

Apparatus for Steering the Arc in a Cathodic Arc Coater

BACKGROUND OF THE INVENTION

1. Technical Field

This invention relates to apparatus for vapor deposition of coatings in general, and to cathodic arc vapor deposition apparatus in particular.

2. Background Information

Vapor deposition as a means for applying a coating to a substrate is a known art that includes processes such as chemical vapor deposition, physical vapor deposition, and cathodic arc vapor deposition. Chemical vapor deposition involves introducing reactive gaseous elements into a deposition chamber containing one or more substrates to be coated. Physical vapor deposition involves providing a source material and a substrate to be coated in a evacuated deposition chamber. The source material is converted into vapor by an energy input, such as heating by resistive, inductive, or electron beam means.

Cathodic arc vapor deposition involves a source material and a substrate to be coated placed in an evacuated deposition chamber. The chamber contains only a relatively small amount of gas. The negative lead of a direct current (DC) power supply is attached to the source material (hereinafter referred to as the "cathode") and the positive lead is attached to an anodic member. An arc-initiating trigger, at or near the same electrical potential as the anode, contacts the cathode and subsequently moves away from the cathode. When the trigger is still in close proximity to the cathode, the difference in electrical potential between the trigger and the cathode causes an arc of electricity to extend therebetween. As the trigger moves further away, the arc jumps between the cathode and the anodic chamber. The exact point, or points, where an arc touches the surface of the cathode is referred to as



1 a cathode spot. Absent a steering mechanism, a cathode spot will
2 move randomly about the surface of the cathode.

3 The energy deposited by the arc at a cathode spot is intense; on
4 the order of 10^5 to 10^7 amperes per square centimeter with a duration
5 of a few to several microseconds. The intensity of the energy raises
6 the local temperature of the cathode spot to approximately equal that of
7 the boiling point of the cathode material (at the evacuated chamber
8 pressure). As a result, cathode material at the cathode spot vaporizes
9 into a plasma containing atoms, molecules, ions, electrons, and
10 particles. Positively charged ions liberated from the cathode are
11 attracted toward any object within the deposition chamber having a
12 negative electrical potential relative to the positively charged ion.
13 Some deposition processes maintain the substrate to be coated at the
14 same electrical potential as the anode. Other processes use a biasing
15 source to lower the potential of the substrate and thereby make the
16 substrate relatively more attractive to the positively charged ions. In
17 either case, the substrate becomes coated with the vaporized material
18 liberated from the cathode.

19 The random movement of the arc can sometimes lead to non-
20 uniform erosion of the cathode, which in turn can limit the useful life
21 of the cathode. To avoid non-uniform erosion, it is known to steer the
22 arc relative to the cathode. United States Patents Nos. 4,673,477,
23 4,849,088, and 5,037,522 are examples of patents that disclose
24 apparatus for steering an arc relative to a cathode. Some prior art
25 steers the arc by mechanically manipulating a magnetic field source
26 relative to the cathode. Other prior art steers the arc by alternately
27 electrically connecting a power supply lead between two ends of a
28 cathode. In both these approaches, the speed of the arc relative to the
29 cathode is limited by the speed of the apparatus manipulating the
30 magnetic field source, or switching the power supply. Another

1 limitation is the complexity of the switching mechanisms and the
2 hardware necessary to manipulate a magnetic field source relative to
3 the cathode. A person of skill in the art will recognize that a
4 production coating environment is harsh and simplicity generally
5 equates with reliability.

6 Presently available cathodic arc coaters typically use a cooled
7 cathode fixed in place within the coater. One cooling scheme provides
8 a manifold attached to the cathode that permits the passage of coolant
9 between the cathode and manifold. Another scheme uses coolant
10 piping connected to a hollow cathode. A problem with either scheme
11 is that the cathode must be machined to accept the manifold or piping.
12 Not all cathode materials are amenable to machining and even where
13 possible, machining adds significantly to the cost of the consumable
14 cathode. Another problem with "directly cooling" the cathode is the
15 labor required to replace the cathode when its useful life has expired.
16 In the previous example where a manifold (or piping) is mechanically
17 attached to the cathode, the manifold (or piping) must be detached from
18 the old cathode and attached to a new one, and the deposition chamber
19 subsequently cleaned of coolant. For those applications which require
20 cathode replacement after each coating run, the labor costs and down
21 time can be considerable. Still another problem with direct cathode
22 cooling is leakage. Coolant leakage occurring during deposition can
23 contaminate the substrates being coated and require extensive cleaning
24 within the deposition chamber. Airfoils for gas turbine engines are an
25 example of an expensive substrate to be coated; one where it would be
26 a distinct advantage to minimize or eliminate losses due to
27 contamination.

