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(54) **FOOTWEAR INCORPORATING PIEZOELECTRIC ENERGY HARVESTING SYSTEM**

(76) Inventor: **Bradbury R. Face**, Norfolk, VA (US)

Correspondence Address:
David J. Bolduc
Face International Corporation
427 W 35th St.
Norfolk, VA 23508 (US)

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(52) **U.S. Cl.** **36/132**

(57) **ABSTRACT**

An article of footwear having a piezoelectric energy harvesting apparatus in the sole member. Walking or running applies a first force deforming a piezoelectric actuator, thereby generating electrical energy. An energy storage circuit stores electrical energy generated by the piezoelectric actuator for later application to electrical devices.

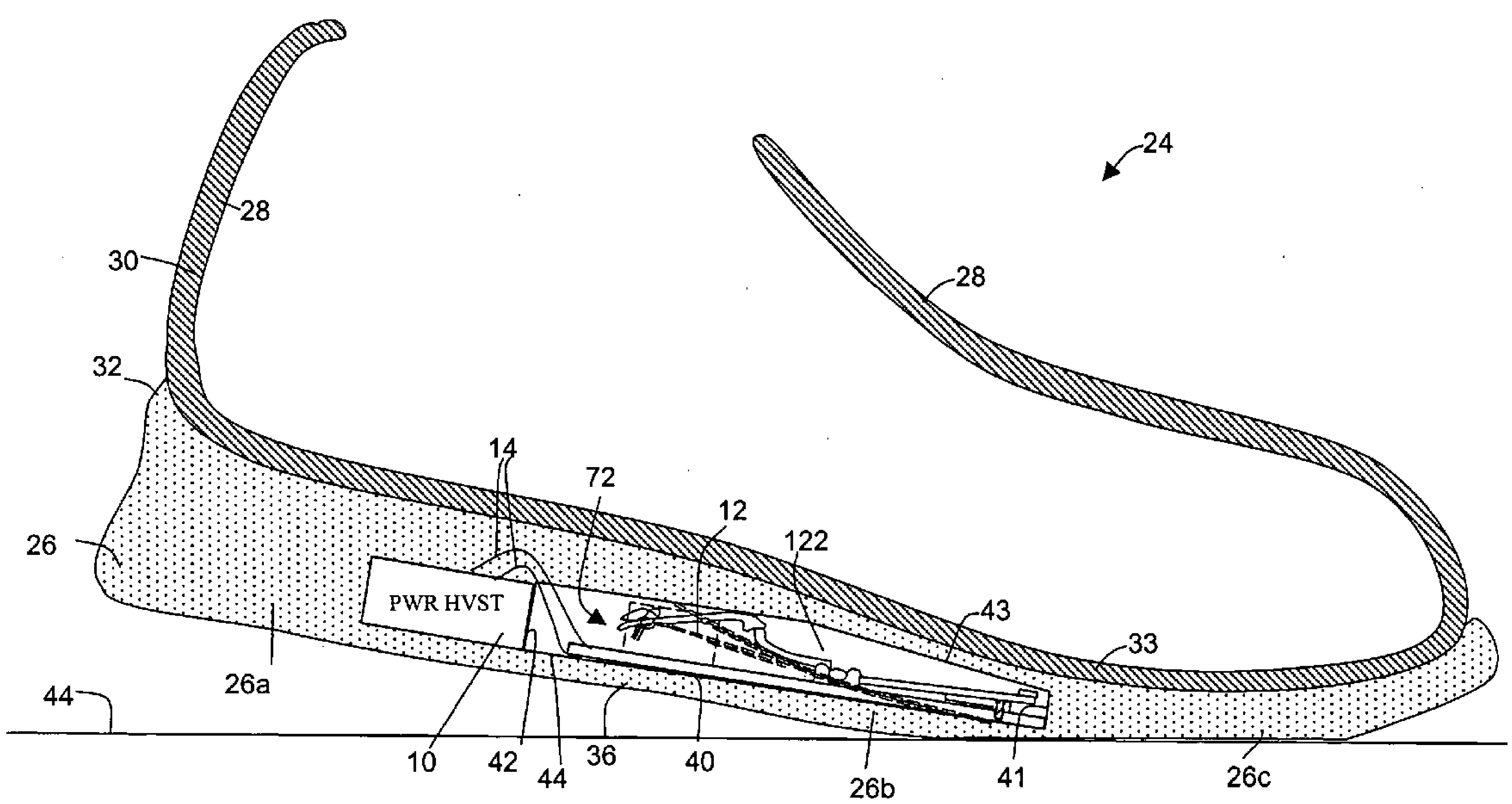
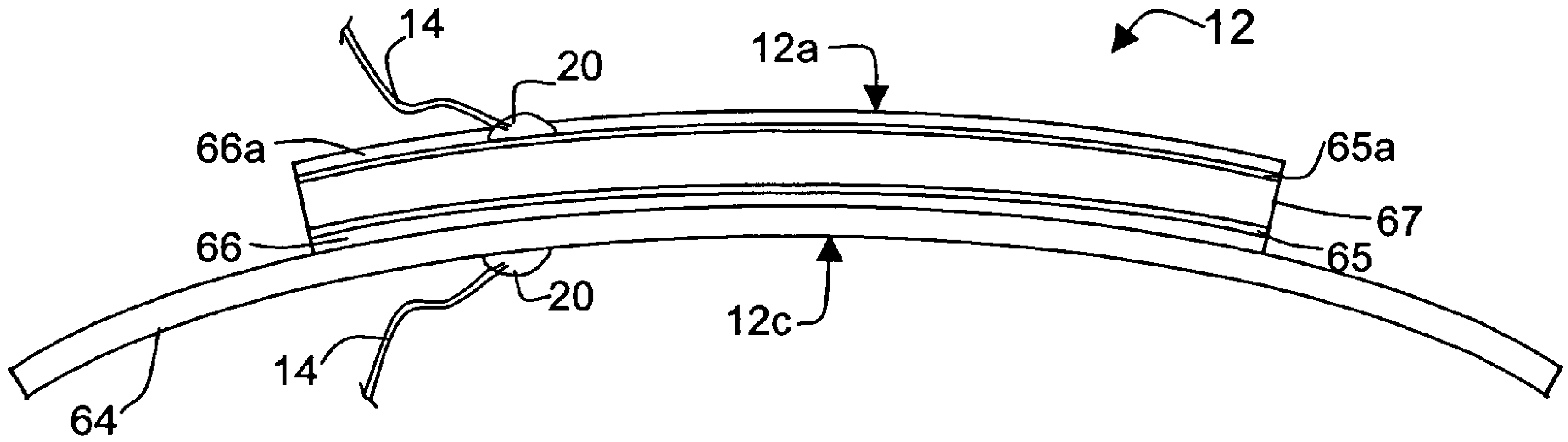


FIG. 1


14
20
12a
12
66a
65a
67
66
65
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12c
14
64

FIG. 1a

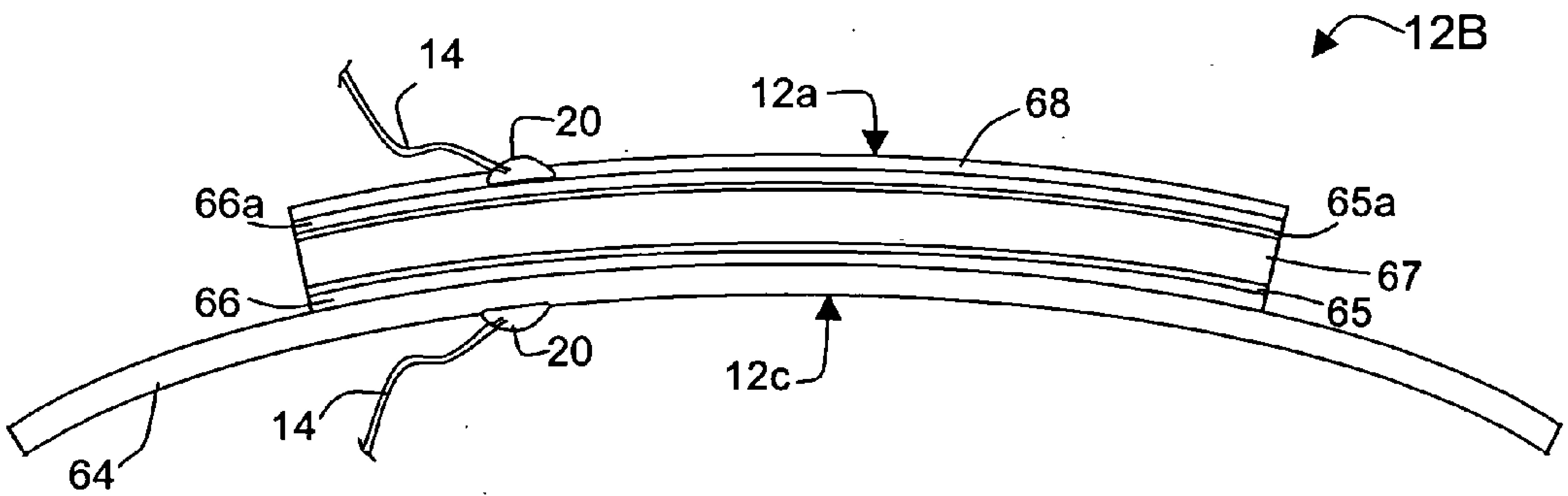
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FIG. 2

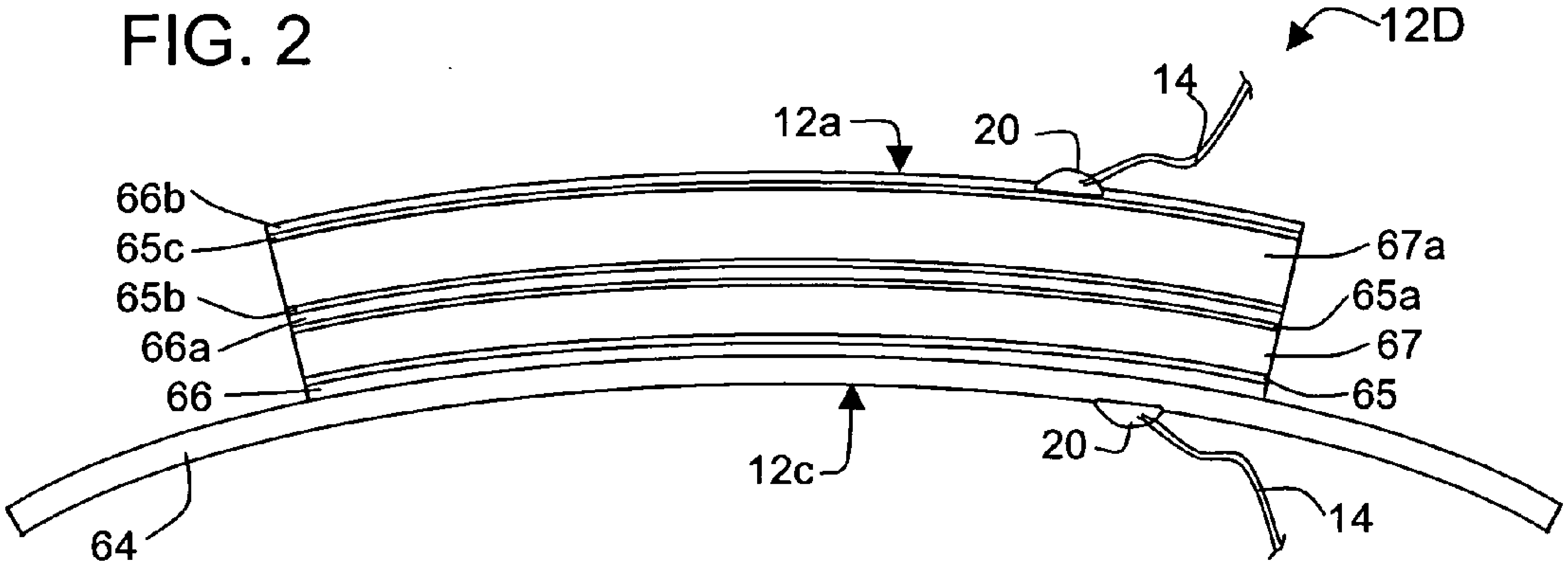


FIG. 2a

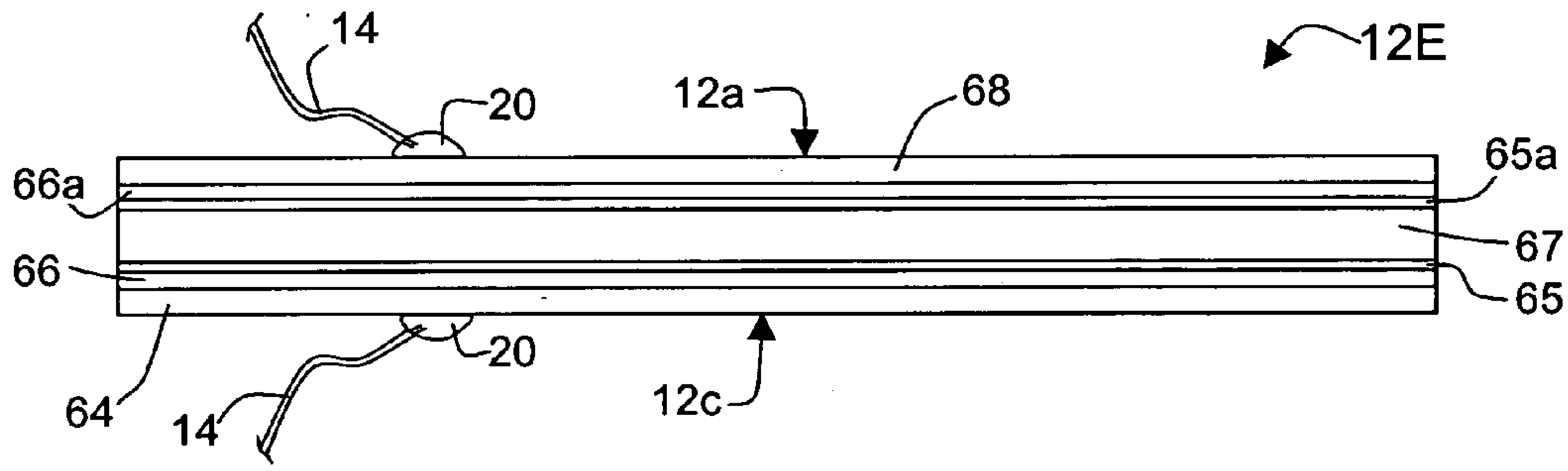


FIG. 2b

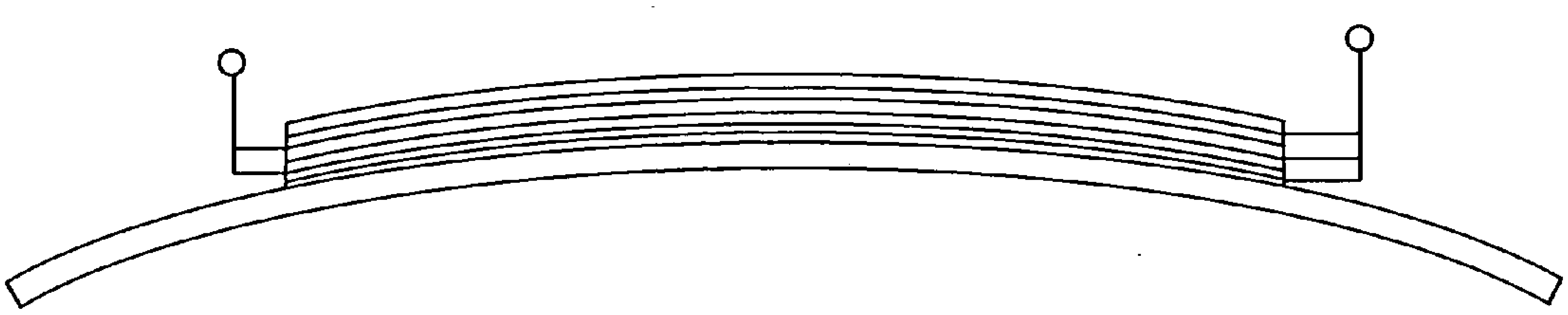
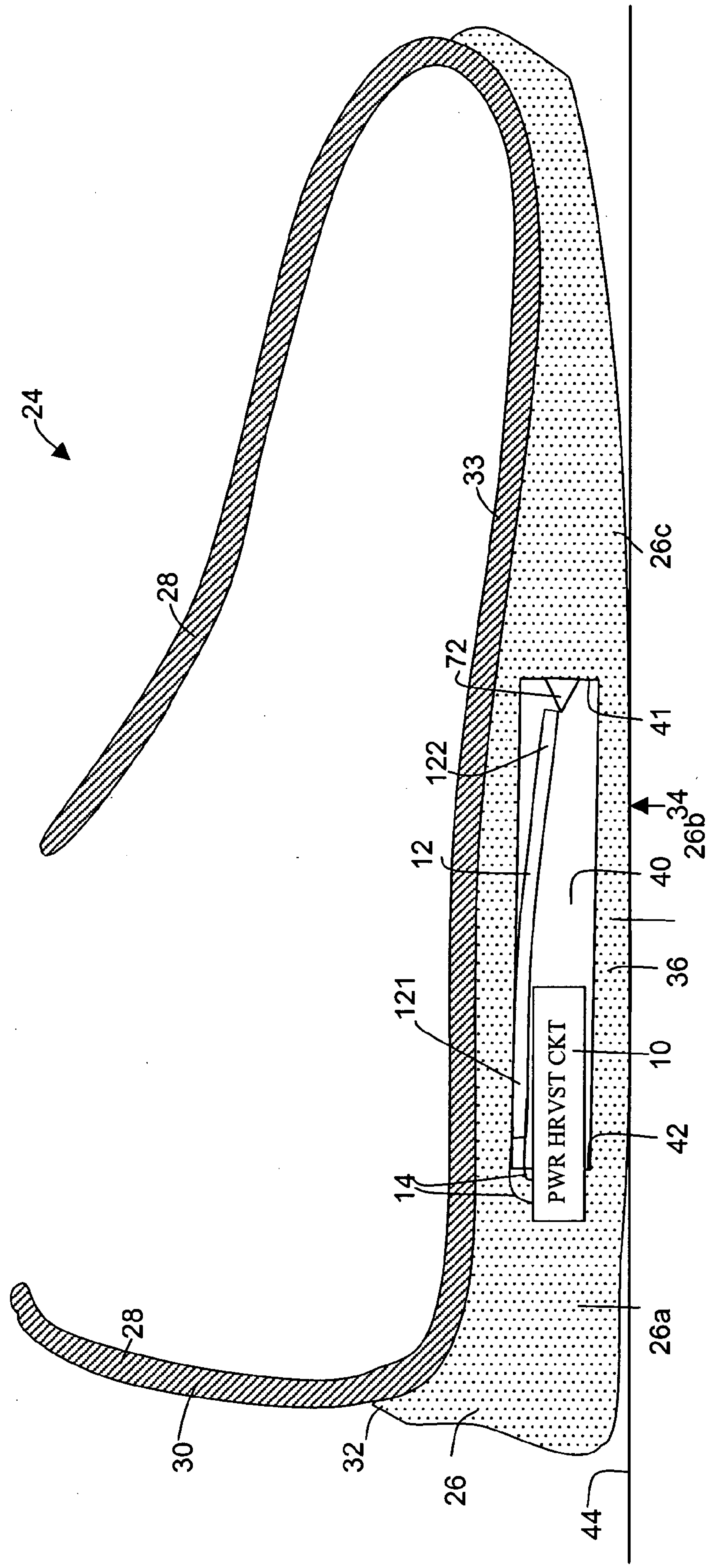


FIG. 3


24
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33
26c
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26a
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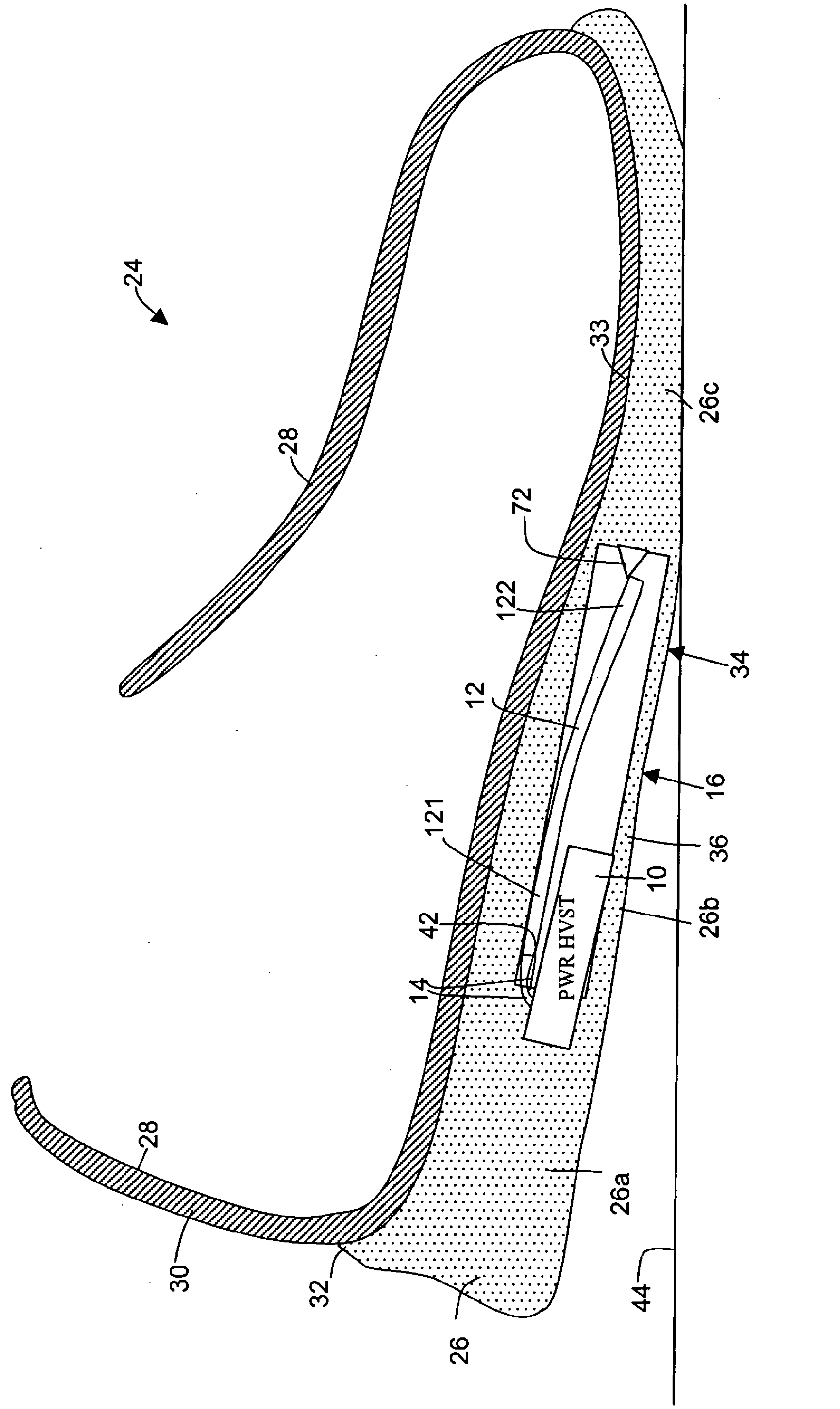
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FIG. 4

