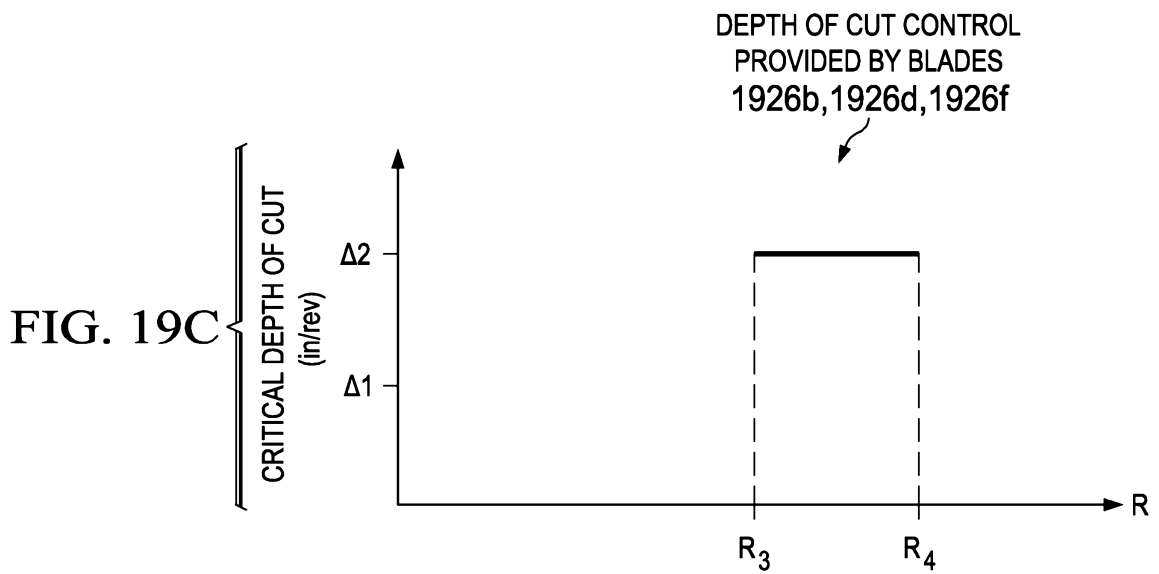
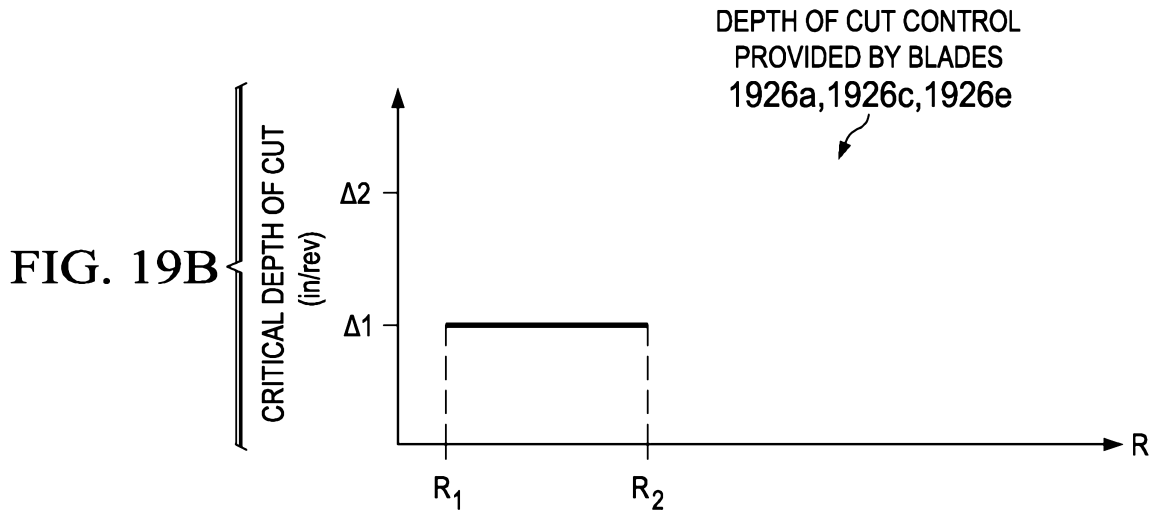