28 In short, what is needed is an apparatus for cathodic arc vapor
29 deposition of material on a substrate that operates efficiently, one
30 capable of consistently providing a high quality coating on a substrate,



1 one that optimizes cathode erosion, and one that operates cost
2 effectively.

3 DISCLOSURE OF THE INVENTION

4 It is, therefore, an object of the present invention to provide an
5 apparatus for cathodic arc vapor deposition of material on a substrate
6 that operates in a cost effective manner.

7 It is another object of the present invention to provide an
8 apparatus for cathodic arc vapor deposition of material on a substrate
9 that provides a uniform high quality coating on every substrate within
10 the apparatus.

11 It is another object of the present invention to provide an
12 apparatus for cathodic arc vapor deposition of material on a substrate
13 that includes apparatus for steering an arc relative to a cathode that
14 overcomes the limitations of the prior art.

15 According to the present invention, an apparatus for applying
16 material by cathodic arc vapor deposition to a substrate is provided
17 which includes a vessel, means for maintaining a vacuum in the
18 vessel, a disk-shaped cathode, means for selectively sustaining an arc of
19 electrical energy between the cathode and an anode, and means for
20 steering the arc around the cathode. The arc of electrical energy
21 extending between the cathode and the anode liberates a portion of the
22 cathode which is subsequently deposited on the substrate located inside
23 the vessel.

24 An advantage of the present invention is that the present
25 invention apparatus for cathodic arc vapor deposition of material on a
26 substrate is designed to operate in a cost effective manner. One cost
27 effective characteristic of the present invention is the cathode. The
28 present invention cathode is preferably disk-shaped and can be cut, for
29 example, from a cylindrical casting. The simply formed cathode



1 requires minimal expensive machining, thereby reducing the cost of the
2 cathode and the overall coating process. Another cost effective
3 characteristic is that the erosion of the cathode is circumferentially
4 uniform. As a result, the life of the cathode can be maximized before
5 replacement is necessary.

6 Another advantage of the present invention is uniformity of the
7 coating process. The means for steering the arc around the cathode
8 increases the uniformity of the cathode erosion. Specifically, steering
9 the arc around the circumference of the cathode at a substantially
10 constant velocity causes uniform circumferential erosion of cathode.
11 The substrates disposed around and equally spaced from the cathode
12 consequently receive a more uniform deposition of coating. In
13 addition, the velocity of the arc around the cathode circumference is a
14 function of the strength of the magnetic field and the amount of current
15 supplied. As a result, the velocity of the arc can be manipulated by
16 changing the amount of current, the strength of the magnetic field, or
17 both.

18 Another advantage of the present invention is the simplicity and
19 reliability of the means for steering the arc around the cathode. The
20 means for steering the arc includes a magnetic field generator having a
21 plurality of side magnets and a ferromagnetic centerpiece; no switching
22 mechanism is required. The absense of a switching mechanism
23 increases the reliability of the steering means.

24 These and other objects, features and advantages of the present
25 invention will become apparent in light of the detailed description of
26 the best mode embodiment thereof, as illustrated in the accompanying
27 drawings.

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1 **BRIEF DESCRIPTION OF THE DRAWINGS**

2 FIG.1 is a diagrammatic view of the present invention cathodic
3 arc vapor deposition apparatus.

4 FIG.2 is a diagrammatic cross-sectional view of a contactor,
5 showing twin magnetic field generators.

6 FIG.3 is a diagrammatic side view of a magnetic field
7 generator.

8 FIG.4 is a top view of the magnetic field generator shown in
9 FIG. 3.

10 FIG.5 is a diagrammatic top view of a magnetic field generator
11 having annular side magnets.

12 FIG.6 is a side view of the magnetic field generator shown in
13 FIG.5.

14 FIG.7 is a diagrammatic view of a cathode and magnetic field
15 generator with a center magnet, including magnetic field lines
16 permeating the cathode.