FIG. 5

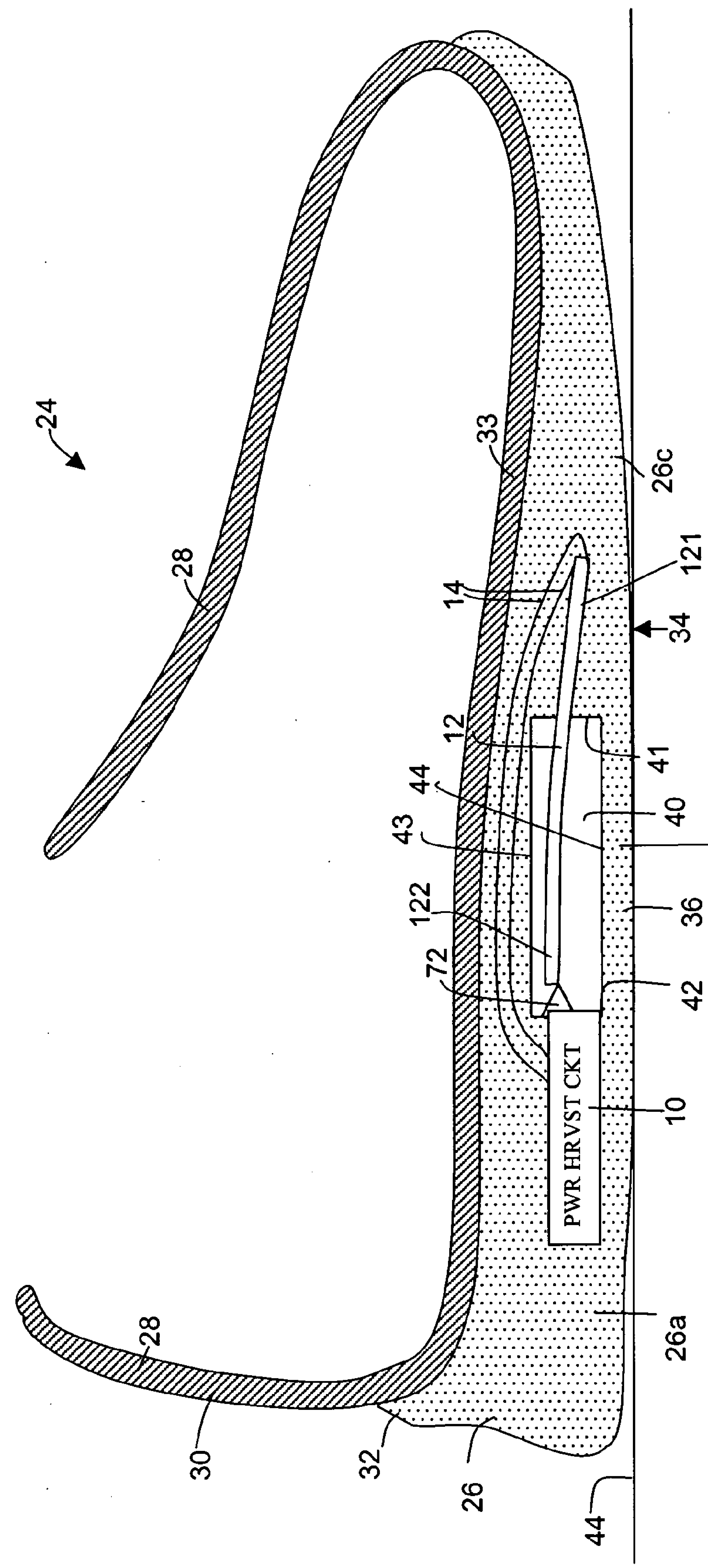
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FIG. 6

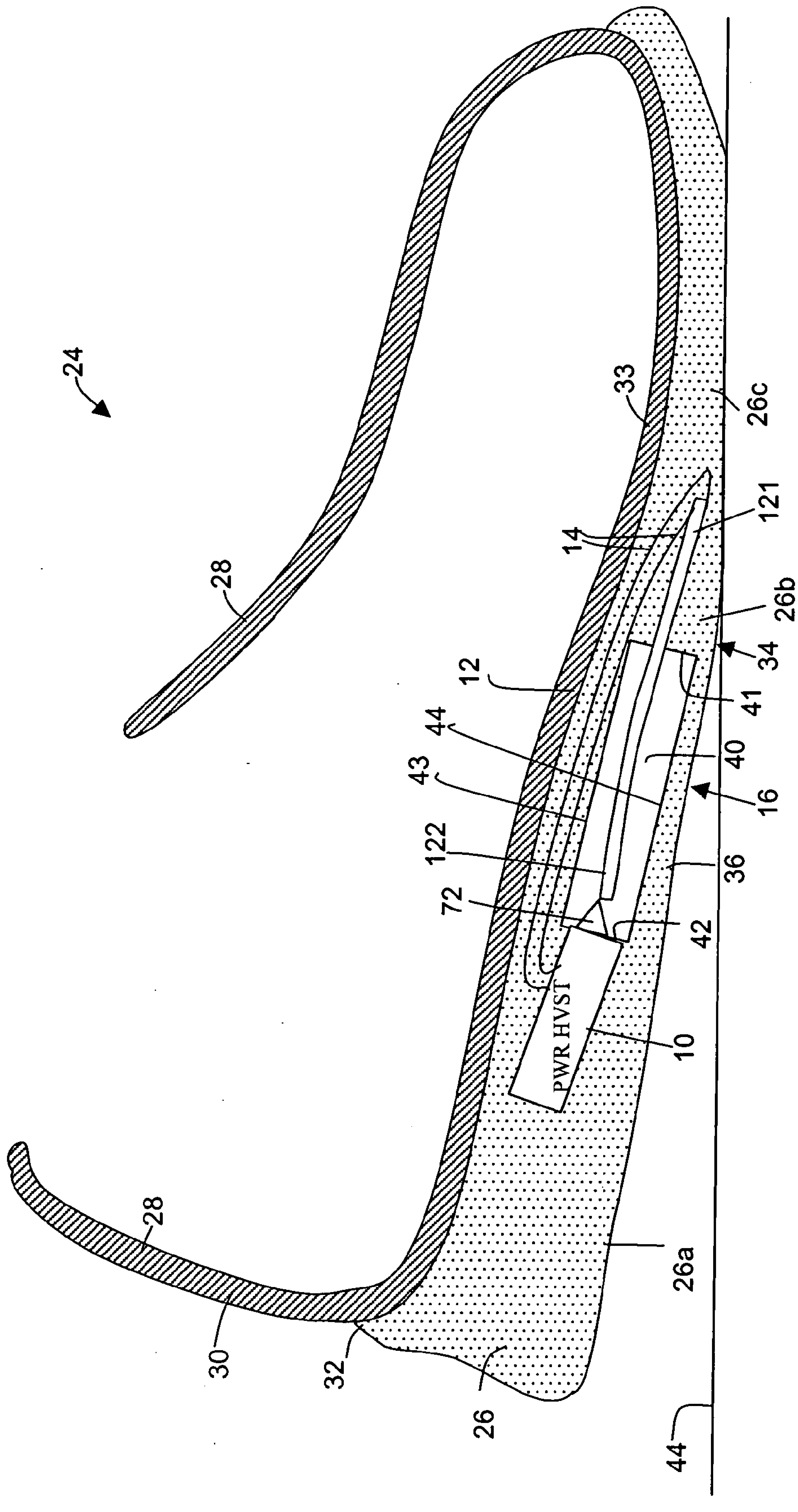
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FIG. 7

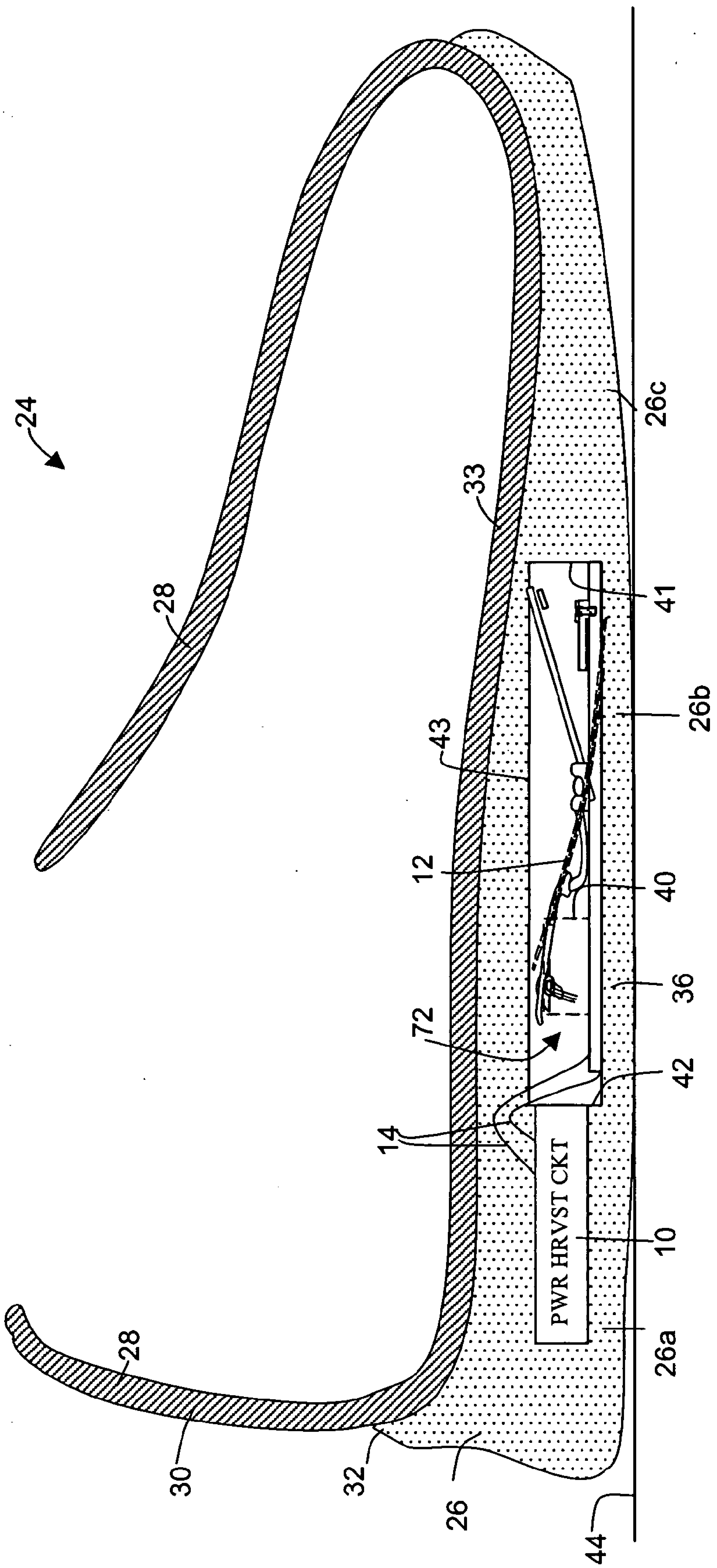
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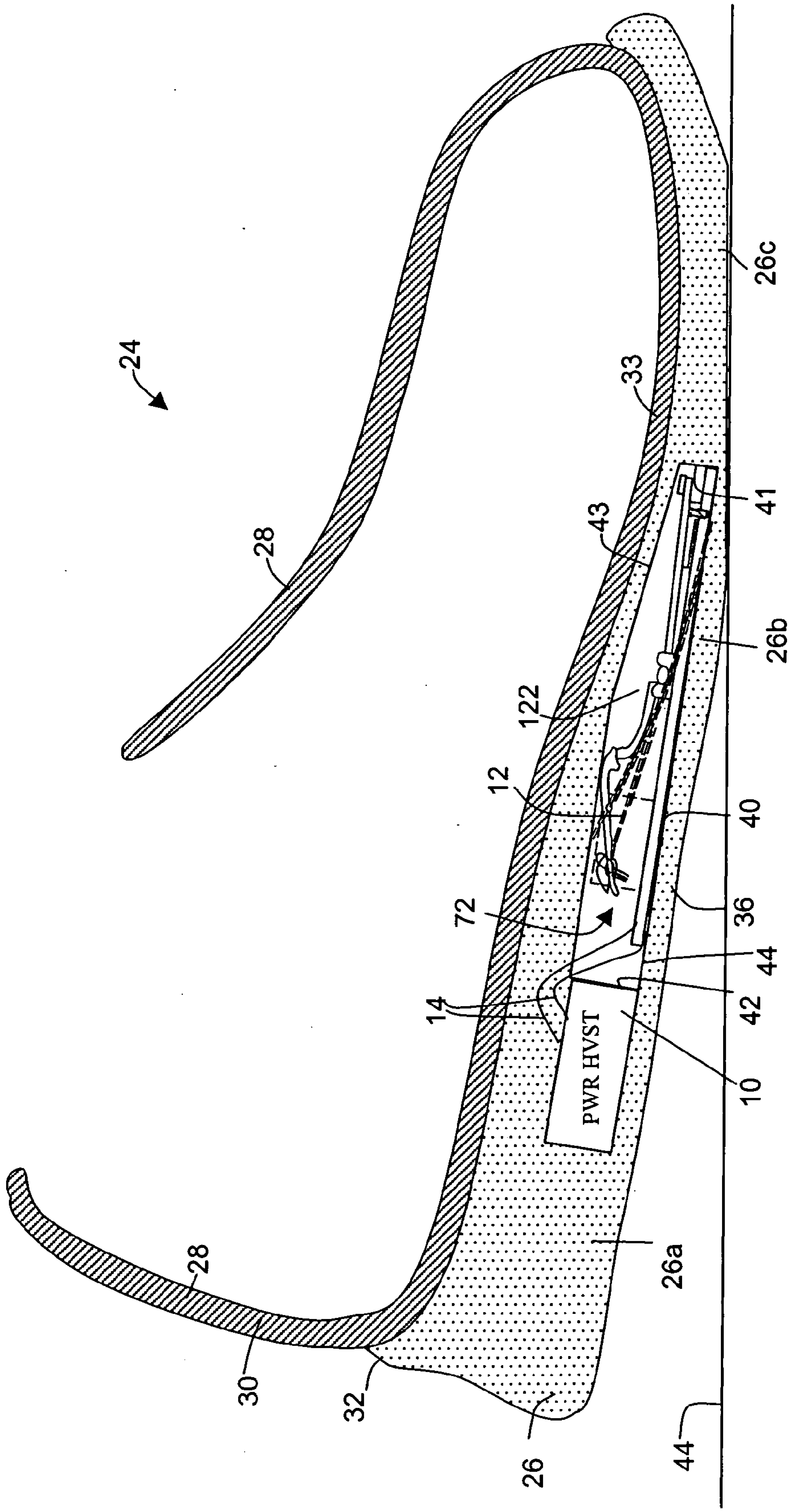
FIG. 8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26a
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PWR HVST
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FIG. 9a