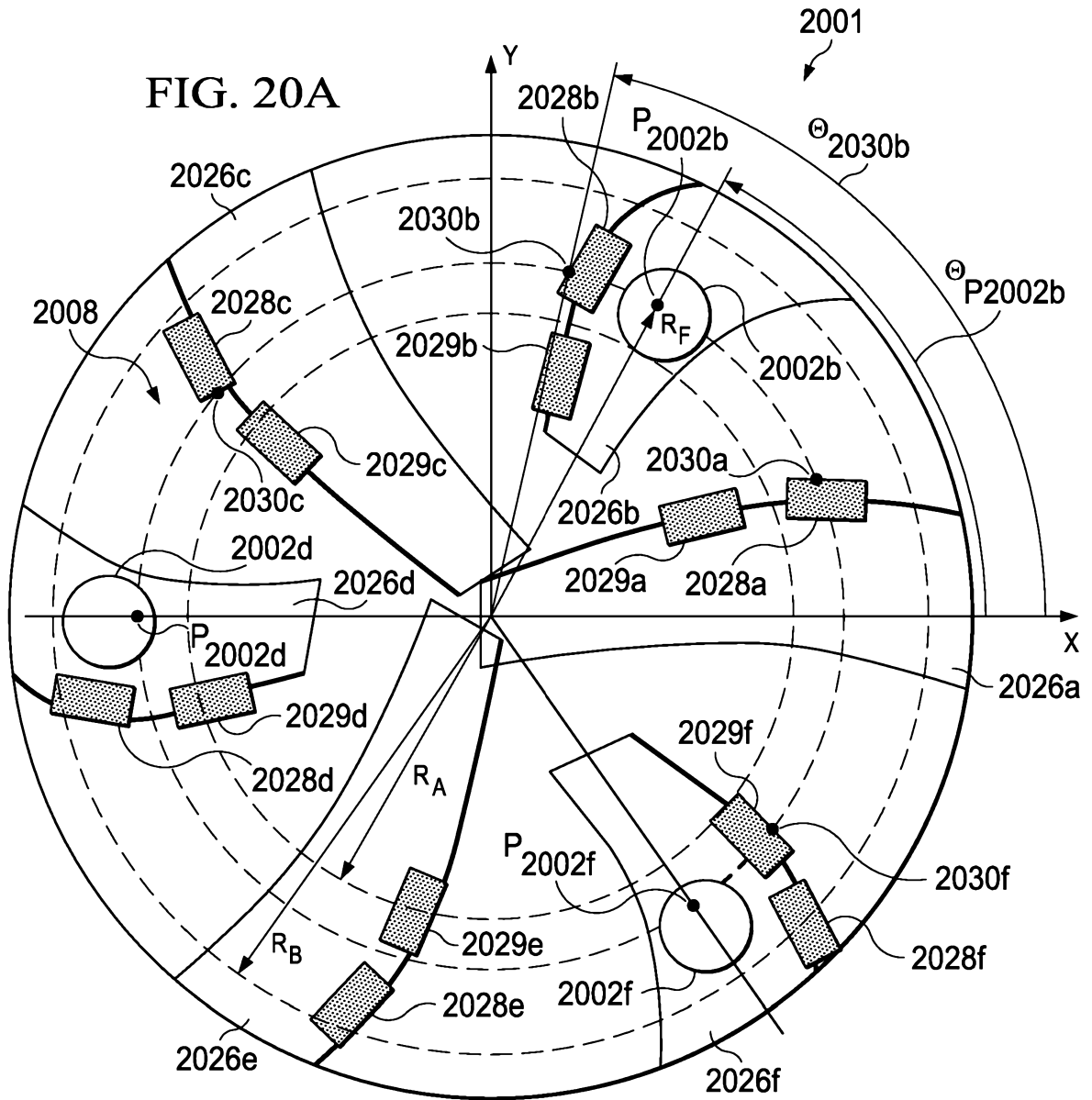