17 FIG.8 is a diagrammatic view of a cathode and magnetic field
18 generator, including magnetic field lines permeating the cathode.

19 **BEST MODE FOR CARRYING OUT THE INVENTION**

20 **I. Apparatus**

21 Referring to FIG.1, an apparatus 10 for cathodic arc vapor
22 deposition on a substrate 12, hereinafter referred to as a "cathodic arc
23 coater", is provided having a vessel 14, means 16 for maintaining a
24 vacuum in the vessel 14, a cathode 18, a contactor 20, and means 22
25 for sustaining an arc of electrical energy between the cathode 18 and an
26 anode 24. A coolant supply 26 maintains the apparatus 10 within
27 acceptable temperatures by cycling coolant through cooling passages
28 28,30 within the vessel 14 and contactor 20. In the preferred
29 embodiment, the means 16 for maintaining a vacuum in the vessel 14



1 includes a mechanical rough vacuum pump 32 and a high volume
2 diffusion-type vacuum pump 34 piped to the interior of the vessel 24.
3 Other vacuum means may be used alternatively.

4 Referring to FIGS. 1 and 2, the cathode 18 is a substantially
5 cylindrical disk having an evaporative surface 36 extending between a
6 pair of end surfaces 38,40. The end surfaces 38,40 are substantially
7 parallel with one another. The coating to be deposited dictates the
8 material composition of the cathode 18, and often the cathode 18 can
9 simply be cut from a cast rod. The axial length 42 of the cathode 18 is
10 preferably longer than the anticipated final width 44 of the erosion
11 pattern 46 along the evaporative surface 36 of the cathode 18. Keeping
12 the erosion pattern 46 between the end surfaces 38,40 minimizes the
13 possibility that the arc will leave the evaporative surface 36 of the
14 cathode 18. The substrates 12 are mounted on a platter 48 that rolls
15 into and out of the vessel 14. The platter 48 includes means for
16 rotating the substrates (not shown).

17 The contactor 20 includes a head 52 attached to a shaft 54. The
18 head 52 is positioned inside the vessel 14 and the shaft 54 extends from
19 the head 52 to outside the vessel 14. An insulative disk 56 electrically
20 insulates the contactor 20 from the vessel 14. The contactor 20
21 preferably further includes a cooling tube 58 coaxially positioned
22 within the shaft 54, a coolant inlet port 60 (see FIG.1) connected to the
23 cooling tube 58, and a coolant exit port 62 connected to the passage 30
24 formed between the coaxial coolant tube 58 and shaft 54. The coaxial
25 arrangement between the cooling tube 58 and the shaft 54 allows
26 coolant from the coolant supply 26 to enter the cooling tube 58 and
27 return via the passage 30 between the shaft 54 and the cooling tube 58,
28 or vice versa.

29 Referring to FIGS. 2-8, the contactor head 52 includes a cup
30 66, a shaft flange 68, and a magnetic field generator 74. The shaft



1 flange 68 is fixed to the shaft 54 and the cup 66 is removably attached
2 to the shaft flange 68. The cup 66, shaft flange 68, and shaft 54 are
3 fabricated from an electrically conductive material such as a copper
4 alloy. The magnetic field generator 74 includes a ferromagnetic center
5 piece 82 , a plurality of side magnets 84, and a center magnet 86. The
6 center piece 82 includes at least one side surface 88 extending between
7 two end surfaces 90, and a hollow 92 for receiving the center magnet
8 86. The side 84 and center 86 magnets are preferably permanent
9 magnets, although alternative magnetic field sources such as
10 electromagnetics may be used. Cylindrical permanent magnets, for
11 example, are advantageous because they are commercially available and
12 relatively inexpensive (see FIGS. 2-4,7, and 8). An annular magnet,
13 segmented or whole, may be used alternatively (see FIGS. 5 and 6).
14 The side magnets 84 are attached to the side surface 88 and the center
15 magnet 86 is either received within the hollow 92 or attached to an end
16 surface 90. FIG.8 shows a magnetic field generator 74 that includes a
17 ferromagnetic center piece 82 and side magnets 84, but does not
18 include a center magnet 86. In all embodiments, the number of side
19 magnets 84 can be varied to accommodate the process at hand.