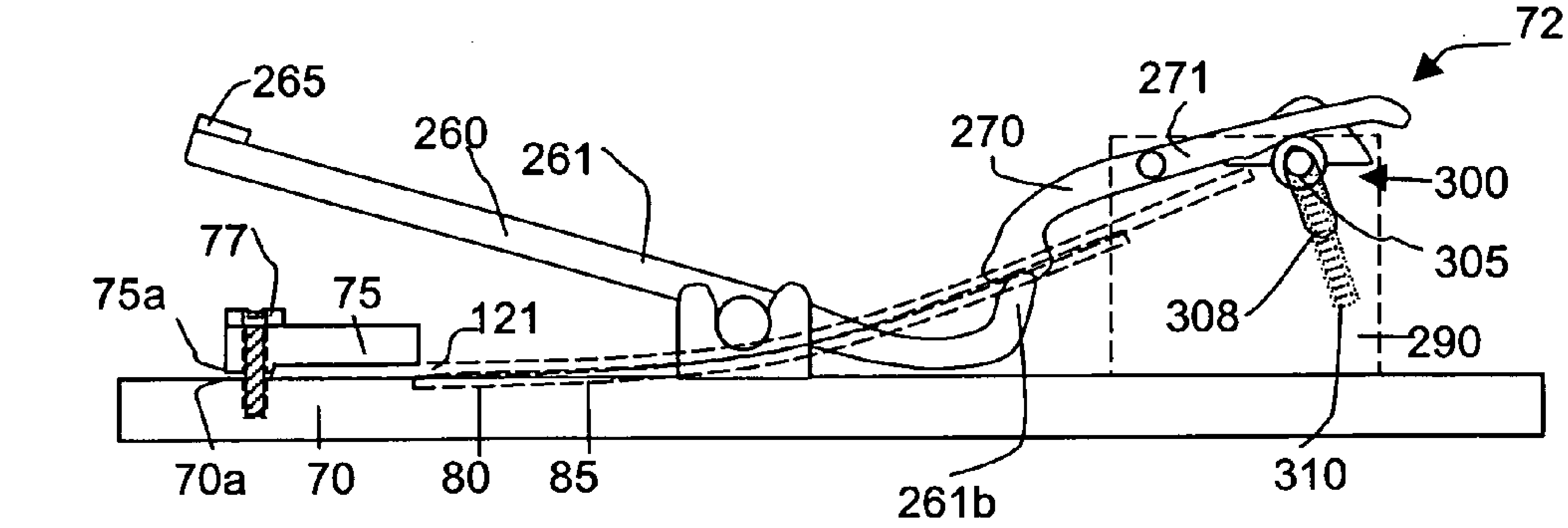


FIG. 9b

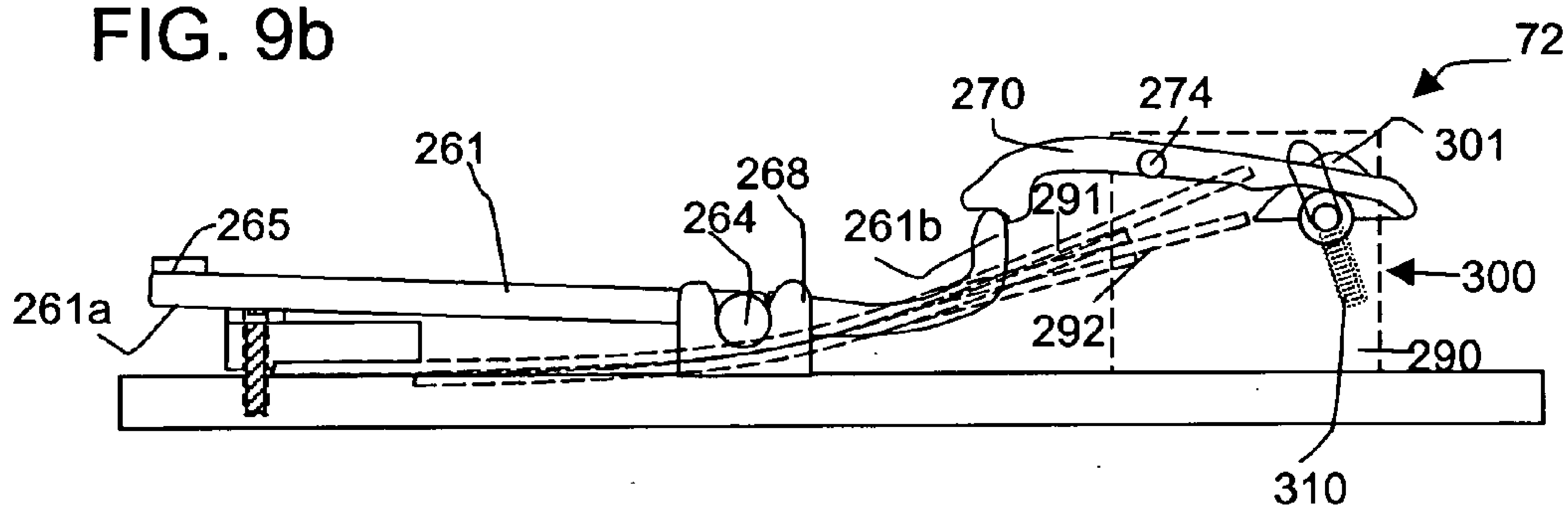


FIG. 9c

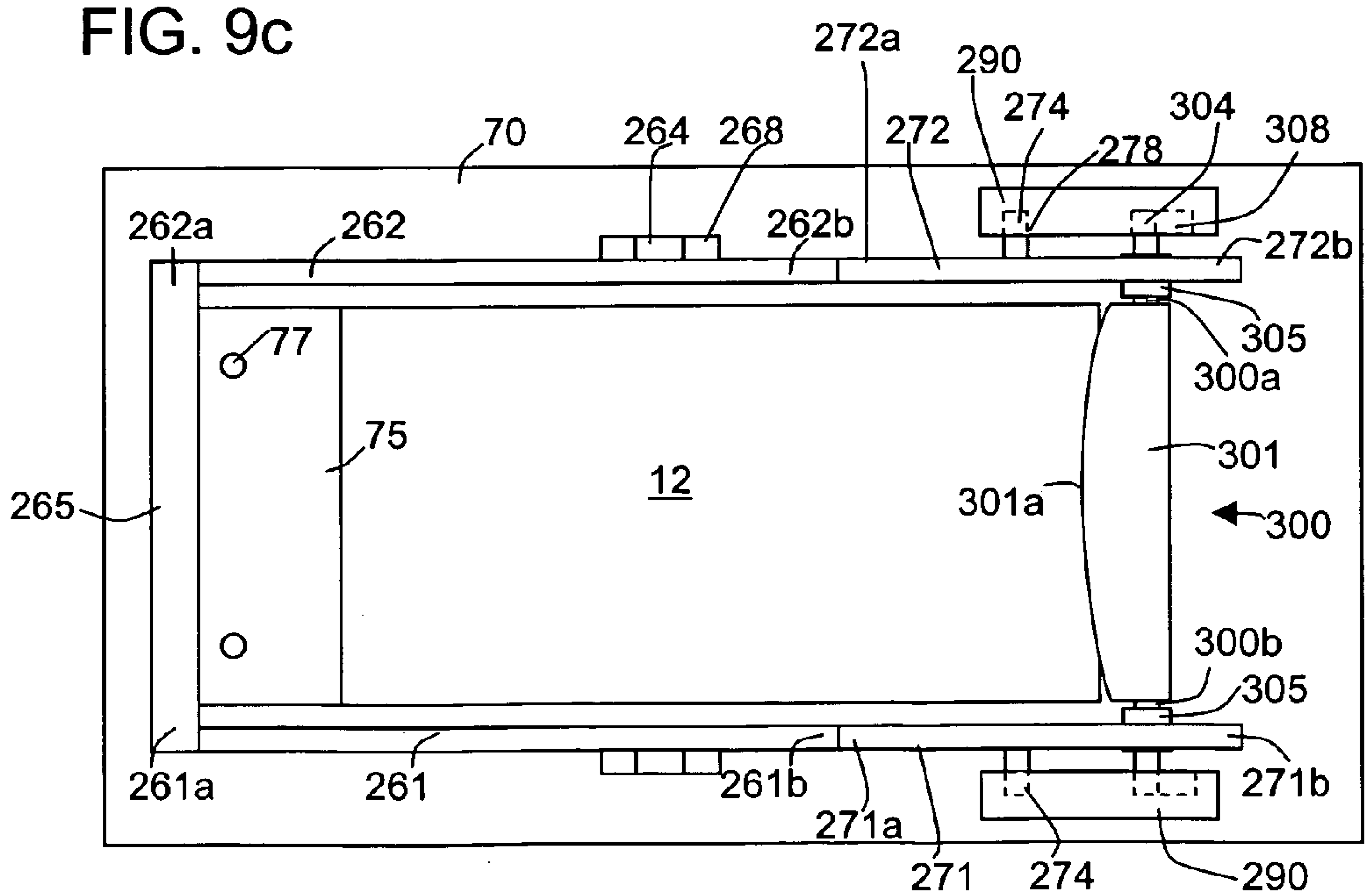


FIG. 10a

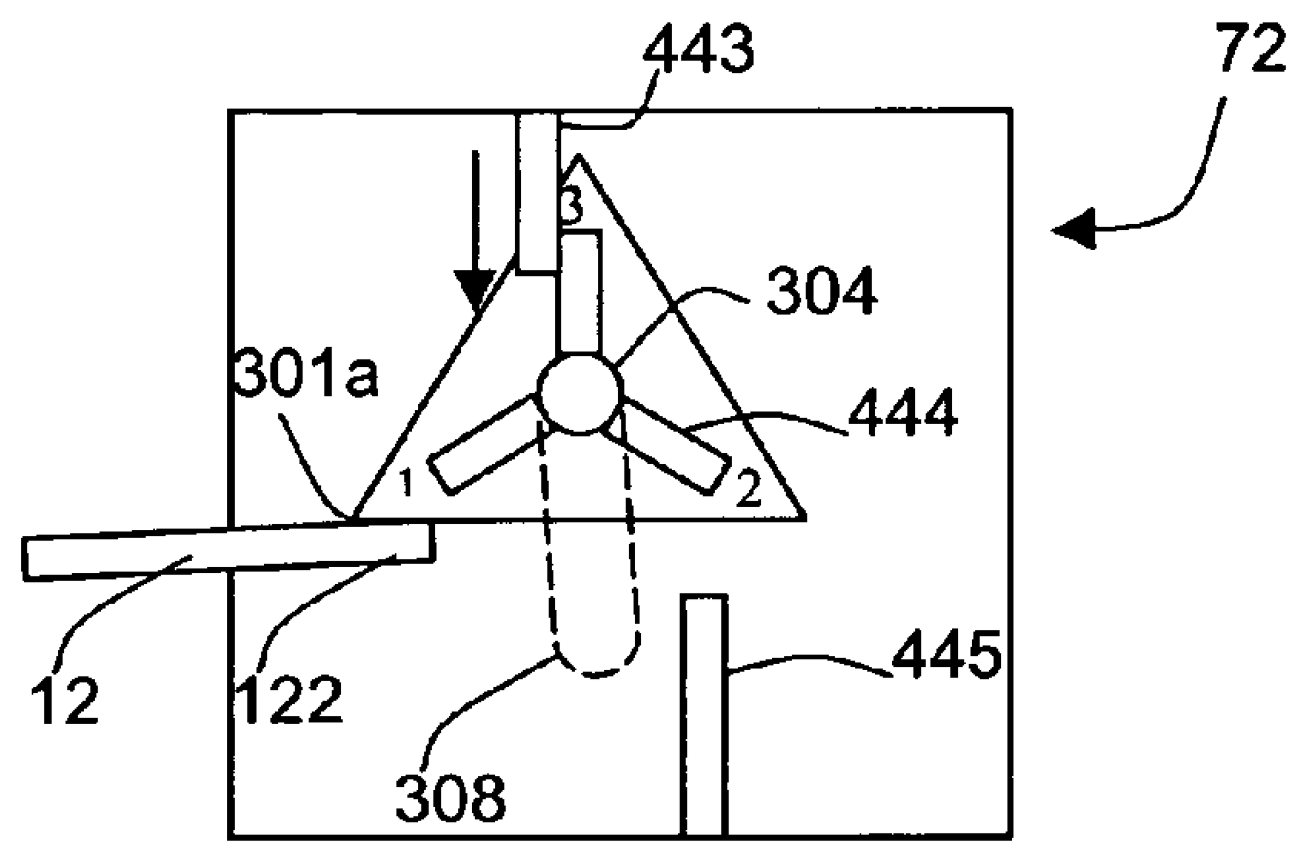


FIG. 10b

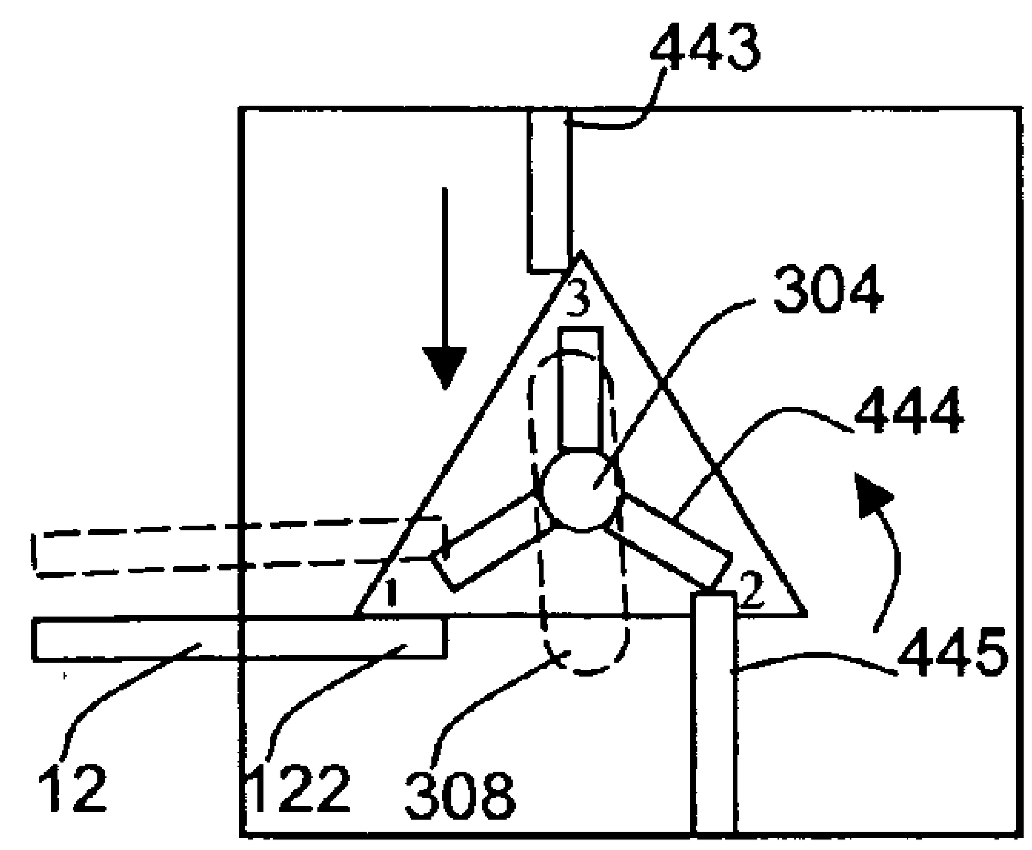


FIG. 10c

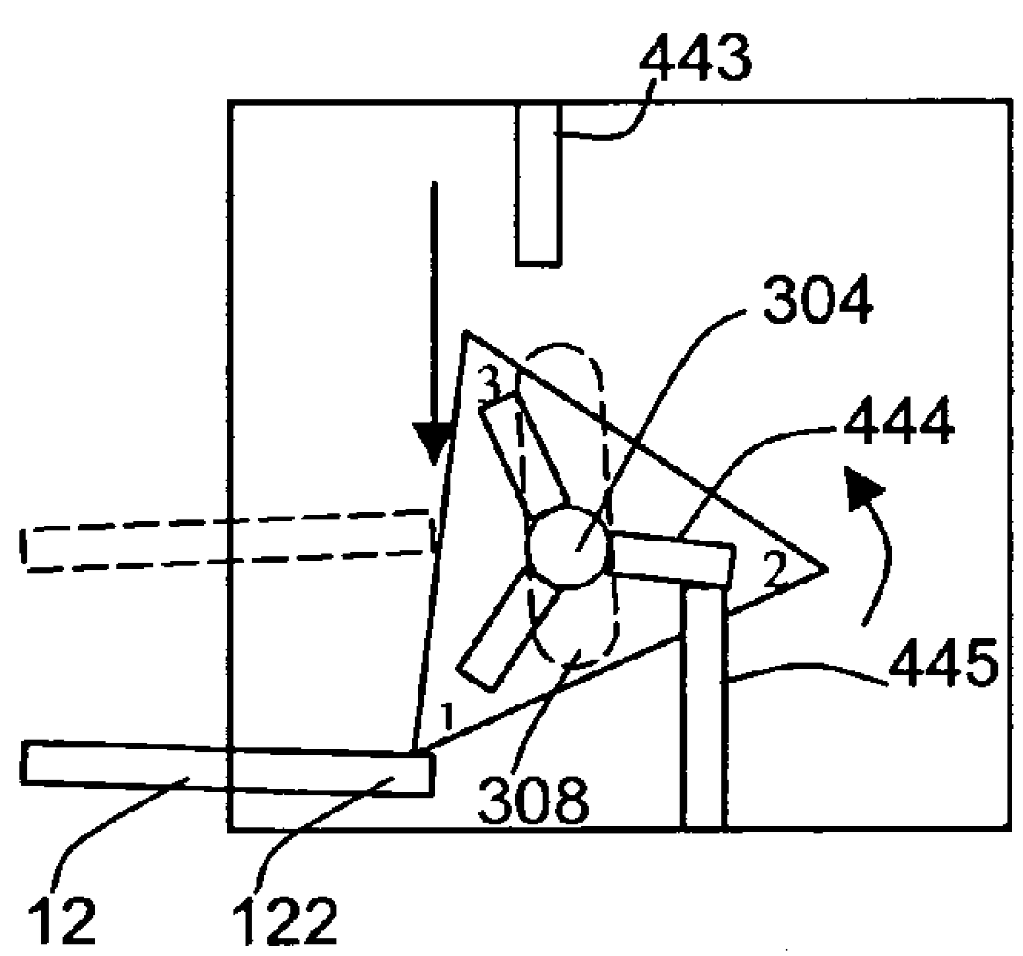


FIG. 10d

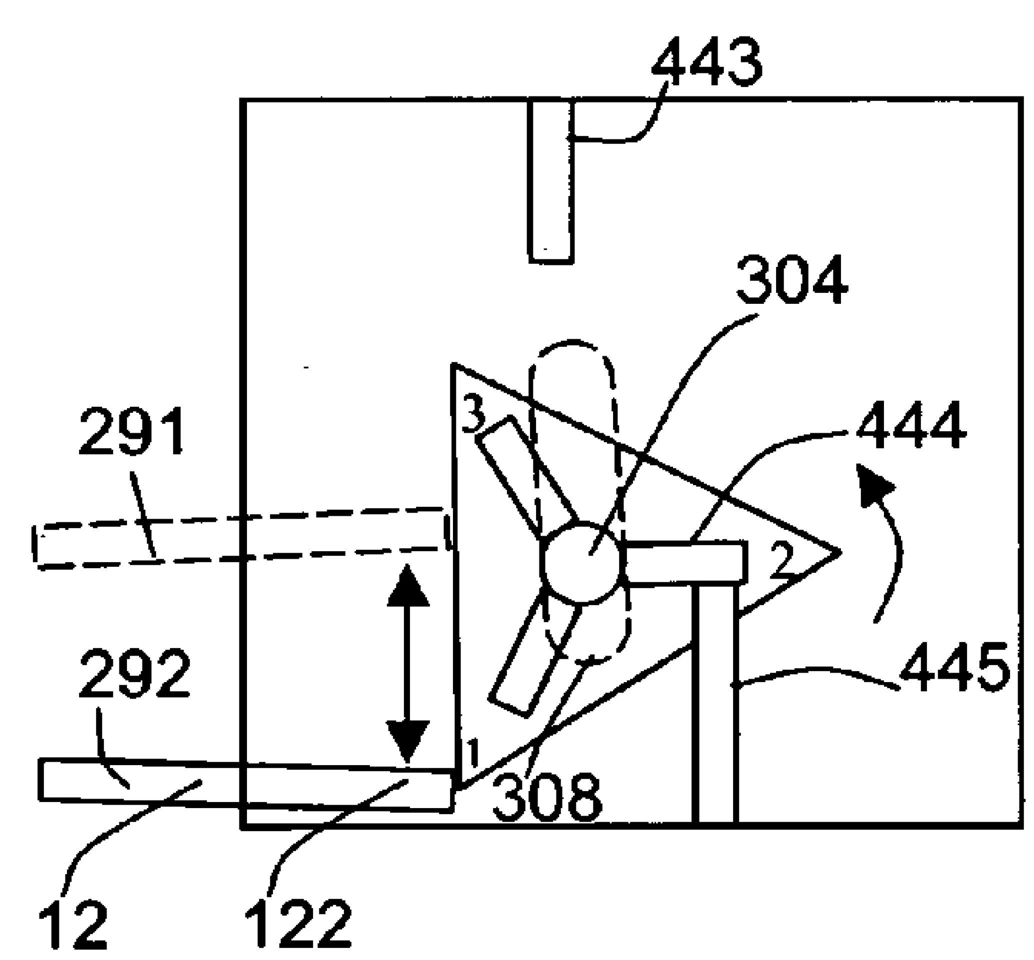


FIG. 10e

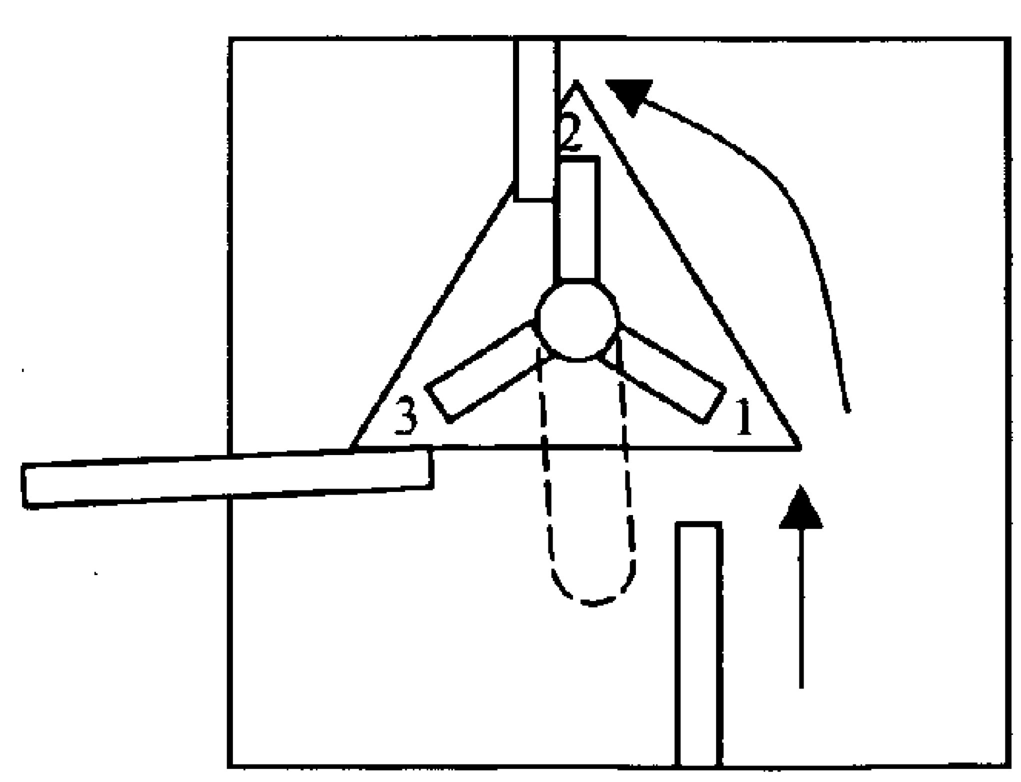


FIG. 11a

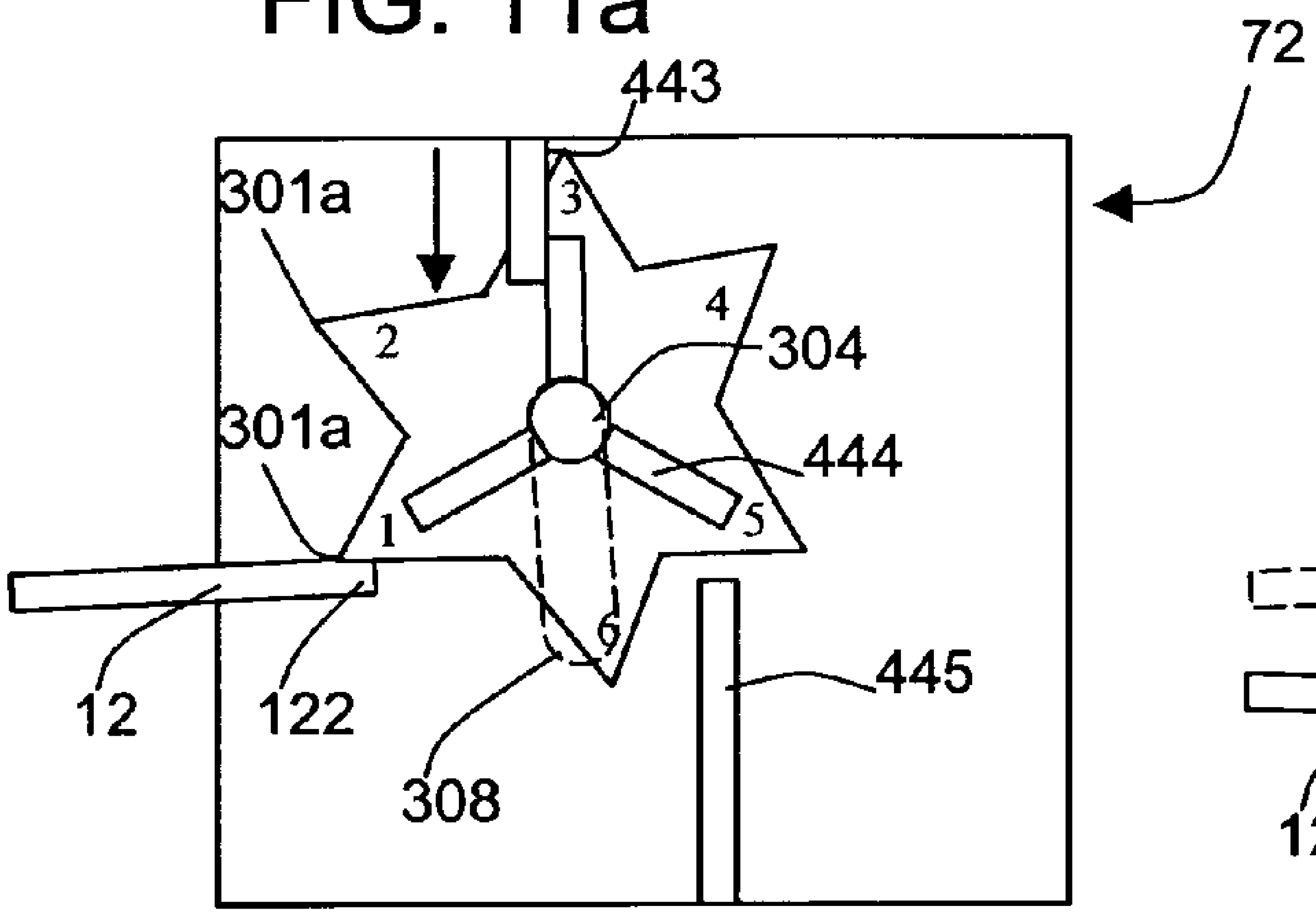


FIG. 11b

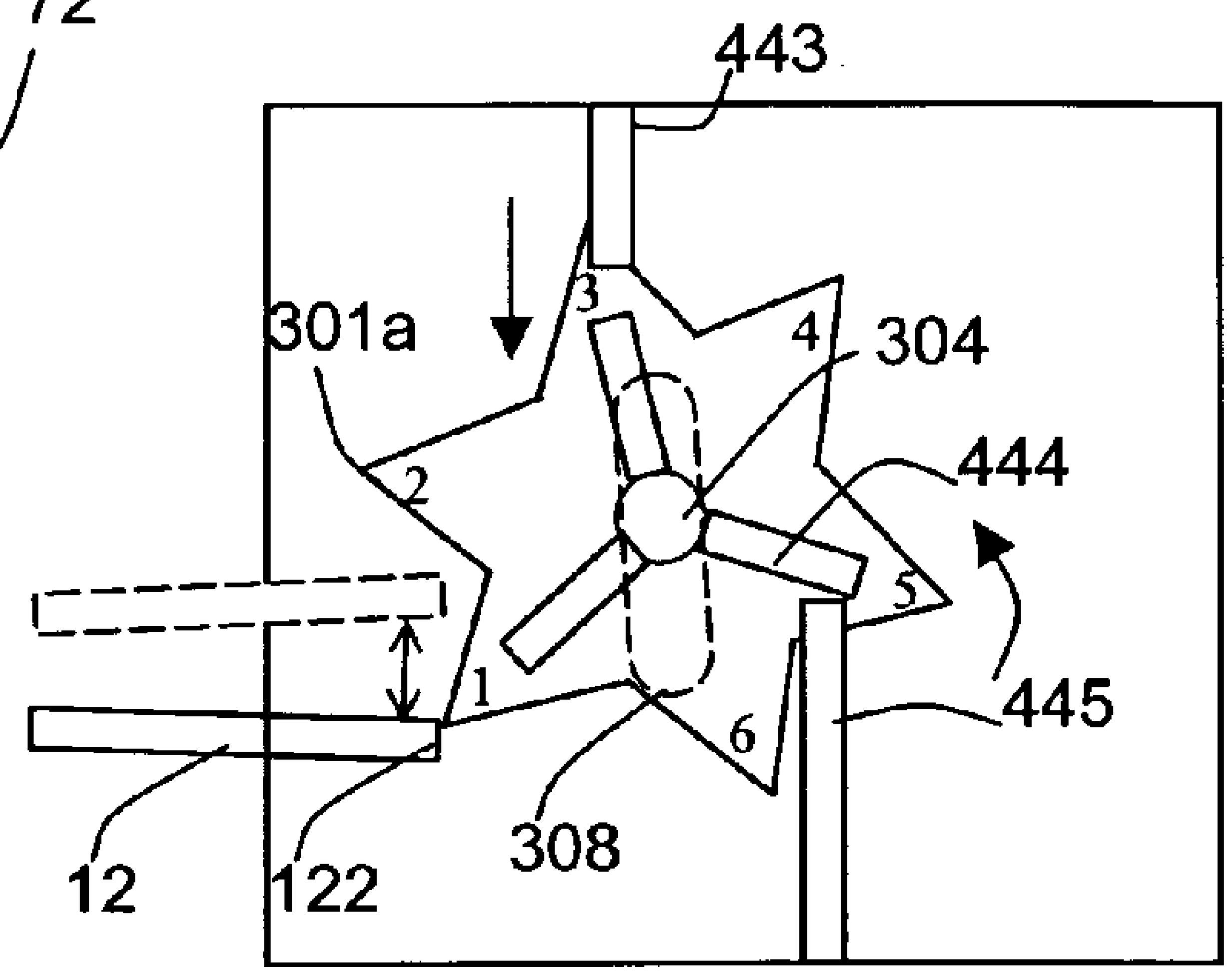


FIG. 11c

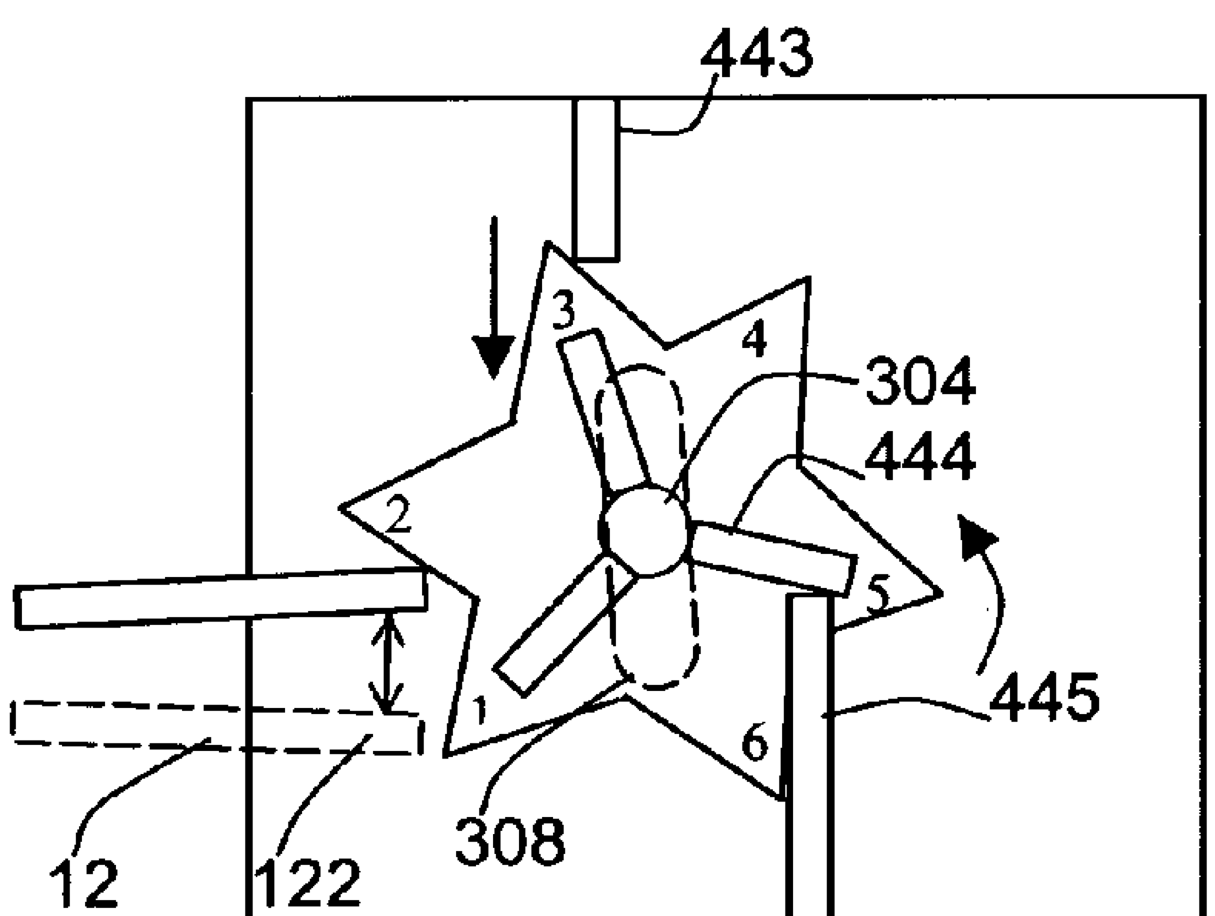


FIG. 11d

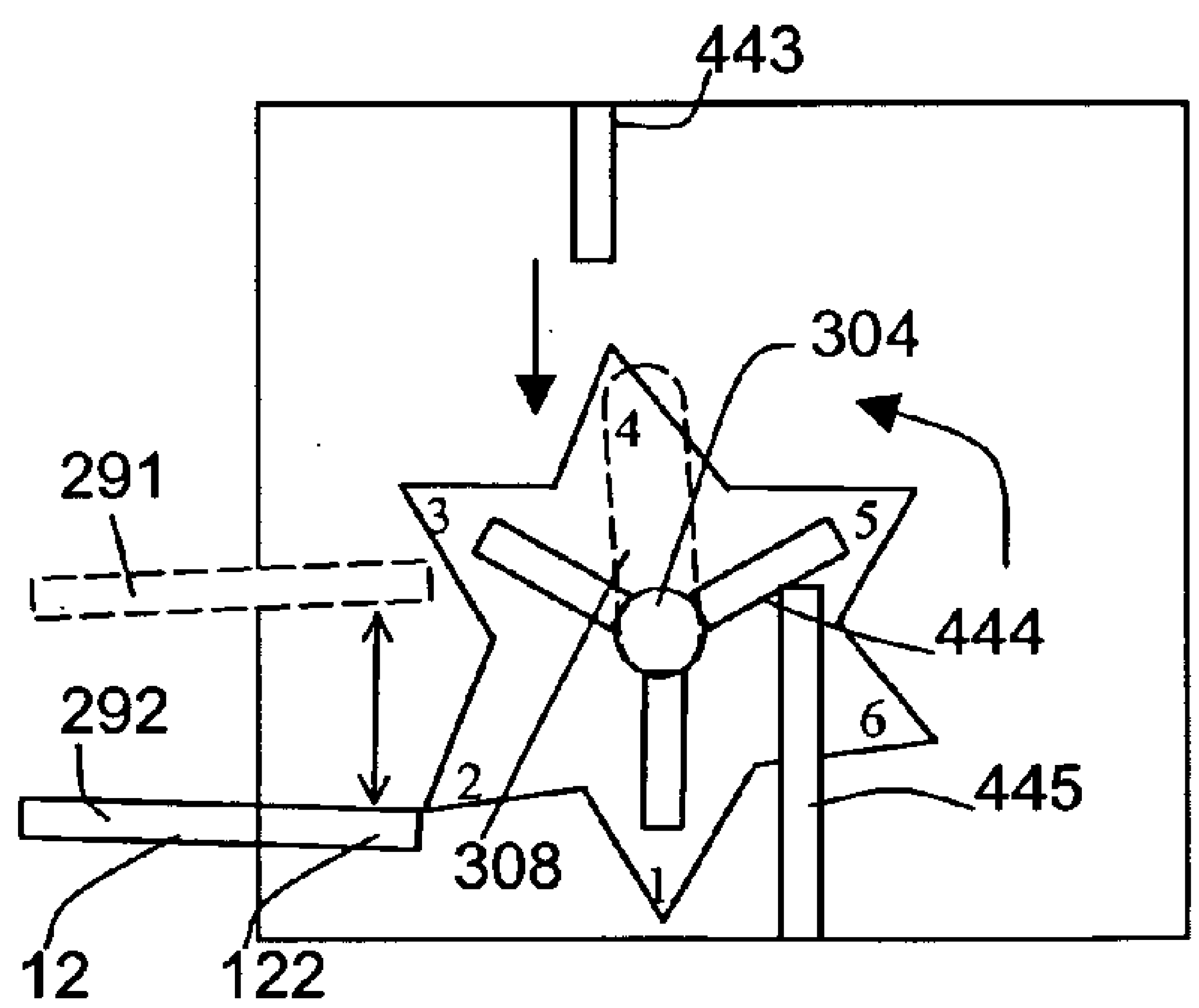


FIG. 11e

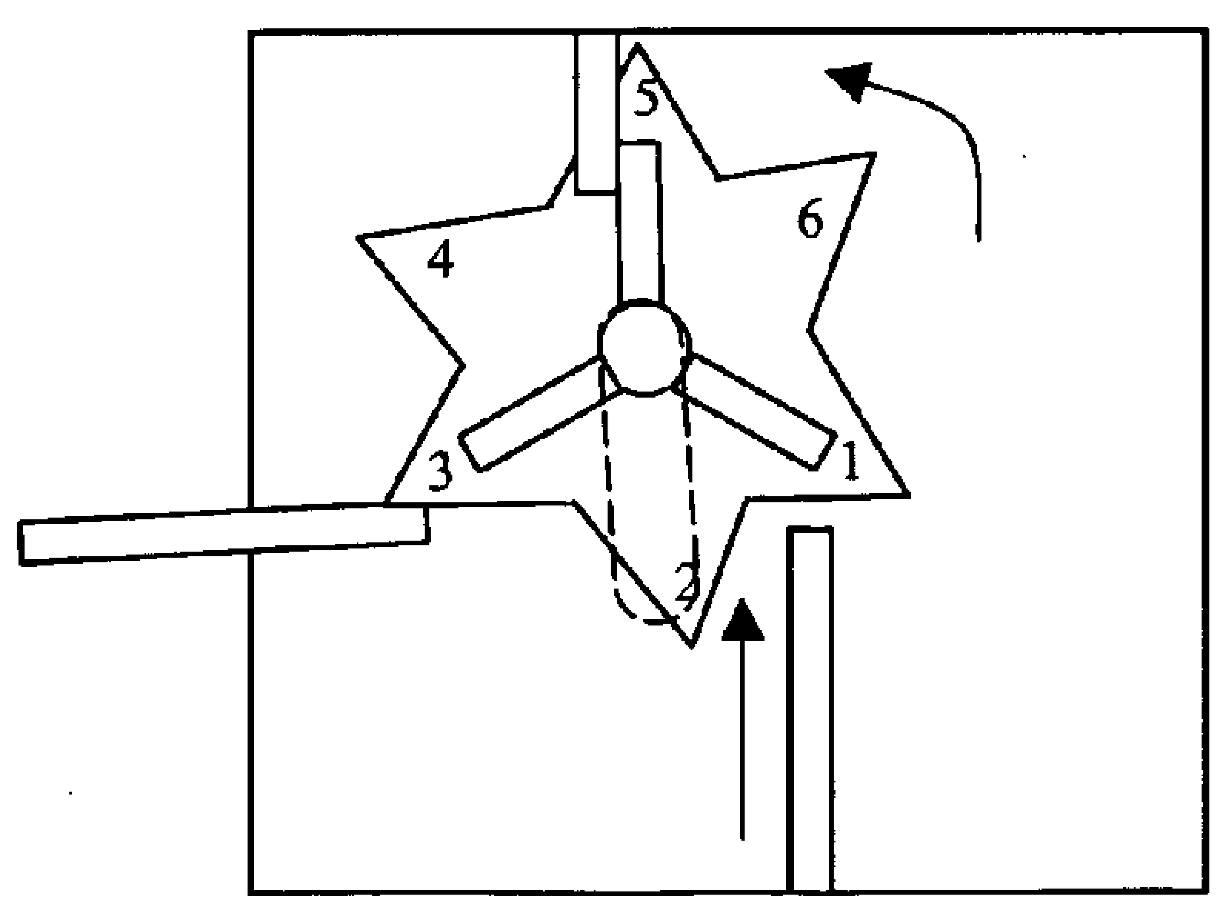