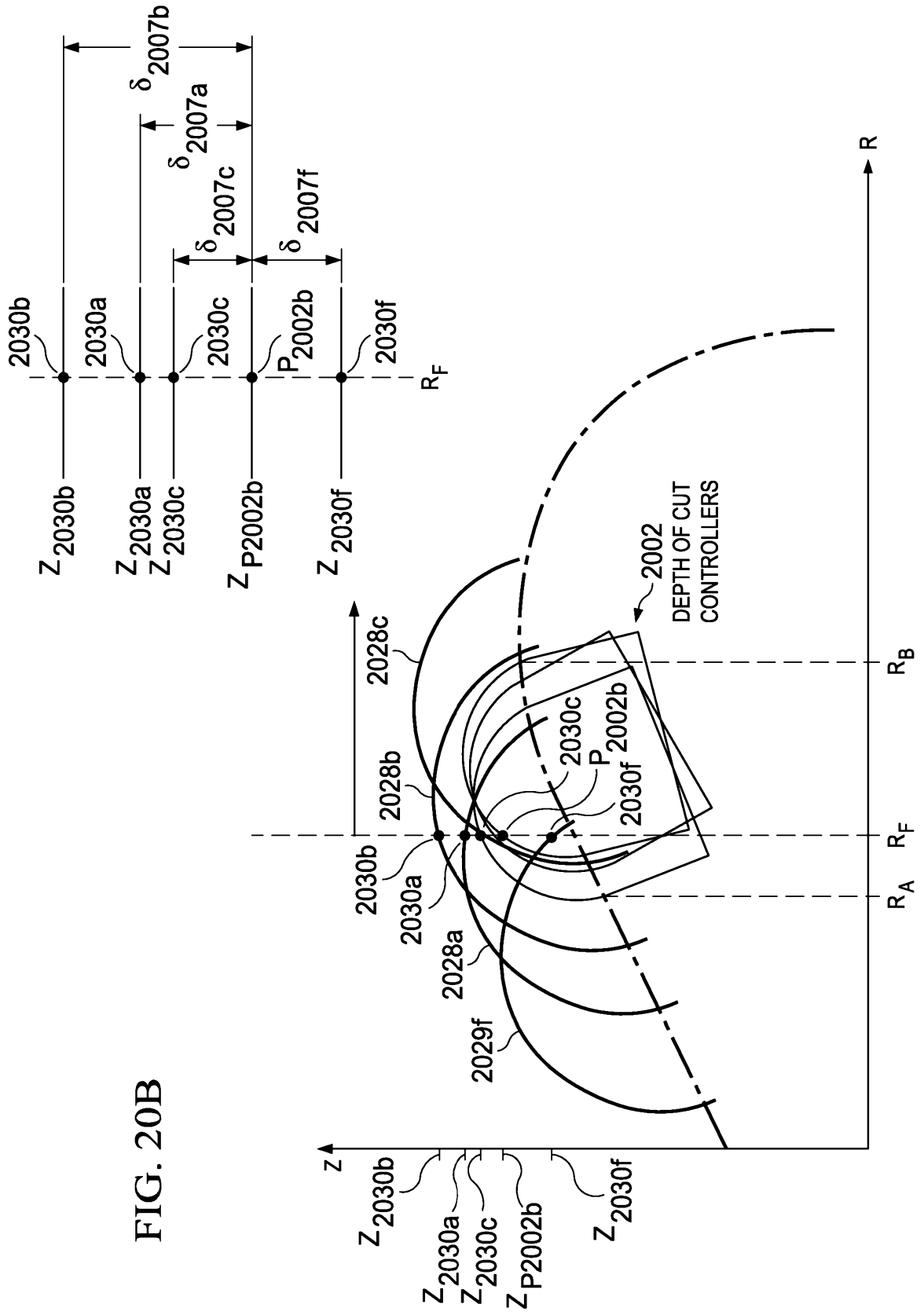


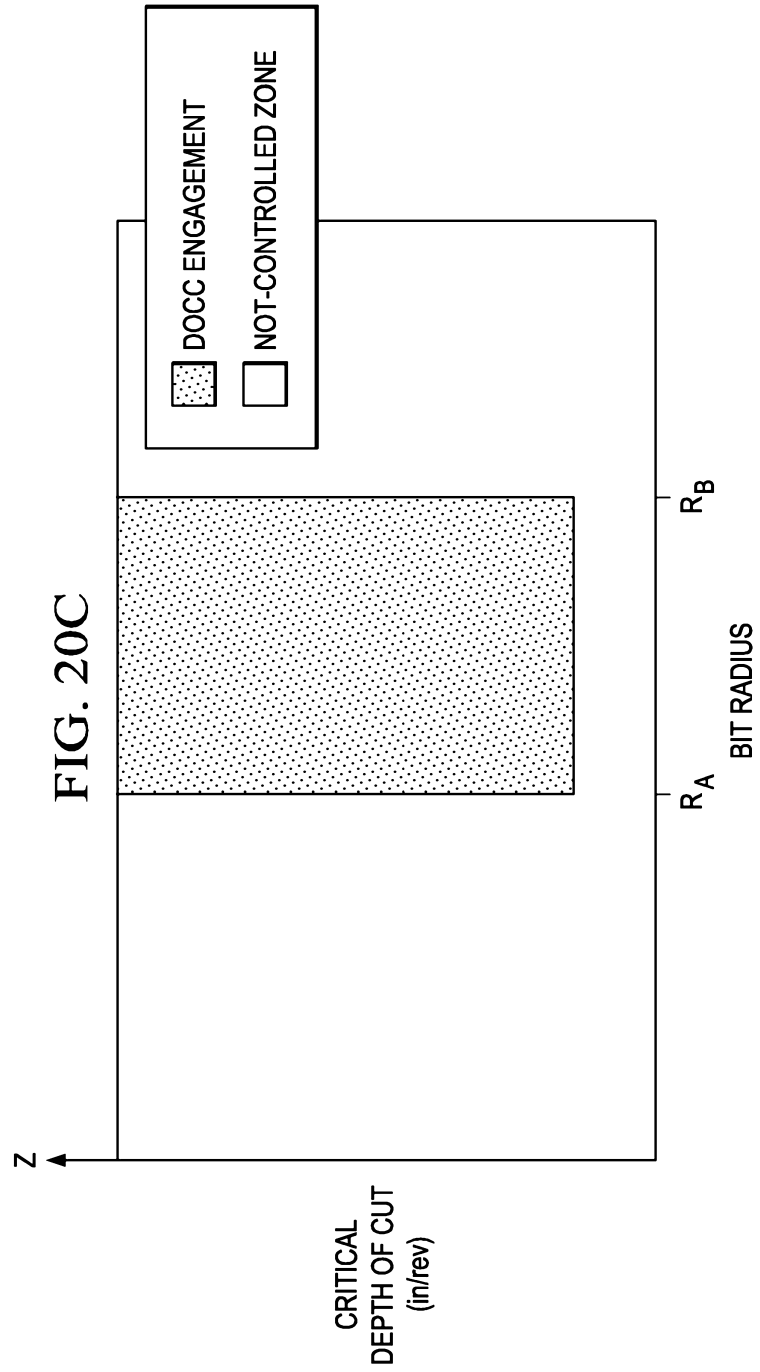
FIG. 19A











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