FIG. 12a

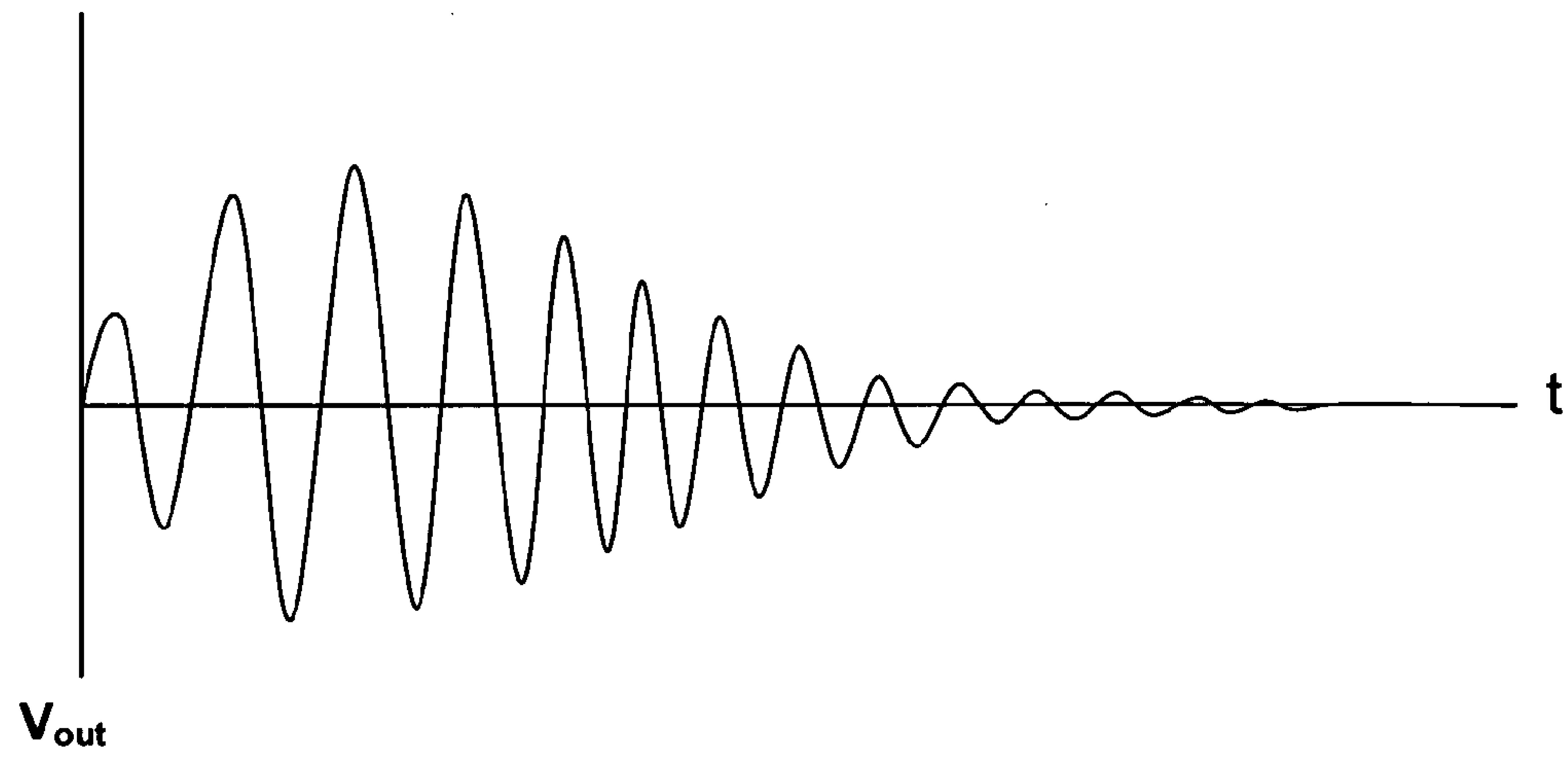


FIG. 12b

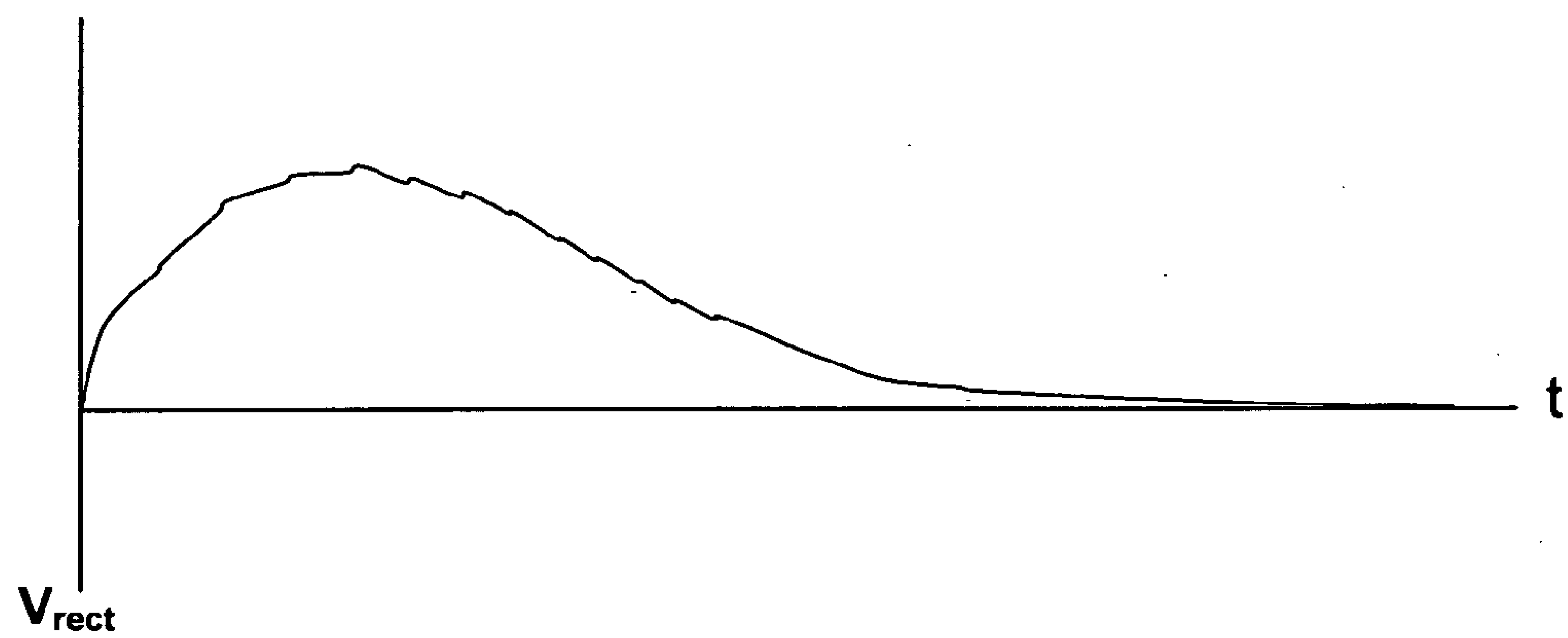


FIG. 12c

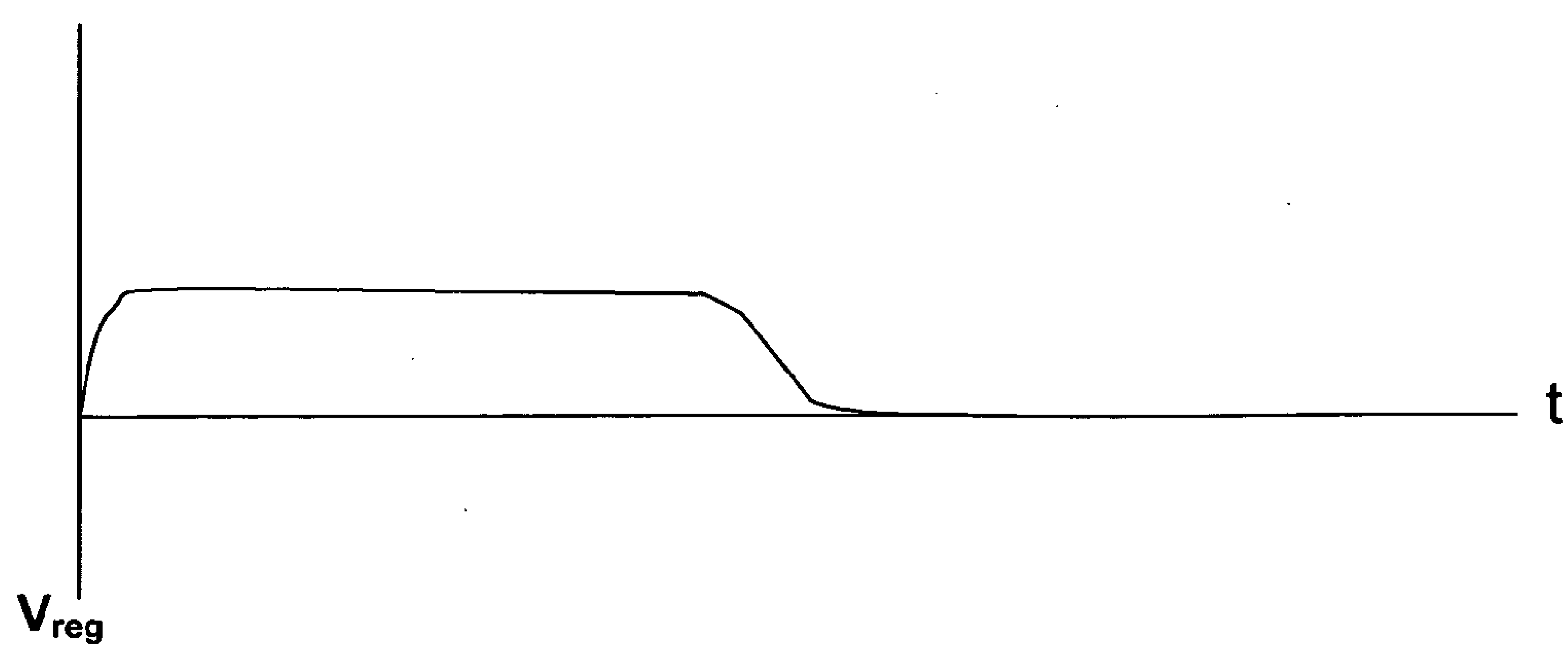


FIG. 12d

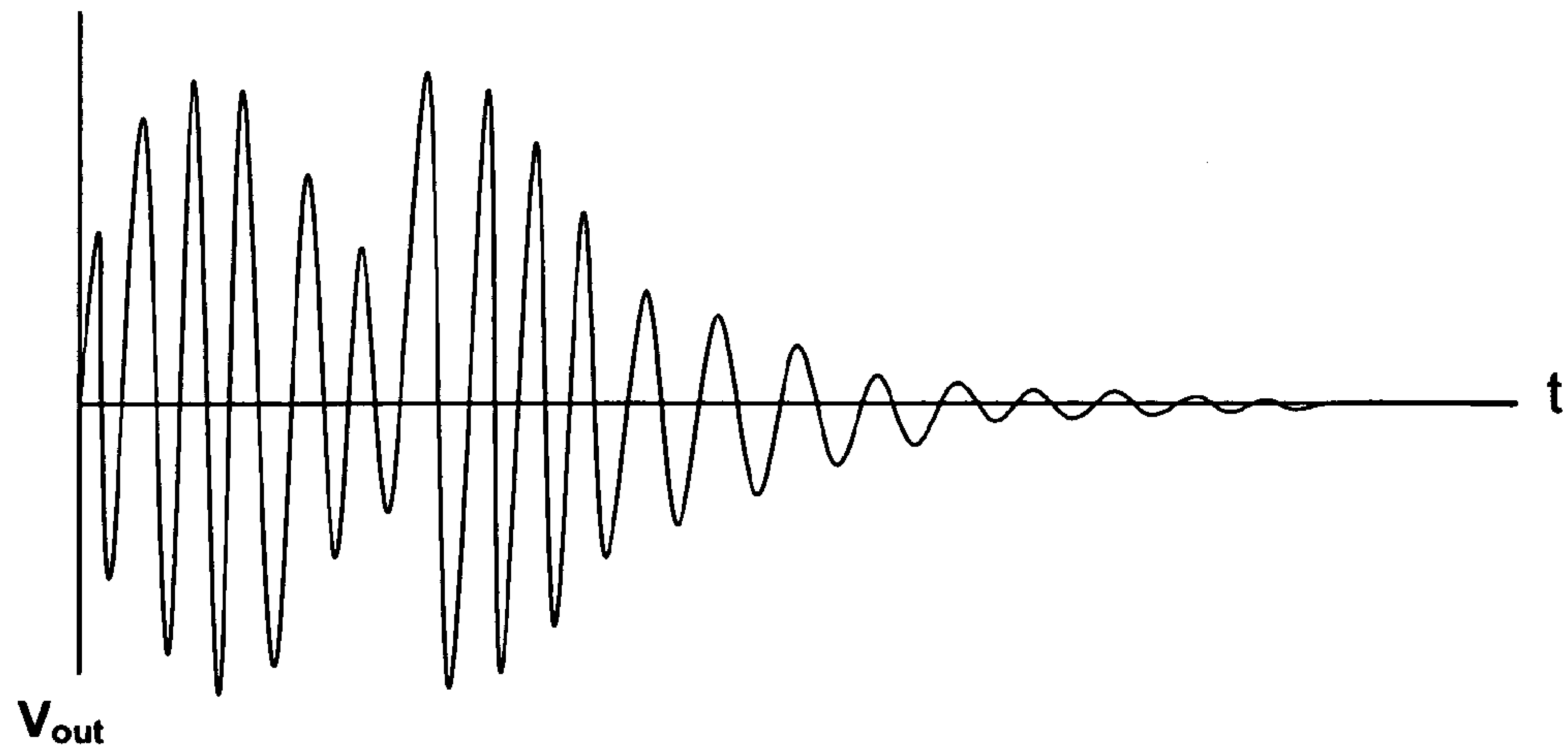


FIG. 12e

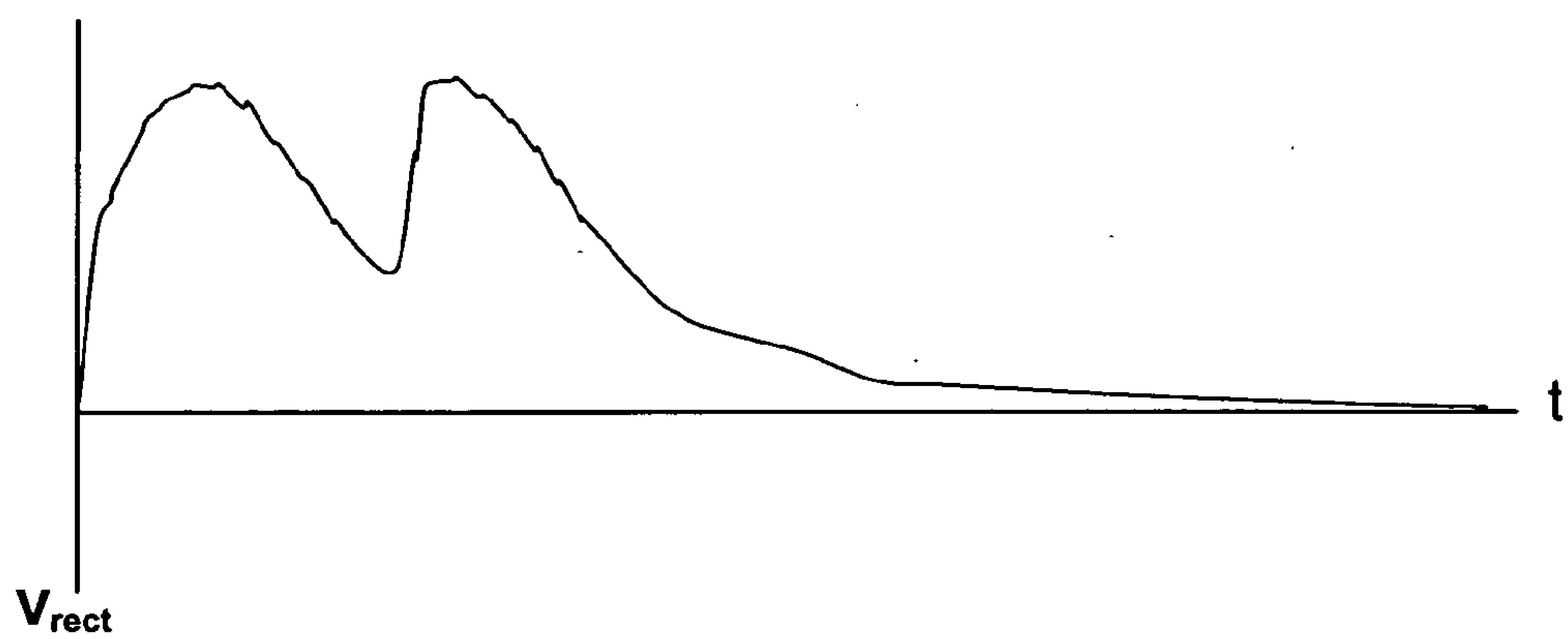


FIG. 12f

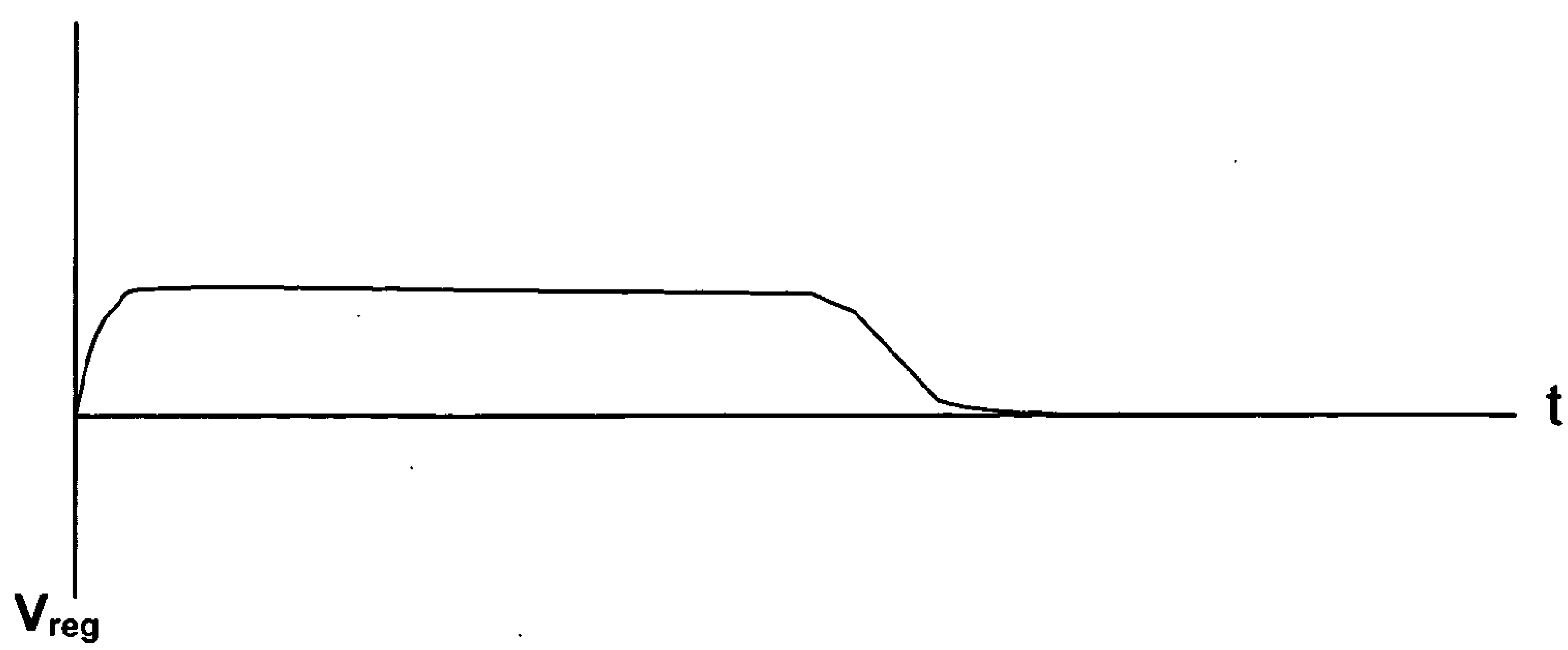
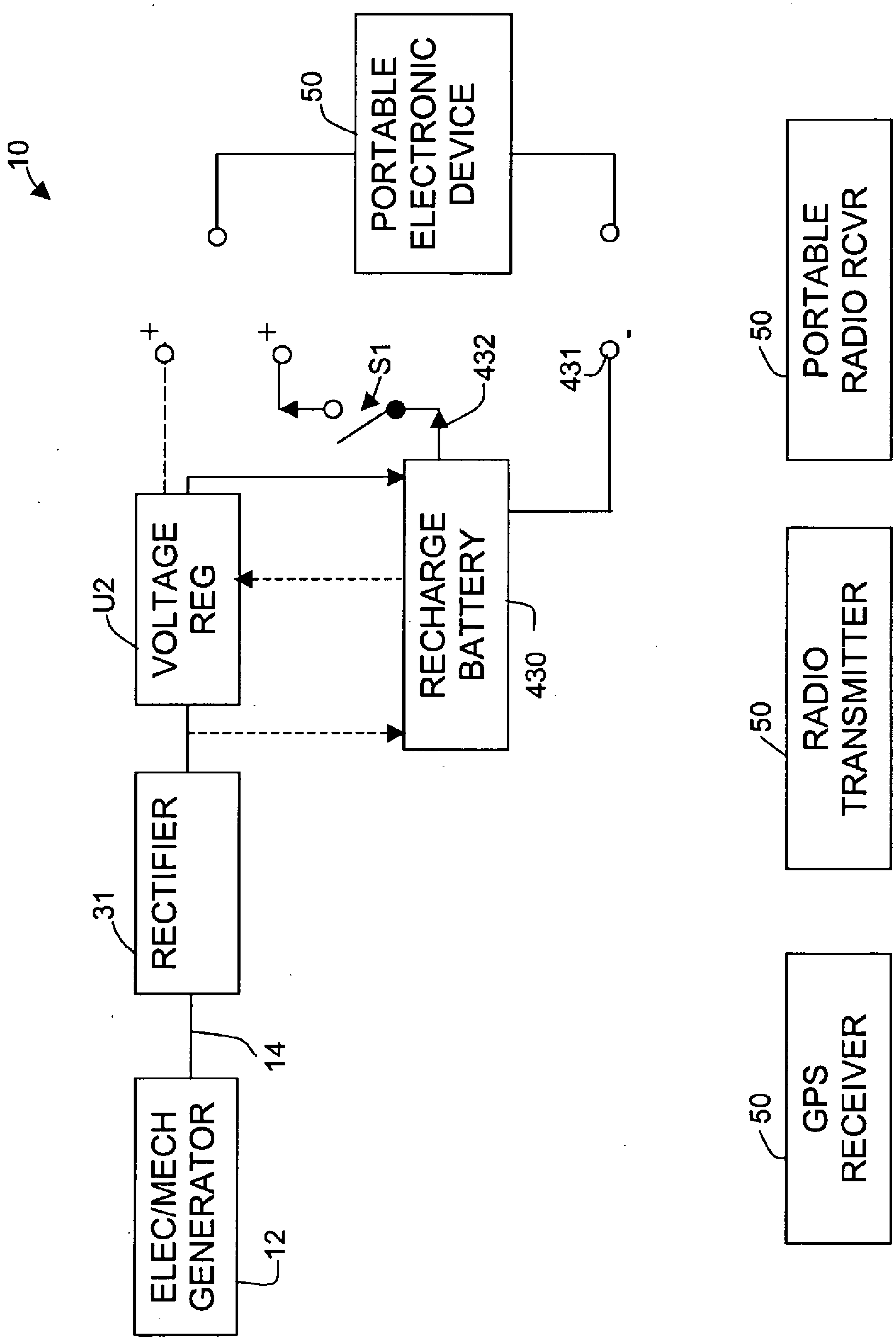
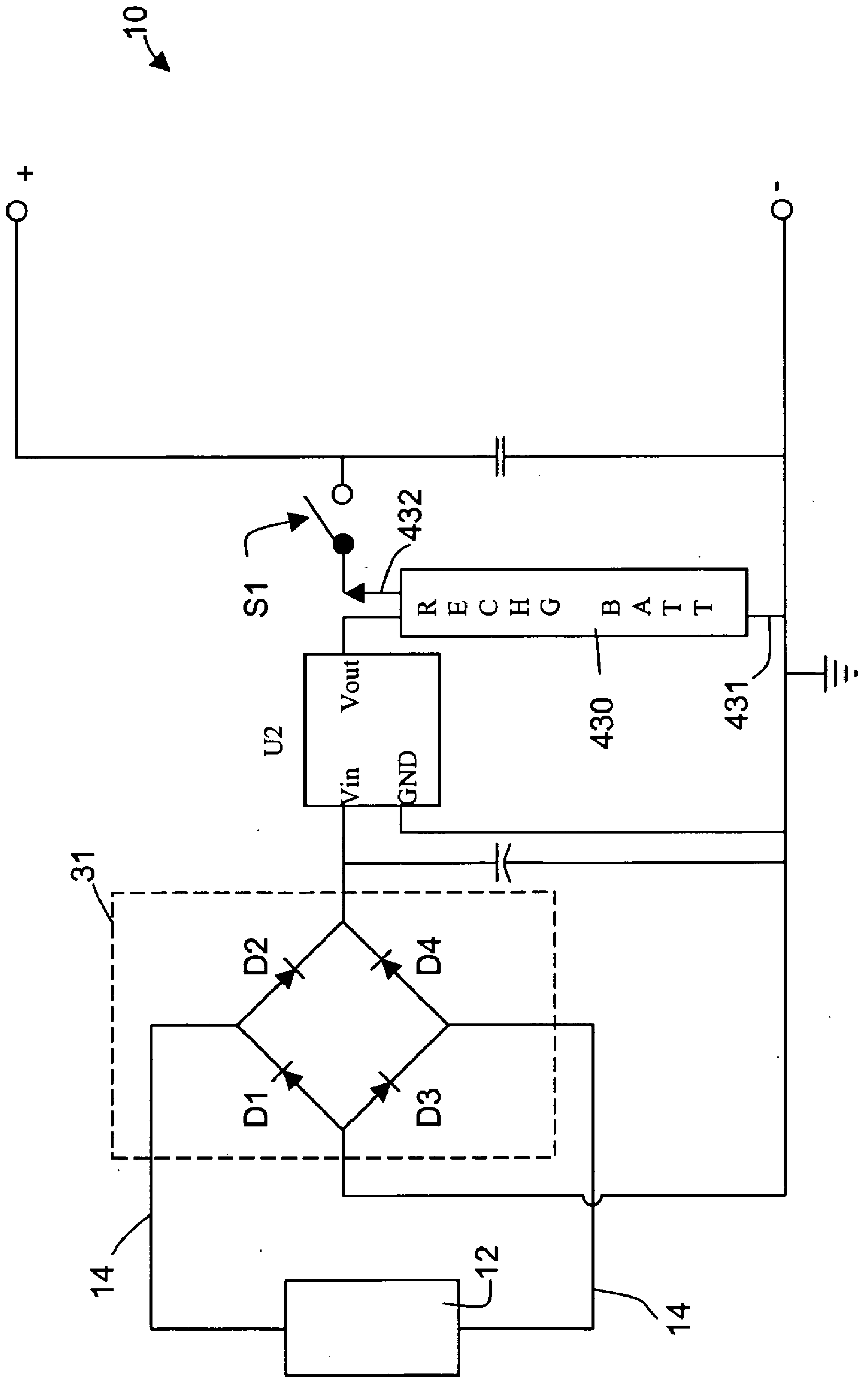


FIG. 13


10
ELEC/MECH GENERATOR
12
14
RECTIFIER
31
VOLTAGE REG
U2
RECHARGE BATTERY
430
431
432
S1
+
+
-
PORTABLE ELECTRONIC DEVICE
50
GPS RECEIVER
50
RADIO TRANSMITTER
50
PORTABLE RADIO RCVR
50


10
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S1
432
RECHG BATT
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431
U2
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Vout
GND
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D2
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D4
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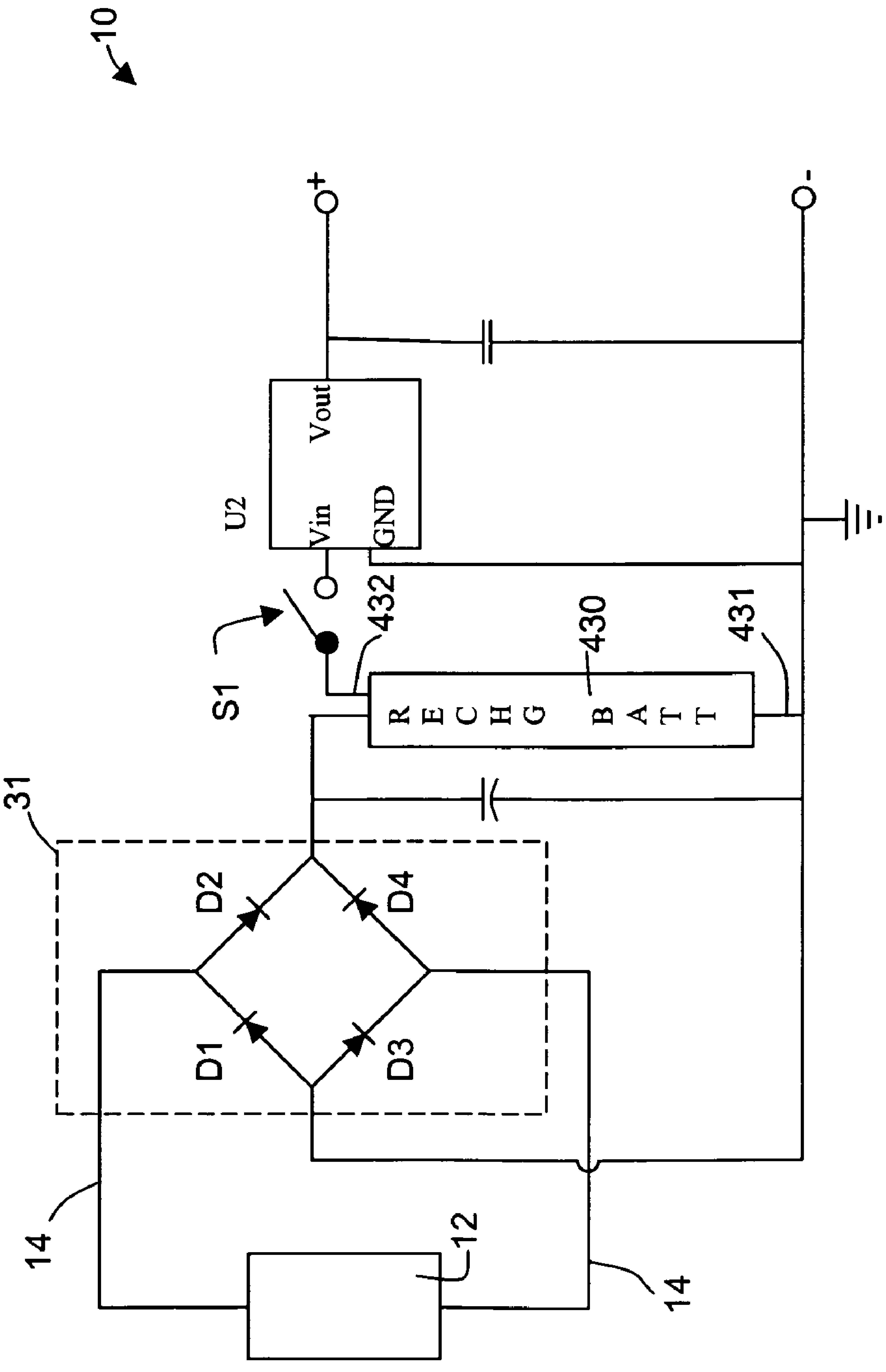
12
14

FIG. 14


10
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D4
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FIG. 15

FOOTWEAR INCORPORATING PIEZOELECTRIC ENERGY HARVESTING SYSTEM

[0001] This application claims the benefit of priority from earlier filed provisional patent application 60/589,087 filed Jul. 19, 2004.

BACKGROUND OF THE INVENTION

[0002] 1. Field of Invention

[0003] The present invention relates to an energy harvesting system incorporated in footwear. More specifically the present invention relates to footwear incorporating at least one piezoelectric element which, when activated, enables the wearer of the footwear to harvest energy from the deformation of the piezoelectric element.

[0004] 2. Description of the Prior Art

[0005] The present invention is a unique article of footwear which incorporates a piezoelectric system which may be advantageously used in a preferred embodiment of the invention to enable the wearer of said article of footwear to store energy harvested from the piezoelectric element. Energy generated by a piezoelectric element as a result of the impact of the footwear against the ground is stored in an energy storage circuit and is later released at an advantageous time.

[0006] The prior art includes devices which emit light when the footwear impacts or departs from the ground. Lighted footwear seen in the prior art typically comprises one or more sources of electric light, a small portable power source, such as a dry-cell battery, and electrical circuitry to connect the power source to the light sources electrically, which circuitry usually includes sensing means for sensing the desirable dynamic forces and switching the light sources on and off in a desirable fashion.

[0007] In U.S. Pat. No. 45,188,447, L. Chiang, et al., describe a lighted footwear system in which the lights are actuated by the impact of the footwear against an object, such as the ground. In this prior system, a piezoelectric crystal operates as a voltage generator to generate a brief voltage pulse, the amplitude of which is related to the amount of inertial force incident upon the crystal. The voltage pulse is used as the input of the battery-driven amplifier, which, in turn, drives the lights, such that the intensity of the single pulse of light emitted by the lights is related to the amount of force with which the footwear impacts the object. The Chiang, et al. device and other prior lighted footwear devices create a lighted effect that is novel and pleasing to the eye, but does not store the energy for later use in any way.

[0008] Accordingly, an inertially responsive article of footwear which is actuated by impact of the footwear against the ground and which incorporates a piezoelectric element capable of sustaining high loads is highly desirable.

SUMMARY OF THE INVENTION

[0009] In view of the foregoing disadvantages in the prior art, the present invention provides an article of footwear which stores energy generated by a piezoelectric element as a result of the impact of the footwear against the ground. The footwear comprises a piezoelectric element in the sole of the footwear, which generates electrical energy when deformed by the impact of the footwear against an object, such as the ground. The electrical energy is stored in energy harvesting and storage circuitry for use at a later time.

[0010] Accordingly, it is an object of the present invention to provide a device of the character described which stores the energy generated by the piezoelectric element upon impact of the footwear against the ground.

[0011] It is a further object of the present invention to provide a device of the character described in which a piezoelectric element is deformed by the impact of the footwear against the ground.

[0012] It is a further object of the present invention to provide a device of the character described in which the voltage potential created by the deformation of the piezoelectric element is stored in energy storage circuitry for use at a later time.

[0013] It is another object of the present invention to provide a device of the character described which is inexpensive and of a simple and uncluttered design.

[0014] Further objects and advantages of this invention will become apparent from a consideration of the drawings and ensuing description thereof.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] **FIG. 1** is an elevation view showing the details of construction of a flextensional piezoelectric transducer used in the present invention, as an electroactive generator;

[0016] **FIG. 1***a* is an elevation view showing the details of construction of the flextensional piezoelectric generator of **FIG. 1** having an additional prestress layer;

[0017] **FIG. 2** is an elevation view showing the details of construction of an alternate multi-layer flextensional piezoelectric generator used in a modification of the present invention;

[0018] **FIG. 2***a* is an elevation view showing the details of construction of the flextensional piezoelectric generator of **FIG. 1***a* with a flat rather than arcuate profile;

[0019] **FIG. 3** is a side elevation with a shoe in phantom showing a piezoelectric energy harvesting system constructed in accordance with the present invention;

[0020] **FIG. 4** is a side elevation of the piezoelectric energy harvesting system shown in **FIG. 3** with a first force being applied to the piezoelectric element, i.e. by bending the shoe by walking;

[0021] **FIG. 5** is a side elevation with a shoe in phantom showing another embodiment of a piezoelectric energy harvesting system constructed in accordance with the present invention;

[0022] **FIG. 6** is a side elevation of the piezoelectric energy harvesting system shown in **FIG. 5** with a first force being applied to the piezoelectric element, i.e. by bending the shoe by walking;

[0023] **FIG. 7** is a side elevation with a shoe in phantom showing yet another embodiment of a piezoelectric energy harvesting system constructed in accordance with the present invention;

[0024] **FIG. 8** is a side elevation of the piezoelectric energy harvesting system shown in **FIG. 7** with a first force being applied to the piezoelectric element, i.e. by deflecting a plucker assembly by walking;

[0025] **FIGS. 9***a-b* are elevations of the plucker assembly in **FIGS. 7-8** showing the plucker and actuator in the undeflected and deflected position;

[0026] **FIG. 9***c* is a plan view of the plucker assembly in **FIGS. 9***a-b;*

[0027] **FIGS. 10***a-e* are detailed elevations of a plucker assembly and actuator edge in the various stages of deflection;

[0028] **FIGS. 11***a-e* are detailed elevations of an alternate "double" plucker assembly and actuator edge in the various stages of deflection;

[0029] **FIGS. 12***a-c* show the electrical signal generated by the transducer of **FIG. 10**, the electrical output signal of the rectifier at the junction with the capacitor and the regulated electrical signal respectively;

[0030] **FIGS. 12***d-f* show the electrical signal generated by the transducer of **FIG. 11** when plucked twice, i.e., sequentially, the electrical output signal of the rectifier at the junction with the capacitor and the regulated electrical signal respectively;

[0031] **FIG. 13** is a schematic of the components of a circuit for an energy harvesting system in the shoes of **FIGS. 3-8**;

[0032] **FIG. 14** is a schematic of an exemplary circuit used as an energy harvesting system in the shoes of **FIGS. 3-8**; and

[0033] **FIG. 15** is a schematic of another exemplary circuit used as an energy harvesting system in the shoes of **FIGS. 3-8**.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0034] As seen in **FIG. 3**, modern footwear, particularly the type of athletic and casual shoes to which the present invention is readily adapted, typically comprise a soft, flexible upper portion **28** adapted to surround at least a portion of the upper surface of a wearer's foot, and a resilient sole portion **26** attached to the bottom of the upper portion **28** and adapted to underlie the wearer's foot and protect it against uncomfortable contact with the ground.

[0035] Typical materials for the upper portion **28** include leather and man-made sheet materials, such as polyvinyl or polyurethane sheets, or combinations of these, which are die- or laser-cut and then stitched together over a foot-shaped cast to form the finished upper **28**. The sole portion **26** is typically molded of man-made elastomeric materials, such as rubber, foamed or solid polyurethane or ethylene vinyl acetate, to include certain common structural features, such as a top, or "footbed," surface **33**, a peripheral sidewall surface **30**, and may further comprise a series of layered components, such as an outsole component, a midsole component, and an insole component (not illustrated). The sole portion **26** is attached on its upper surface **32** to a lower margin of the upper portion **28**, typically by adhesive means.

[0036] As shown in **FIG. 3**, a piezoelectric energy harvesting system **24** is advantageously disposed in or molded into a cavity **40** located in the sole portion **26**, such that when the contact surface **34** of the sole portion **26** impacts the ground **44** the piezoelectric energy harvesting system **24** is actuated. It should be understood that the piezoelectric energy harvesting system **24** is mounted in the sole portion **26** substantially near the contact surface **34**, such that the energy transferred to the piezoelectric energy harvesting system **24** by the impact of the contact surface **34** with the ground **44** is maximized, and attenuation of said energy in the section **36** of the sole portion **26** between the ground **44** and the piezoelectric energy harvesting system **24** is minimized. The piezoelectric harvesting system is preferably located in a rear portion, or heel portion, of the sole portion, but may advantageously be located anywhere in the sole portion such as the front or central portions which are subject to deflective forces that may be transferred to the piezoelectric energy harvesting system.

Electroactive Generator

[0037] Piezoelectric and electrostrictive materials (generally called "electroactive" devices herein) develop an electric field when placed under stress or strain. The electric field developed by a piezoelectric or electrostrictive material is a function of the applied force and displacement causing the mechanical stress or strain. Conversely, electroactive devices undergo dimensional changes in an applied electric field. The dimensional change (i.e., expansion or contraction) of an electroactive element is a function of the applied electric field. Electroactive devices are commonly used as drivers, or "actuators" due to their propensity to deform under such electric fields. These electroactive devices when used as transducers or generators also have varying capacities to generate an electric field in response to a deformation caused by an applied force. In such cases they behave as electrical generators.

[0038] Electroactive devices include direct and indirect mode actuators, which typically make use of a change in the dimensions of the material to achieve a displacement, but in the present invention are preferably used as electromechanical generators. Direct mode actuators typically include a piezoelectric or electrostrictive ceramic plate (or stack of plates) sandwiched between a pair of electrodes formed on its major surfaces. The devices generally have a sufficiently large piezoelectric and/or electrostrictive coefficient to produce the desired strain in the ceramic plate. However, direct mode actuators suffer from the disadvantage of only being able to achieve a very small displacement (strain), which is, at best, only a few tenths of a percent. Conversely, direct mode generator-actuators require application of a high amount of force to piezoelectrically generate a pulsed momentary electrical signal of sufficient magnitude to activate a latching relay.

[0039] Indirect mode actuators are known to exhibit greater displacement and strain than is achievable with direct mode actuators by achieving strain amplification via external structures. An example of an indirect mode actuator is a flextensional transducer. Flextensional transducers are composite structures composed of a piezoelectric ceramic element and a metallic shell, stressed plastic, fiberglass, or similar structures. The actuator movement of conventional flextensional devices commonly occurs as a result of expansion in the piezoelectric material which mechanically couples to an amplified contraction of the device in the transverse direction. In operation, they can exhibit several orders of magnitude greater strain and displacement than can be produced by direct mode actuators.

[0040] The magnitude of achievable deflection (transverse bending) of indirect mode actuators can be increased by constructing them either as "unimorph" or "bimorph" flextensional actuators. A typical unimorph is a concave structure composed of a single piezoelectric element externally bonded to a flexible metal foil, and which results in axial buckling (deflection normal to the plane of the electroactive element) when electrically energized. Common unimorphs can exhibit transverse bending as high as 10%, i.e., a deflection normal to the plane of the element equal to 10% of the length of the actuator. A conventional bimorph device includes an intermediate flexible metal foil sandwiched between two piezoelectric elements. Electrodes are bonded to each of the major surfaces of the ceramic elements and the metal foil is bonded to the inner two electrodes. Bimorphs exhibit more displacement than comparable unimorphs because under the applied voltage, one ceramic element will contract while the other expands. Bimorphs can exhibit transverse bending of up to 20% of the bimorph length.

[0041] For certain applications, asymmetrically stress biased electroactive devices have been proposed in order to increase the transverse bending of the electroactive generator, and therefore increase the electrical output in the electroactive material. In such devices, (which include, for example, "Rainbow" actuators (as disclosed in U.S. Pat. No. 5,471,721), and other flextensional actuators) the asymmetric stress biasing produces a curved structure, typically having two major surfaces, one of which is concave and the other which is convex.

[0042] Thus, various constructions of flextensional piezoelectric and ferroelectric generators may be used including: indirect mode actuators (such as "moonies" and, CYMBAL); bending actuators (such as unimorph, bimorph, multimorph or monomorph devices); prestressed actuators (such as "THUNDER" and rainbow" actuators as disclosed in U.S. Pat. No. 5,471,721); and multilayer actuators such as stacked actuators; and polymer piezofilms such as PVDF. Many other electromechanical devices exist and are contemplated to function similarly to generate power for harvesting in the invention.

[0043] Referring to **FIG. 1**: The electroactive generator preferably comprises a prestressed unimorph device called "THUNDER", which has improved displacement and load capabilities, as disclosed in U.S. Pat. No. 5,632,841. THUNDER (which is an acronym for THin layer composite UNimorph ferroelectric Driver and sEnsoR), is a unimorph device in which a pre-stress layer is bonded to a thin piezoelectric ceramic wafer at high temperature. During the cooling down of the composite structure, asymmetrical stress biases the ceramic wafer due to the difference in thermal contraction rates of the pre-stress layer and the ceramic layer. A THUNDER element comprises a piezoelectric ceramic layer bonded with an adhesive (preferably an imide) to a metal (preferably stainless steel) substrate. The substrate, ceramic and adhesive are heated until the adhesive melts and they are subsequently cooled. During cooling as the adhesive solidifies the adhesive and substrate thermally contracts more than the ceramic, which compressively stresses the ceramic. Using a single substrate, or two substrates with differing thermal and mechanical characteristics, the actuator assumes its normally arcuate shape. The transducer or electroactive generator may also be normally flat rather than arcuate, by applying equal amounts of prestress to each side of the piezoelectric element, as dictated by the thermal and mechanical characteristics of the substrates bonded to each face of the piezo-element.

[0044] The THUNDER element **12** is as a composite structure, the construction of which is illustrated in **FIG. 1**. Each THUNDER element **12** is constructed with an electroactive member preferably comprising a piezoelectric ceramic layer **67** of PZT which is electroplated **65** and **65***a* on its two opposing faces. A pre-stress layer **64**, preferably comprising spring steel, stainless steel, beryllium alloy, aluminum or other flexible substrate (such as metal, fiberglass, carbon fiber, KEVLAR™, composites or plastic), is adhered to the electroplated **65** surface on one side of the ceramic layer **67** by a first adhesive layer **66**. In the simplest embodiment, the adhesive layer **66** acts as a prestress layer. The first adhesive layer **66** is preferably LaRC™-SI material, as developed by NASA-Langley Research Center and disclosed in U.S. Pat. No. 5,639,850. A second adhesive layer **66***a*, also preferably comprising LaRC-SI material, is adhered to the opposite side of the ceramic layer **67**. During manufacture of the THUNDER element **12** the ceramic layer **67**, the adhesive layer(s) **66** and **66***a* and the pre-stress layer **64** are simultaneously heated to a temperature above the melting point of the adhesive material. In practice the various layers composing the THUNDER element (namely the ceramic layer **67**, the adhesive layers **66** and **66***a* and the pre-stress layer **64**) are typically placed inside of an autoclave, heated platen press or a convection oven as a composite structure, and slowly heated under pressure by convection until all the layers of the structure reach a temperature which is above the melting point of the adhesive **66** material but below the Curie temperature of the ceramic layer **67**. Because the composite structure is typically convectively heated at a slow rate, all of the layers tend to be at approximately the same temperature. In any event, because an adhesive layer **66** is typically located between two other layers (i.e. between the ceramic layer **67** and the pre-stress layer **64**), the ceramic layer **67** and the pre-stress layer **64** are usually very close to the same temperature and are at least as hot as the adhesive layers **66** and **66***a* during the heating step of the process. The THUNDER element **12** is then allowed to cool.

[0045] During the cooling step of the process (i.e. after the adhesive layers **66** and **66***a* have re-solidified) the ceramic layer **67** becomes compressively stressed by the adhesive layers **66** and **66***a* and pre-stress layer **64** due to the higher coefficient of thermal contraction of the materials of the adhesive layers **66** and **66***a* and the pre-stress layer **64** than for the material of the ceramic layer **67**. Also, due to the greater thermal contraction of the laminate materials (e.g. the first pre-stress layer **64** and the first adhesive layer **66**) on one side of the ceramic layer **67** relative to the thermal contraction of the laminate material(s) (e.g. the second adhesive layer **66***a*) on the other side of the ceramic layer **67**, the ceramic layer deforms in an arcuate shape having a normally convex face **12***a* and a normally concave face **12***c*, as illustrated in **FIGS. 1 and 2**.

[0046] Referring to **FIG. 1***a:* One or more additional pre-stressing layer(s) may be similarly adhered to either or both sides of the ceramic layer **67** in order, for example, to increase the stress in the ceramic layer **67** or to strengthen the THUNDER element **12**B. In a preferred embodiment of the invention, a second prestress layer **68** is placed on the concave face **12***a* of the THUNDER element **12**B having the second adhesive layer **66***a* and is similarly heated and cooled. Preferably the second prestress layer **68** comprises a layer of conductive metal. More preferably the second prestress layer **68** comprises a thin foil (relatively thinner than the first prestress layer **64**) comprising aluminum or other conductive metal. During the cooling step of the process (i.e. after the adhesive layers **66** and **66***a* have re-solidified) the ceramic layer **67** similarly becomes compressively stressed by the adhesive layers **66** and **66***a* and pre-stress layers **64** and **68** due to the higher coefficient of thermal contraction of the materials of the adhesive layers **66** and **66***a* and the pre-stress layers **64** and **68** than for the material of the ceramic layer **67**. Also, due to the greater thermal contraction of the laminate materials (e.g. the first pre-stress layer **64** and the first adhesive layer **66**) on one side of the ceramic layer **67** relative to the thermal contraction of the laminate material(s) (e.g. the second adhesive layer **66***a* and the second prestress layer **68**) on the other side of the ceramic layer **67**, the ceramic layer **67** deforms into an arcuate shape having a normally convex face **12***a* and a normally concave face **12***c*, as illustrated in **FIG. 1***a*.

[0047] Alternately, the second prestress layer **68** may comprise the same material as is used in the first prestress layer **64**, or a material with substantially the same mechanical strain characteristics. Using two prestress layers **64**, **68** having similar mechanical strain characteristics ensures that, upon cooling, the thermal contraction of the laminate materials (e.g. the first pre-stress layer **64** and the first adhesive layer **66**,) on one side of the ceramic layer **67** is substantially equal to the thermal contraction of the laminate materials (e.g. the second adhesive layer **66***a* and the second prestress layer **68**) on the other side of the ceramic layer **67**, and the ceramic layer **67** and the transducer **12** remain substantially flat, but still under a compressive stress.

[0048] Alternatively, the substrate comprising a separate prestress layer **64** may be eliminated and the adhesive layers **66** and **66***a* alone or in conjunction may apply the prestress to the ceramic layer **67**. Alternatively, only the prestress layer(s) **64** and **68** and the adhesive layer(s) **66** and **66***a* may be heated and bonded to a ceramic layer **67**, while the ceramic layer **67** is at a lower temperature, in order to induce greater compressive stress into the ceramic layer **67** when cooling the transducer **12**.

[0049] Referring now to **FIG. 2**: Yet another alternate THUNDER generator element **12**D includes a composite piezoelectric ceramic layer **69** that comprises multiple thin layers **69***a* and **69***b* of PZT which are bonded to each other or cofired together. In the mechanically bonded embodiment of **FIG. 2**, two layers **69***a* and **69***b*, or more (not shown) may be used in this composite structure **12**D. Each layer **69***a* and **69***b* comprises a thin layer of piezoelectric material, with a thickness preferably on the order of about 1 mil. Each thin layer **69***a* and **69***b* is electroplated **65** and **65***a*, and **65***b* and **65***c* on each major face respectively. The individual layers **69***a* and **69***b* are then bonded to each other with an adhesive layer **66***b*, using an adhesive such as LaRC-SI. Alternatively, and most preferably, the thin layers **69***a* and **69***b* may be bonded to each other by cofiring the thin sheets of piezoelectric material together. As few as two layers **69***a* and **69***b*, but preferably at least four thin sheets of piezoelectric material may be bonded/cofired together. The composite piezoelectric ceramic layer **69** may then be bonded to prestress layer(s) **64** with the adhesive layer(s) **66** and **66***a*, and heated and cooled as described above to make a modified THUNDER transducer **12**D. By having multiple thinner layers **69***a* and **69***b* of piezoelectric material in a modified transducer **12**D, the composite ceramic layer generates a lower voltage and higher current as compared to the high voltage and low current generated by a THUNDER transducer **12** having only a single thicker ceramic layer **67**. Additionally, a second prestress layer may be used comprise the same material as is used in the first prestress layer **64**, or a material with substantially the same mechanical strain characteristics as described above, so that the composite piezoelectric ceramic layer **69** and the transducer **12**D remain substantially flat, but still under a compressive stress.

[0050] Referring now to **FIG. 2***b*: Yet another alternate THUNDER generator element **12**E includes another composite piezoelectric ceramic layer **169** that comprises multiple thin layers **169***a-f* of PZT which are cofired together. In the cofired embodiment of **FIG. 2***b*, two or more layers **169***a-f*, and preferably at least four layers, are used in this composite structure **12**E. Each layer **169***a-f* comprises a thin layer of piezoelectric material, with a thickness preferably on the order of about 1 mil, which are manufactured using thin tape casting for example. Each thin layer **169***a-f* placed adjacent each other with electrode material between each successive layer. The electrode material may include metallizations, screen printed, electro-deposited, sputtered, and/or vapor deposited conductive materials. The individual layers **169***a-f* and internal electrodes are then bonded to each other by cofiring the composite multi-layer ceramic element **169**. The individual layers **169***a-f* are then poled in alternating directions in the thickness direction. This is accomplished by connecting high voltage electrical connections to the electrodes, wherein positive connections are connected to alternate electrodes, and ground connections are connected to the remaining internal electrodes. This provides an alternating up-down polarization of the layers **169***a-f* in the thickness direction. This allows all the individual ceramic layers **169***a-f* to be connected in parallel. The composite piezoelectric ceramic layer **169** may then be bonded to prestress layer(s) **64** with the adhesive layer(s) **66** and **66***a*, and heated and cooled as described above to make a modified THUNDER transducer **12**D.

[0051] Referring again to **FIGS. 2, 2***a* and **2***b*: By having multiple thinner layers **69***a* and **69***b* (or **169***a-f*) of piezoelectric material in a modified transducer **12**D-F, the composite ceramic layer generates a lower voltage and higher current as compared to the high voltage and low current generated by a THUNDER transducer **12** having only a single thicker ceramic layer **67**. This is because with multiple thin paralleled layers the output capacitance is increased, which decreases the output impedance, which provides better impedance matching with the electronic circuitry connected to the THUNDER element. Also, since the individual layers of the composite element are thinner, the output voltage can be reduced to reach a voltage which is closer to the operating voltage of the electronic circuitry (in a range of 3.3V-10.0V) which provides less waste in the regulation of the voltage and better matching to the desired operating voltages of the circuit. Thus the multilayer element (bonded or cofired) improves impedance matching with the connected electronic circuitry and improves the efficiency of the mechanical to electrical conversion of the element.

[0052] A flexible insulator may be used to coat the convex face **12***a* of the transducer **12**. This insulative coating helps prevent unintentional discharge of the piezoelectric element through inadvertent contact with another conductor, liquid or human contact. The coating also makes the ceramic element more durable and resistant to cracking or damage from impact. Since LaRC-SI is a dielectric, the adhesive layer **67***a* on the convex face **12***a* of the transducer **12** may act as the insulative layer. Alternately, the insulative layer may comprise a plastic, TEFLON or other durable coating.

[0053] Electrical energy may be recovered from or introduced to the generator element **12** (or 12D) by a pair of electrical wires **14**. Each electrical wire **14** is attached at one end to opposite sides of the generator element **12**. The wires **14** may be connected directly to the electroplated **65** and **65***a* faces of the ceramic layer **67**, or they may alternatively be connected to the pre-stress layer(s) **64** and or **68**. The wires **14** are connected using, for example, conductive adhesive, or solder **20**, but most preferably a conductive tape, such as a copper foil tape adhesively placed on the faces of he electroactive generator element, thus avoiding the soldering or gluing of the conductor. As discussed above, the prestress layer **64** is preferably adhered to the ceramic layer **67** by LaRC-SI material, which is a dielectric. When the wires **14** are connected to the pre-stress layer(s) **64** and/or **68**, it is desirable to roughen a face of the pre-stress layer **68**, so that the pre-stress layer **68** intermittently penetrates the respective adhesive layers **66** and **66***a*, and makes electrical contact with the respective electroplated **65** and **65***a* faces of the ceramic layer **67**. Alternatively, the Larc-SI adhesive layer **66** may have a conductive material, such as Nickel or aluminum particles, used as a filler in the adhesive and to maintain electrical contact between the prestress layer and the electroplated faces of the ceramic layer(s). The opposite end of each electrical wire **14** is preferably connected to an electric pulse modification circuit **10**.

[0054] Prestressed flextensional transducers **12** are desirable due to their durability and their relatively large displacement, and concomitant relatively high voltage that such transducers are capable of developing when deflected by an external force. The present invention however may be practiced with any electroactive element having the properties and characteristics herein described, i.e., the ability to generate a voltage in response to a deformation of the device. For example, the invention may be practiced using magnetostrictive or ferroelectric devices. The transducers also need not be normally arcuate, but may also include transducers that are normally flat, and may further include stacked piezoelectric elements.

[0055] In the preferred embodiment of the present invention, the piezoelectric energy harvesting system **24** comprises a piezoelectric actuator element **12**, electrical wires **14** and energy storage circuitry **10**. In the preferred embodiment of the invention, the actuator element **12** is a flextensional piezoelectric transducer. Various constructions of flextensional piezoelectric transducers may be used (including, for example, "moonies", "rainbows", and other unimorph, bimorph, multimorph or monomorph devices, as disclosed in U.S. Pat. No. 5,471,721), but the actuator element **12** preferably comprises a Thin Layer Unimorph Driver and Sensor, "THUNDER™," (as disclosed in U.S. Pat. No. 5,632,841) actuator constructed in accordance with the following description.

[0056] THUNDER actuators **12** are composite structures such as is illustrated in **FIG. 1-2**. Each THUNDER actuator **12** is preferably constructed with a PZT piezoelectric ceramic layer **67** which is electroplated **65** and **65***a* on its two opposing faces. A steel, stainless steel, beryllium alloy or other metal first pre-stress layer **64** is adhered to the electroplated **65** surface on one side of the ceramic layer **67** by a first adhesive layer **66**. The first adhesive layer **66** is preferably LaRC™-SI material, as developed by NASA-Langley Research Center and disclosed in U.S. Pat. No. 5,639,850. A second adhesive layer **66***a*, also preferably comprising LaRC-SI material, is adhered to the opposite side of the ceramic layer **67**. During manufacture of the THUNDER actuator **12** the ceramic layer **67**, the adhesive layers **66** and **66***a* and the first pre-stress layer **64** are simultaneously heated to a temperature above the melting point of the adhesive material, and then subsequently allowed to cool, thereby re-solidifying and setting the adhesive layers **66** and **66***a*. During the cooling process the ceramic layer **67** becomes compressively stressed, due to the higher coefficient of thermal contraction of the material of the pre-stress layer **64** than for the material of the ceramic layer **67**. Also, due to the greater thermal contraction of the laminate materials (e.g. the first pre-stress layer **64** and the first adhesive layer **66**) on one side of the ceramic layer **67** relative to the thermal contraction of the laminate material(s) (e.g. the second adhesive layer **66***a*) on the other side of the ceramic layer **67**, the ceramic layer deforms in an arcuate shape having a normally concave face **12***a* and a normally convex face **12***c*. One or more additional pre-stressing layer(s) **64***a* may be similarly adhered to either or both sides of the ceramic layer **67** in order, for example, to increase the stress in the ceramic layer **67** or to strengthen the actuator **12**.

[0057] Electrical energy may be introduced to or recovered from the actuator element **12** by a pair of electrical wires **14** attached at one end to opposite sides of the actuator element **12**. The opposite ends of the electrical wires **14** are connected to the electric energy storage circuitry **10**. As discussed above, the pre-stress layers **64** and **64***a* are preferably adhered to the ceramic layer **67** by LaRC-SI material. The wires **14** may be connected (for example by glue or solder **20**) directly to the electroplated **65** and **65***a* faces of the ceramic layer **67**, or they may alternatively be connected to the pre-stress layers **64** and **64***a*. LaRC-SI is a dielectric. When the wires **14** are connected to the pre-stress layers **64** and **64***a*, it is desirable to roughen a face of each pre-stress layer **64** and **64***a*, so that the pre-stress layers **64** and **64***a* intermittently penetrate the respective adhesive layers **66** and **66***a*, and make electrical contact with the respective electroplated **65** and **65***a* faces of the ceramic layer **67**.

[0058] In operation, as the wearer of the shoe walks or runs, each time the contact surface **34** of the sole portion **26** impacts the ground **44** or similar surface a first force (indicated by arrow **16** in **FIG. 4**) substantially normal to the contact surface **34** of the sole portion **26**, deforms the section

36 of the sole portion **26** between the contact surface **34** and the piezoelectric element **12**, which, in turn, deforms the piezoelectric element **12**. By virtue of the piezoelectric effect, the deformation of the piezoelectric element **12** at each impact produces a pulse of electrical energy. The pulse or pulses of electrical energy are transmitted via the electrical wires **14** to the electrical energy storage circuitry **10**.

[0059] As shown in **FIGS. 3-8**, a piezoelectric energy harvesting system **24** is advantageously disposed in or molded into a cavity **40** located in the sole portion **26**, such that when the contact surface **34** of the sole portion **26** impacts the ground **44** or when the sole portion **26** is bent, the piezoelectric energy harvesting system **24** is actuated. It should be understood that the piezoelectric energy harvesting system **24** is mounted in the sole portion **26** substantially near the contact surface **34**, such that the energy transferred to the piezoelectric energy harvesting system **24** by the impact or bending of the contact surface **34** with the ground **44** is maximized, and attenuation of said energy in the section **36** of the sole portion **26** between the ground **44** and the piezoelectric energy harvesting system **24** is minimized. The piezoelectric harvesting system **24** is preferably located in a rear portion **26*a*** or central bending portion **26*b***, of the sole portion **26**, but may advantageously be located anywhere in the sole portion **26** such as the front **26*c*** or central **26*b*** portions which are subject to deflective forces that may be transferred to the piezoelectric energy harvesting system **24**.

[0060] Referring to FIGS. **3-4**: in one embodiment of the energy harvesting system, the transducer **12** is preferably mounted within the recess **40** to the top portion of the recess **40** (adjacent the footbed). More specifically, as can be seen in **FIG. 3**, in this preferred embodiment one end of the transducer **12** is mounted to the top portion **43** of the recess **40** on its convex face, such that the free end **122** of the transducer **12** extends downwardly from the top **43** and back walls **42** towards the bottom **44** and front walls **41** of the recess **40**. Alternatively, one end **121** of the transducer **12** is mounted to the bottom portion **44** of the recess **40** on its convex face, such that the free end **122** of the transducer **12** extends upwardly from the bottom and back walls towards the top and front walls of the recess **40**. The free end **122** of the transducer **12** extends in proximity to but not in contact with the front wall **41** of the recess **40**. On the front wall **41** of the recess **40** is mounted a deflector **72** which extends towards the back wall **42** of the recess **40** and in proximity to the free end **122** of the transducer **12**. The deflector **72** extends into the cavity a distance past the end **122** of the actuator **12**, and when the sole portion is bent, the actuator is rotated with respect to the deflector such that the end of the actuator is bent and deflected by the deflector **72**. Conversely, when the sole portion is straightened from the bent position, the actuator **12** is again rotated with respect to the deflector **72** such that the end **122** of the actuator **12** is bent and deflected by the deflector **72**. In yet another alternative embodiment, the end **121** of the transducer **12** may be mounted to the top or bottom walls in proximity to the front wall of the recess. The free end **122** extend upwardly from the bottom wall or downwardly from the top wall towards the back wall of the cavity **40**, and the deflector **72** is mounted to the back wall in a similar manner as the front mounted deflector. Alternatively, the free end **122** of the generator may extend towards the wall opposite the wall to which it is mounted, and that wall may act as the deflector **72**. For example, where the fixed end **121** of the piezoelectric generator element **12** is mounted to the top wall in proximity to the rear surface of the cavity **40**, the free end **122** tends toward the front surface and bottom surface of the cavity **40**. When the contact surface is bent, as by walking, the free end is deflected by the front surface or the bottom surface of the cavity **40**. Likewise the free end **122** of the generator **12** may be deflected by the rear or top surfaces of the cavity if it is mounted to the front or bottom surfaces of the cavity **40**.

[0061] Referring again to **FIGS. 3 and 4**: In operation, as shown in **FIG. 4**, when a force indicated by arrow **16** is applied to the transducer **12**, the force deforms the electroactive layer **67** (via deformation of the resilient deformable section **36** of the sole **26**. The force may be applied to the transducer **12** by mechanical means located within the sole portion of the footwear. Preferably, the force is applied by a mechanical deflector **72** (e.g., fulcrum, finger, a plucker, a plunger, striker, toggle or roller switch) capable of developing a mechanical impulse for application to and removal from the transducer **12**. The mechanical impulse (or removal thereof) is of sufficient force to cause the transducer **12** to deform quickly and accelerate over a distance (approximately 10 mm), and upon release to oscillate between deflected positions about the undeflected position, which generates an electrical signal for harvesting/storage for later use or connection to electrical devices. Preferably the mechanical deflection means **72** is a plucker **72** which is stationary with respect to the sole portion **26** of the footwear, and an edge of the transducer **12** is applied to and released by the deflector **72** by virtue of the deformation of the sole portion to which the transducer **12** is attached. Alternately, the deflector **72** moves in response to the force on the contact surface and causes a deflection of the actuator/generator).

[0062] Now referring to **FIGS. 5 and 6**: In another embodiment of the energy harvesting system, the transducer **12** is preferably mounted within the recess **40** tthrough the front portion **41** of the recess **40**. As can be seen in **FIG. 5**, in this embodiment one end of the transducer **12** is mounted to the front portion **41** of the recess **40**, such that the convex face of the transducer **12** extends from the front wall **41** towards the top **43** and back walls **42** of the recess **40**. The free end **121** of the transducer **12** extends in proximity to but not in contact with the back wall **42** of the recess **40**. On the back wall of the recess **40** is mounted a deflector **72** which extends towards the front wall **41** of the recess **40** and in proximity to the free end **122** of the transducer **12**. The deflector extends into the cavity a distance past the end of the actuator **12**, and when the sole portion is bent, the actuator is rotated with respect to the deflector such that the end of the actuator is bent and deflected by the deflector **72**. Conversely, when the sole portion is straightened from the bent position, the actuator **12** is again rotated with respect to the deflector **72** such that the end of the actuator **12** is bent and deflected by the deflector **72**. Although the transducer end **121** may be mounted to the front wall **41** of the recess **40**, it may also extend into the back wall **42** and the sole portion therebehind. The actuator **12** may be mounted to/within the back portion **42** such that the convex face of the actuator faces up, and extends upwardly from the back wall **42** towards the front wall **41** and top wall **43** of the recess with the deflector on the front wall **41** of the recess **40**. In yet another embodiment the end **121** of the actuator **12** may be mounted to and/or within the front wall **41** of the recess with the free end extending toward the back wall **42**, and with the convex face of the actuator **12** facing either the top wall **43** or the bottom wall **44** of the cavity. In this last embodiment, the deflector **72** is mounted to the back wall **42** of the recess.

[**0063**] In operation, as shown in **FIG. 6**, when a force indicated by arrow **16** is applied to the transducer **12**, the force deforms the electroactive layer **67**. The force may be applied to the transducer **12** by mechanical means located within the sole portion of the footwear. Preferably, the force is applied by a mechanical deflector **72** (e.g., a plucker, a plunger, striker, toggle or roller switch) capable of developing a mechanical impulse for application to and removal from the transducer **12**. The mechanical impulse (or removal thereof) is of sufficient force to cause the transducer **12** to deform quickly and accelerate over a distance (approximately 10 mm), and upon release to oscillate between deflected positions about the undeflected position, which generates an electrical signal for harvesting/storage for later use or connection to electrical devices.

[**0064**] Preferably the mechanical deflection means **72** is a plucker **72** which is stationary with respect to the sole portion **26** of the footwear. The free end **122** of the transducer **12** is applied to and released from the deflector **72** by virtue of the deformation of the sole portion to which the opposite end **121** of the transducer **12** is attached.

[**0065**] Referring now to FIGS. **7-8**: **FIGS. 7-8** show an alternate embodiment of a deflector assembly mounted within the recess for deflection of the transducer **12**. The deflector assembly comprises a pair of counter-rotating levers and a plucker assembly for deflecting the free end of the transducer **12**. The motion of walking and bending the sole portion deflects one counter-rotating lever, to cause the other counter-rotating lever to push the paddle assembly against the free end **122** of the transducer **12**. The end **122** of the transducer **12** is then released and caused to oscillate thereby generating an electrical signal.

[**0066**] More specifically, Referring now to **FIGS.** **9***a-c:* **FIGS. 11***a-c* show the preferred embodiment of a base plate **70** with a deflector assembly **72** and containing the transducer **12**. The transducer **12** is mounted with one end **121** of the transducer **12** placed between the surfaces the clamping and base plates **75** and **70** with fasteners **77** (screws, bolts, etc . . .) such that the substrate **64** contacts both surfaces **75***a* and **70***a*. The ceramic layer **67** which extends above the surface of the substrate **64** on the convex face **12***a* extends into the recessed area **80** of the base plate **70**. This prevents the ceramic layer **67** from contacting the upper surface **70***a* of the base plate **70**, and cushions the ceramic layer **67** against the compliant layer **85** in the recess **80**, thereby reducing potential for damage to the ceramic layer **67**. A deflector assembly **72** is mounted on the base plate **70** above and to the sides of the transducer **12**. This deflector assemble **72** has a lower profile than previously described deflector assemblies **72** by virtue of the use of two cooperating counter-rotating lever assembles **260**, **270** and a plucker assembly **300**.

[**0067**] Referring again to **FIGS. 9***a-c*: The deflector assembly comprises a swing arm **260**, which is essentially a first lever mounted above the clamped end **121** of the transducer **12** and tending towards the free end **122**. The swing arm **260** preferably has two pivot arms **261** and **262** connected by a cross bar **265**. The pivot arms **261** and **262** tend from above the clamped end **121** of the transducer **12** and tending towards the free end **122** of the transducer **12**, along each side of the transducer **12** to prevent contact therebetween. A first end **261***a*, **262***a* of each pivot arm **261**, **262** is connected to the two ends of a cross bar **265**, which is situated above the clamping plate **75**. Each pivot arm **261**, **262**, has a pin **264** extending outwardly from the transducer **12**, located centrally on the pivot arms **261**, **262**. The pins are pivotably mounted within fulcrum clips **268**, which allows the swing arm assembly **260** to pivot about the pins **264** and the fulcrum clips **268**. The ends **261***b*, **262***b* of the pivot arms **261**, **262** opposite the crossbar **265** are preferably upwardly curved to tend substantially vertically, or more preferably slightly off vertical and towards the free end **122** of the transducer **12** and rocker arm **270** assemblies. The curved ends **261**,*b*, **262***b* of the pivot arms **261**, **262** may alternately be C-shaped, i.e., first curve downwardly (towards the base plate **70**, and then upwardly. To accommodate the downward curve of the pivot arm ends **261***b*, **262***b*, the base plate **70** may contain recesses (not shown) within which the curved ends **261***b*, **262***b* may housed.

[**0068**] Referring again to **FIGS. 9***a-c*: The deflector assembly also comprises a rocker assembly **270**, which is essentially a pair of second levers **271**, **272** mounted above the free end **122** of the transducer **12** and tending towards and beyond the free end **122**. The rocker assembly **270** preferably has two rocker arms **271** and **272** pivotably mounted to contact both the pivot arms **261**, **262** and the plucker assembly **300**. The rocker arms **271** and **272** tend from above the curved ends **261***b*, **262***b* of the pivot arms **261**, **262** and tend towards and slightly beyond the free end **122** of the transducer **12**, and along each side of the transducer **12** to prevent contact therebetween. Each of the rocker arms **271**, **271** has a pin **274** thereon, extending outwardly from the transducer **12**. Each of these pins **274** is pivotably mounted within a pivot hole **278** of the plucker housing **290**. This allows each rocker arm **271**, **272**, to rotate about its respective pin **274** in response to a force on either end **271***a*, **272***a*, **271***b*, **272***b* of the rocker arm **271**, **272**. Each first end **271***a*, **272***a* of the rocker arms **271**, **272** is in contact with the second ends **261***b*, **262***b* of the pivot arms **261**, **262**. When the crossbar **265** is depressed, the second ends **261***b*, **262***b* of the pivot arms **261**, **262** move upwardly and contact the first ends **271***a*, **272***a* of the rocker arms **271**, **272**, causing the rocker arms **271**, **272** to rotate about the rocker arm pins **274**. This causes the second ends **271***b*, **272***b* of the rocker arms **271**, **272** to be depressed.

[**0069**] Referring again to **FIGS. 9***a-c*: The deflector assembly also comprises a plucker assembly **300**, which is essentially a slidably mounted curved paddle situated above the free end **122** of the transducer **12**. The plucker assembly **300** is in contact with the rocker assembly **270** and is adapted to side downwardly within a pair of grooves in response to a downward motion from the second ends **271***b*, **272***b* of the rocker arms **271**, **272**. More specifically, the plucker assembly **300** comprises a plucker paddle **301**, situated above and in contact with the free end **122** of the transducer **12**. Connected to each end **300***a*, **300***b* of the plucker paddle **301** is a roller **305**, which is in contact with the rocker arms **271**, **272**. Tending outwardly from each roller **305** is a slide pin **304**. The slide pins **304** are slidably mounted within slide grooves **308** in the plucker housings **290**. The slide grooves **308** tend from a maximum vertical position and downwardly away from the free end **122** of the transducer **12** to a minimum position beyond the free end **122** of the transducer **12**. Thus, when the plucker assembly **300** is moved downwardly, the slide pins **304** and slide grooves **308** cause the plucker paddle **301** to move simultaneously downward and away from the free end of **122** the transducer **12**.

[**0070**] Thus, when the crossbar **265** is depressed, the second ends **261***b*, **262***b* of the pivot arms **261**, **262** move upwardly and contact the first ends **271***a*, **272***a* of the rocker arms **271**, **272**, causing the rocker arms **271**, **272** to rotate about the rocker arm pins **274**. This causes the second ends **271***b*, **272***b* of the rocker arms **271**, **272** to be depressed. As the second ends **271***b*, **272***b* of the rocker arms **271**, **272** are depressed, they contact the rollers **305** with a downward force, and the plucker assembly **300** is guided by the slide pins **304** and slide grooves **308** to cause the plucker paddle **301** to move simultaneously downward and away from the free end of **122** the transducer **12**. The minimum or lowest position of the plucker assembly is beyond the free end **122** of the transducer **12**, and therefore, as the plucker paddle **301** moves downward and outward, the free end **122** of the transducer **12** is released by the plucker paddle **301**. Thus as the plucker assembly is depressed, the free end **122** of the transducer **12** is depressed from its neutral position **291** to a deflected position **292** at which position the paddle **301** releases the free end **122** of the transducer **12**. The free end **122** of the transducer **12** then oscillates between positions **291** and **292**.

[**0071**] Referring now to **FIG. 9***c:* The plucker paddle **301** preferably has an edge **301***a* that contacts the free end **122** of the transducer **12** that has a radius in both in the thickness dimension (i.e., vertically corresponding to the thickness of the transducer **12** edge) and the transverse dimension (i.e., horizontally corresponding to the length of the transducer **12** edge) in order to advantageously release the free end **122** very quickly, i.e., without dragging across the end **122** of the transducer **12**, which slows its release. It has been found that the more quickly and cleanly you release the end **122** of the transducer **12** during a "pluck", the greater the output. This increases output without increasing the required plucking force. To be precise, the energy developed by the piezoelectric element **67** has been found to be a function of the acceleration of the piezoelectric element **67**, rather than the speed of the "pluck." It is possible "pluck" very slowly, and get excellent performance, so long as the piezoelectric element **67** is released fully and completely and as nearly instantly as possible. To determine the desired shape of the tip **301***a* of the plucker paddle **301**, several plucker paddles were designed and released very, very slowly, in attempting to get a quick "release" of the end **122** of the transducer **12**. If the plucker paddle **301** did not have a radius on the tip, but instead had a rectangular shape, it was found that the end **301***a* of the plucker paddle **301** (the thickness dimension) actually "dragged" across the edge **122** of the transducer **12**, slowing the release, and decreasing the electrical output. Thus, increasing the rate of "release" of the element's edge **122** improved the acceleration and the output. Thus, the radius of the tip **301***a* (in the thickness dimension) of the "plucker" paddle **301** contributes substantially to how quickly the transducer **12** edge **122** gets off the paddle. This has been shown to have a direct effect on electrical performance, because a smaller radius equates to a quicker "release" which equates to greater electrical output. If the paddle **301** is manufactured from sufficiently hard materials, or is hardened, the edge **301***a* of the paddle **301** can be made with an even smaller radius. The tip **301***a* of the plucking paddle **301** may be coated with a very hard material with low friction, thereby lowering the plucking resistance. This approach can prove to be useful in increasing the power output of a transducer **12** without increasing the required displacement or amount of bending, and may allow the generation of the same amount of energy with lower "button force" by the user of the device, as well as being useful in increasing wear resistance for applications requiring many hundreds of thousands of switch cycles.

[**0072**] The transducer **12** is typically is curved along its length, i.e., the longitudinal dimension and this curvature allows the element **12** to be bent or "plucked" substantially before it reaches a flattened state. The transducer **12** is also curved across its transverse dimension, i.e., the transverse dimension normal to the thickness and longitudinal dimensions. To ensure a quick "release", the shape of the edge **301***a* of the plucking paddle **300** should generally match this transverse curve. The radius curvature of the transducer **12** in the transverse plane is approximately 6 inches, and therefore the same radius should be used for the curve edge **301***a* in the transverse plane of the paddle **301**. Different sized transducers **12** will have higher or lower transverse radii of curvature, so regardless of the size of the transducer **12**, the radius of curvature for the curved edge **301***a* in the transverse plane of the paddle **301** should substantially match the transverse curvature of the transducer **12**.

[**0073**] Although both paddle **301** dimensions affect durability, and both dimensions affect performance, the tip radius has more of an effect on element **12** performance, while the transverse curve has a greater effect on the element's **12** substrate wear, and therefore is more of an influence on its life expectancy. This is because the transverse radius determines how much of the paddle **301** contacts the element **12**. A greater contact area is equates with less wear and longer substrate life, i.e., durability. As stated above, by manufacturing the paddle **301** from sufficiently hard or hardened materials, the edge **301***a* of the paddle **301** can be made with very small radius. The tip **301***a* of the plucking paddle **301** may be coated with a very hard material with low friction, thereby lowering the plucking resistance. Hardened, low friction materials are useful in increasing the power output of a transducer **12** without increasing the required displacement or amount of bending, or allowing the generation of similar electrical energy output with lower "button force", and increasing wear resistance.

[**0074**] Referring again to **FIGS. 9***a-c*: In order to return the deflector assembly **72** to its normal elevated position, the levers **260**, **270** and/or plucker assembly **300** are preferably spring loaded. More specifically, one or more springs **310** are located in contact with the deflector assembly **72**, and are placed in compression or tension upon actuation of the assembly **72**, which springs' **310** restoring force is used to return the deflector assembly **72** to its neutral position. As shown in **FIGS. 11***a-c*, in the preferred embodiment of the invention, two springs **310** are located within cavities **320** in the plucker housings **290**, below the pins **304**. For simplicity of illustration, the springs **310** are shown as coiled springs **310**, but are preferably leaf springs **310**. Upon downward deflection of the crossbar **265** and thereby the pivot bar assembly **260** and rocker assembly **270**, the pins **304** travel down the grooves **308** and compress the springs **310** in the cavities **320**. Upon release of pressure from the crossbar **265**, the springs **310** restore the pivot bar **260**, rocker bars **270** and plucker **300** to their undeflected positions. While the springs **310** shown are in the housings **290**, other placements of the springs **310** may also be desirable, including, for example: spring(s) **310** may be placed beneath the cross bar **265**, on either side of the fulcrum **268** of the pivot bars **261**, **262** or rocker arms **270**; one or more rotational or clock springs **310** may be placed on the pins **264** of the pivot bars **261**, **262**, on the pins **274** of the rocker arms **271**, **272**, on the pivot bar fulcrums **268**, or the rocker arm pin holes **278**; springs **310** may be placed in the groove **308** or recess **320** above or below the plucker bar pins **304**; one or more springs **310** may be attached to the plucker bar **301**; and the opposing side of the spring **310** (not attached to the deflector assembly **72**) may be attached to the base plate **70**, the plucker housing **290**, the fulcrum **268** or to another part of the deflector assembly **72** to restore it to its undeflected position.

[**0075**] Referring now to **FIGS. 10***a-e:* To facilitate efficient plucking and maximize vibration of the transducer **12**, the plucker assembly is preferably configured so as to rotate during each actuation and to cock after each actuation. Specifically, with a triangularly shaped plucker paddle **301**, any one of the three faces **301***b*, **301***c*, **301***d* of the plucker paddle **301** (having a substantially triangular cross-section) may engage the edge of the transducer. As the plucker paddle **301** moves downward and outward from the transducer edge, a rotation mechanism (including a pin **445** and radial ridge **444** as shown in the figures) causes the plucker paddle edge to rotate away from the transducer edge **122**. As the plucker paddle rotates, it reaches a point where the transducer edge **122** is released. Since the plucker paddle **301** has rotated, it also does not interfere with the vibration of the transducer edge. When the downward force is removed from the plucker assembly, the spring loaded plucker paddle **301** is returned upward towards its starting position, and rotates until the radial ridge **444** contacts a rotational stop **443**, so that the plucker paddle **301** is again is a position to engage the transducer edge.

[**0076**] Referring again to **FIGS. 10***a-e*: More specifically, the plucker paddle **301** is shaped substantially like a triangular prism. In the center of each triangular face of the paddle is a pin **304** that travels along the groove **308** in the plucker housing. Each triangular face of the paddle also preferably has threes raised ridges **444** thereon extending from the center of the triangular face outwardly towards the edges of the triangular faces adjacent the flat paddle surfaces and most preferably towards each apex of the triangular faces. The plucker housings each have a vertical ridge or pin **443** against which the raised ridge rests when the plucker paddle is in its maximum position. This maintains the bottom surface of the plucker paddle (opposite the apex bisected by the raised ridge) in an essentially horizontal position above and/or against the edge of the transducer **12**.

[**0077**] A force applied to the deflector assembly **72** described above causes the piezoelectric transducer **12** to deform from position **291** to position **292** and by virtue of the piezoelectric effect, the deformation of the piezoelectric element **67** generates an instantaneous voltage between the faces **12***a* and **12***c* of the transducer **12**, which produces an electrical signal. Furthermore, when the force is removed from the piezoelectric transducer **12**, i.e., when released by the plucker assembly **300** at position **292**, the transducer **12** oscillates between positions **291** and **292** until it gradually returns to its original shape. As the transducer **12** oscillates, the ceramic layer **67** strains, becoming alternately more compressed and less compressed. The polarity of the voltage produced by the ceramic layer **67** depends on the direction of the strain, and therefore, the polarity of the voltage generated in compression is opposite to the polarity of the voltage generated in tension. Therefore, as the transducer **12** oscillates, the voltage produced by the ceramic element **67** oscillates between a positive and negative voltage for a duration of time. The duration of the oscillation, and therefore the duration of the oscillating electrical signal produced, is preferably in the range of 100-250 milliseconds, depending on the shape, mounting and amount of force applied to the transducer **12**. The wave form of the oscillating voltage is illustrated in **FIG. 12***a*.

[**0078**] As previously mentioned, the applied force causes the piezoelectric transducer **12** to deform. By virtue of the piezoelectric effect, the deformation of the piezoelectric element **67** generates an instantaneous voltage between the faces **12***a* and **12***c* of the transducer **12**, which produces a pulse of electrical energy. Furthermore, when the force is removed from the piezoelectric transducer **12**, the transducer **12** recovers its original arcuate shape. This is because the bending of the substrate (and attached layers) stores mechanical (spring) energy which is released upon removal of the force. Additionally, the substrate or prestress layers **64** and **68** to which the ceramic **67** is bonded exert a compressive force on the ceramic **67**, and the transducer **12** thus has an additional restoring force that causes the transducer **12** to return to its undeformed neutral state. On the recovery stroke of the transducer **12**, the ceramic **67** returns to its undeformed state and thereby produces another electrical pulse of opposite polarity. The downward (applied) or upward (recovery) strokes cause a force over a distance that is of sufficient magnitude to create the desired electrical pulse. The duration of the recovery stroke, and therefore the duration of the pulse produced, is preferably in the range of 50-100 milliseconds, depending on the mechanical properties of the transducer, including its natural frequency of vibration.

[**0079**] In the preferred embodiment of the invention, the transducer **12** is clamped at one end **121** and the mechanical impulse is applied to the edge on the free end **122**, i.e., at the end opposite to the clamped end **121** of the transducer **12**. By applying the force to the edge on the free end **122** of the transducer **12** and releasing it, the actuator oscillates between the release position, to another position past the undeformed position, and then oscillates (in a dampened manner) between the deformed positions while returning to the undeformed position, by virtue of the substrate's (spring steel) restoring force. Therefore, the electrical pulse that is generated upon removal of the force is an oscillating wave (rather than a single pulse as with the prior actuating means disclosed above).

[**0080**] The applied force causes the piezoelectric transducer **12** to deform and by virtue of the piezoelectric effect, the deformation of the piezoelectric element **67** generates an instantaneous voltage between the faces **12***a* and **12***c* of the transducer **12**, which produces an electrical signal. Furthermore, when the force is removed from the piezoelectric transducer **12**, the transducer **12** oscillates between positions

291 and **292** until it gradually returns to its original shape. As the transducer **12** oscillates, the ceramic layer **67** strains, becoming alternately more compressed and less compressed. The polarity of the voltage produced by the ceramic layer **67** depends on the direction of the strain, and therefore, the polarity of the voltage generated in compression is opposite to the polarity of the voltage generated in tension. Therefore, as the transducer **12** oscillates, the voltage produced by the ceramic element **67** oscillates between a positive and negative voltage for a duration of time. The duration of the oscillation, and therefore the duration of the oscillating electrical signal produced, is preferably in the range of 100-500 milliseconds, depending on the shape, mounting and amount of force and number of plucks applied to the edge of the transducer **12**.

[**0081**] The electrical signal generated by the transducer **12** is applied to downstream circuit elements **10** via wires **14**, and conductive foil, solder or conductive adhesive connected to the transducer **12**. More specifically, a first wire **14** is connected to the electrode **90** which extends into the recess **80** and contacts the electrode **68** on the convex face **12***a* of the transducer **12** or to a foil adhered to the lower face **12***a* of the transducer **12**. Preferably the wire **14** is attached to a conductive foil (not shown) adhered to the face **12***a* of the transducer **12** situated above the recess **80** and compliant layer **85**. Alternately, the wire **14** is connected to the electrode **90** outside of the recess close to the end of the base plate **70** opposite the end having the clamping member **75**. A second wire **14** is connected directly to the first prestress layer **64**, i.e., the substrate **64** which acts as an electrode on the concave face **12***c* of the transducer **12**.

[**0082**] Referring now to **FIGS. 11***a-e:* To facilitate efficient plucking and maximize vibration of the transducer **12**, an alternate plucker assembly is configured not only to rotate during each actuation and to cock after each actuation, but to also pluck the end of the transducer twice. Specifically, with a "double plucker" paddle comprises a paddle with six apexes **301***a*, and any one of the six downward facing faces of the plucker paddle apexes (each having a substantially triangular cross-section) may engage the edge **122** of the transducer. As the "double plucker" paddle moves downward and outward from the transducer edge, a rotation mechanism (including a pin **445** and radial ridge **443** as shown in the figures) causes the edge **301***a* of a first apex of the "double plucker" paddle to rotate away from the transducer edge **122**. As the plucker paddle **301** rotates, it reaches a point where the transducer edge **122** is released. Since the "double plucker" paddle has rotated, it also does not interfere with the vibration of the transducer edge **122**. This allows the transducer to vibrate for a duration of time, preferably on the order of 75-150 milliseconds.

[**0083**] As the "double plucker" paddle continues to move downward and outward from the transducer edge **122**, the rotation mechanism (including a pin **445** and radial ridge **444** as shown in the figures) causes the edge **301***a* of the second apex of the "double plucker" paddle to reengage the end **122** of the transducer, after it has vibrated for a duration, preferably for at least 75 milliseconds. As the "double plucker" paddle continues to rotate, it reaches a point, once again, where the transducer edge **122** is released. Since the "double plucker" paddle has rotated, it also does not interfere with the vibration of the transducer edge **122**, which vibrates for an additional 75-250 milliseconds. When the downward force is removed from the "double plucker" assembly, the spring loaded "double plucker" paddle is returned upward towards its starting position, and rotates until the radial ridge **444** contacts a rotational stop **443**, so that the "double plucker" paddle is again is a position to engage the transducer edge, with the third and fourth apex edges.

[**0084**] Referring again to **FIGS. 11***a-e:* More specifically, the "double plucker" paddle is shaped substantially like a six pointed star prism, similar to the "Star of David" with the apexes offset to allow two successive engagements of the transducer edge, while allowing the transducer edge to vibrate between successive engagements without interference from the plucker paddle edges. In the center of each star face of the paddle is a pin that travels along the groove in the plucker housing. Each star face of the paddle also preferably has three raised ridges thereon extending from the center of the star face outwardly towards the edges of the faces adjacent the flat paddle surfaces and most preferably towards alternate apexes of the six point star faces. The plucker housings each have a vertical ridge or pin against which the raised ridge rests when the plucker paddle is in its maximum position. This maintains the bottom surface of the plucker paddle (opposite the apex bisected by the raised ridge) in an essentially horizontal position above and/or against the edge of the transducer **12**.

[**0085**] A force applied to the deflector assembly **72** described above causes the piezoelectric transducer **12** to deform from position **291** to position **292** and by virtue of the piezoelectric effect, the deformation of the piezoelectric element **67** generates an instantaneous voltage between the faces **12***a* and **12***c* of the transducer **12**, which produces an electrical signal. Furthermore, when the force is removed from the piezoelectric transducer **12**, i.e., when released by the first apex of the "double plucker" assembly **300** at position **292**, the transducer **12** oscillates between positions **291** and **292** for a duration of time, but before the amplitude of the oscillation has dropped below a level corresponding to a desired threshold output voltage. Furthermore, when the force from the second apex applied and removed from the piezoelectric transducer **12**, i.e., when released by the second apex of the "double plucker" assembly **300** at position **292**, the transducer **12** oscillates between positions **291** and **292** until it gradually returns to its original shape. As the transducer **12** oscillates, the ceramic layer **67** strains, becoming alternately more compressed and less compressed. The polarity of the voltage produced by the ceramic layer **67** depends on the direction of the strain, and therefore, the polarity of the voltage generated in compression is opposite to the polarity of the voltage generated in tension. Therefore, as the transducer **12** oscillates, the voltage produced by the ceramic element **67** oscillates between a positive and negative voltage for a duration of time. The duration of the oscillation, and therefore the duration of the oscillating electrical signal produced, is preferably in the range of 150-350 milliseconds, depending on the shape, mounting and amount of force applied to the transducer **12**. The wave form of the oscillating voltage is illustrated in **FIG. 12***d*. The rectified waveform is shown in **FIG. 12***e* and the regulated waveform is shown in **FIG. 12***f*.

[**0086**] The electrical signal from the wires **14** connected to the generator/transducer **12** is applied to energy storage circuitry **10** including capacitors and/or batteries. Furthermore the electrical signal is preferably rectified, most preferably using a full bridge rectifier. The output signal of the rectifier may also be input into a voltage regulator in order to control the amount of voltage applied to the energy storage element.

[0087] Referring now to FIGS. 13-15: The transducer **12** is first connected to a rectifier **31**. Preferably the rectifier **31** comprises a bridge rectifier **31** comprising four diodes D**1**, D**2**, D**3** and D**4** arranged to only allow positive voltages to pass. The first two diodes D**1** and D**2** are connected in series, i.e., the anode of D**1** connected to the cathode of D**2**. The second two diodes D**3** and D**4** are connected in series, i.e., the anode of D**3** connected to the cathode of D**4**. The anodes of diodes D**2** and D**4** are connected, and the cathodes of diodes D**1** and D**3** are connected, thereby forming a bridge rectifier. The rectifier is positively biased toward the D**2**-D**4** junction and negatively biased toward the D**1**-D**3** junction. One of the wires **14** of the transducer **12** is electrically connected between the junction of diodes D**1** and D**2**, whereas the other wire **14** (connected to the opposite face of the transducer **12**) is connected to the junction of diodes D**3** and D**4**. The junction of diodes D**1** and D**3** are connected to ground. A capacitor C**11** is preferably connected on one side to the D**2**-D**4** junction and on the other side of the capacitor C**11** to the D**1**-D**3** junction in order to isolate the voltages at each side of the rectifier from each other. Therefore, any negative voltages applied to the D**1**-D**2** junction or the D**3**-D**4** junction will pass through diodes D**1** or D**3** respectively to ground. Positive voltages applied to the D**1**-D**2** junction or the D**3**-D**4** junction will pass through diodes D**2** or D**4** respectively to the D**2**-D**4** junction. The rectified waveform is shown in **FIG. 10***b*.

[0088] The circuit also comprises a voltage regulator U**2**, which controls magnitude of the input electrical signal downstream of the rectifier **31**. The rectifier **31** is electrically connected to a voltage regulator U**2** with the D**2**-D**4** junction connected to the Vin pin of the voltage regulator U**2** and with the D**1**-D**3** junction connected to ground and the ground pin of the voltage regulator U**2**. The voltage regulator U**2** comprises for example a LT1121 chip voltage regulator U**2** with a 3.3 volts DC output. The output voltage waveform is shown in **FIG. 12***c* and comprises a substantially uniform voltage signal of 3-12 volts having a duration of approximately 100-250 milliseconds, depending on the load applied to the transducer **12**. The regulated waveform is shown in **FIG. 12***b*. Each of these output waveforms is the result of successive footfalls. Therefor the energy storage element is successively charged with this waveform upon each footfall.

[0089] The output voltage signal from the voltage regulator (at the Vout pin) may then be transmitted via another conductor to the capacitor or battery. For example, long life rechargeable batteries **430** may be included in the circuitry and may be recharged through the electromechanical transducers **12**. These rechargeable batteries **430** may thus provide stored or backup power to the an electrical device **50** connected to the output terminals of the battery **430**. In the circuit of **FIGS. 13 and 14**, the ground terminal of the battery is electrically connected to ground and the positive terminal is connected to the output side of the rectifier before the voltage regulator. In the preferred circuit of **FIGS. 13 and 15**, the ground terminal of the battery is connected to ground and the positive terminal is connected to the output side of the voltage regulator U**2** before the electrical device **50**.

[0090] Referring again to FIGS. **13**-**15**: The circuit of **FIG. 14** includes a rechargeable battery as in the circuit of **FIG. 13**. However, in this circuit, the output of the voltage regulator U**2** is connected only to the positive/charging terminal of the rechargeable battery **430**. The output of the rechargeable battery **430** is connected to the input side of a portable electronic device through a switch S**1**. The switch S**1** may comprise a transistor. When the switch is closed/energized, electrical power is applied to the electronic device. The switch may be energized when the deflection means activates the transducer **12**. When the transducer **12** is deflected, an electrical output is produced, most of which is rectified and regulated, and then used of charge the battery **430**. A small amount of the electrical power is tapped by a filter/trigger from the transducer **12** (using for example a BJT connected between a grounded resistor and a second resistor between the BJT and the transducer **12**), which electrical energy is applied to the switching device S**1** in order to electrically connected the battery to the transmitter subcircuit.

[0091] The electrical storage circuitry also has an output by which the stored energy may be used to power electrical devices **50** such as radios, transmitters, receivers, GPS devices and the like. To facilitate the use of the stored electrical energy, the energy storage element has a positive connection **432** and a ground connection **431** which may simply consist of two wires. Preferably, the wires are further connected to a power jack to which these electrical devices may be connected. Examples of these connections include plug and socket connection and RCA jacks, coaxial and uniaxial power jacks and the like. Plugging of the device **50** into the power jack across the output terminals **431**, **432** of the battery **430** may be provide the electrical contact to close a switch S**1** connected to the output (positive terminal) of the battery **430**.

[0092] While the above description contains many specificities, these should not be construed as limitations on the scope of the invention, but rather as an exemplification of one preferred embodiment thereof. Many other variations are possible, for example: More than one piezoelectric element **12** may be employed; The electrical energy storage circuitry **10** may comprise an amplifier, for amplifying the voltage applied to the piezoelectric element(s) **12**; The electrical energy storage circuitry **10** may comprise a capacitor or capacitors for storage of the electrical energy; The piezoelectric element may comprise a either flat or arcuate ferroelectric gernerators.

[0093] Accordingly, the scope of the invention should be determined not by the embodiment illustrated, but by the appended claims and their legal equivalents.

I claim:

1. An energy harvesting system comprising: An article of footwear comprising a shoe upper member having a bottom edge, a sole member having a footbed, a contact surface, a heel portion, an instep portion, and a deformable resilient section;

said bottom edge of said shoe upper member being attached to said footbed;

said sole member having a cavity between said contact surface and said footbed, said cavity having an upper surface opposite a lower surface, and a front surface opposing a back surface;

said deformable resilient section being disposed between said lower surface of said cavity and said contact surface; and

a piezoelectric generator apparatus within said cavity having a first end and a second end and having first and second electroded major faces;

said first end of said piezoelectric generator apparatus being mounted to said front surface, said back surface, said upper surface or said lower surface;

said second end of said piezoelectric generator apparatus being located in said cavity opposite to said front surface, said back surface, said upper surface or said lower surface to which said first end of said piezoelectric generator apparatus is mounted;

a deflector assembly within said cavity adjacent said second end of said piezoelectric generator apparatus; and

energy storage means for storing piezoelectric electrical energy, said energy storage means being in electrical communication with each of said first and second electroded major faces;

whereby, upon application of a first force to said contact surface, said first force causes a deformation of said deformable resilient section;

and whereby said deformation of said resilient deformable section causes a deformation of said second end of said piezoelectric generator apparatus by said deflector assembly, thereby generating piezoelectric electrical energy with said piezoelectric generator apparatus.

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