20 Referring to FIGS. 1 and 2, apparatus 94 is included for
21 rotating the magnetic field generator. The rotation apparatus 94
22 includes a rod 96 extending through the coolant tube 58 and into the
23 head 52 where it connects with the ferromagnetic center piece 82. The
24 opposite end of the rod 96 is connected to a variable speed drive motor
25 98 via a drive belt 100 (see FIG.1).

26 The cathodic arc coater 10 may also include an actuator 102 for
27 selectively actuating the contactor 20 into electrical contact with the
28 cathode 18 which includes a pair of two-way actuating cylinders 104
29 (hydraulic or pneumatic) acting between the vessel 14 and a shaft
30 flange 106 attached to the contactor shaft 54. Mechanical apparatus



1 may be used in place of the actuating cylinders 104. A commercially
2 available controller (not shown) can be used to control the position and
3 force of the cylinders 104 (or mechanical apparatus). FIG.1 shows the
4 cathode 18 disposed between a fixed support 19 and an actuable
5 contactor 20. FIG.2 shows an alternative cathode 18 arrangement
6 wherein a contactor 20 is in contact with each end surface 38,40 of the
7 cathode 18. The second contactor 20 may be fixed or actuable.

8 The cathodic arc coater 10 preferably includes a biasing source
9 108 for electrically biasing the substrates 12. Negatively biasing the
10 substrates 12 relative to the anode 24 makes the substrates 12
11 electrically attractive to positive ions liberated from the cathode 18. A
12 contact 110 electrically connects the biasing source 108 to the platter
13 48. The substrates 12, which are electrically connected to the platter
14 48, are consequently electrically connected to the biasing source 108.
15 Other means for electrically connecting the substrates 12 to the biasing
16 source 108 may be used alternatively.

17 Deflector shields 112 are used throughout the coater 10 to
18 confine the vaporized cathode materials in the area of the substrates 12.
19 The deflector shields 112 attached to the vessel 14 , platter 48, and
20 contactor 20 also minimize undesirable material build-up on those
21 surfaces. In the preferred embodiment, the deflector shields 112
22 attached to the vessel 14 are electrically connected to the vessel 14 and
23 are made of an electrically conductive material resistant to corrosion,
24 such as stainless steel.

25 The means 22 for sustaining an arc of electrical energy between
26 the cathode 18 and an anode 24 includes a direct current (D.C.) power
27 supply 114. In the preferred embodiment, the positive lead 115 of the
28 power supply 114 is connected to the vessel 14, thereby making the
29 vessel 14 act as an anode. The negative lead 117 of the power supply
30 114 is electrically connected to the contactor shaft 52. Alternative



embodiments may use an anode (not shown) disposed inside the vessel 14. An arc initiator 116, maintained at or near the electrical potential of the vessel 14, is used to initiate an arc.

II. Operation of the Apparatus

Referring to FIG.1, in the operation of the present invention cathodic arc coater 10, a plurality of substrates 12 and a cathode 18 are attached to the platter 48 and loaded into the vessel 14. The substrates 12 have been previously degreased and substantially cleaned, although each will likely have some molecular contaminant and oxidation remaining on its exterior surface. The actuating cylinders 104 subsequently actuate the contactor 20 into electrical contact with the cathode 18 and the vessel 14 is closed.

The mechanical rough vacuum pump 32 is operated to evacuate the vessel 14 to a predetermined pressure. Once that pressure is reached, the high volume diffusion vacuum pump 34 further evacuates the vessel 14 to near vacuum conditions. The substrates 12 are then cleaned of any remaining contaminants and/or oxidation by a method such as "sputter cleaning". Sputter cleaning is a process well known in the art and will not be described in detail here. Other cleaning methods may be used alternatively. After the substrates 12 are cleaned, the contaminants are purged typically using an inert gas.

Prior to initiating an arc several steps are completed, including: (1) the substrates 12 are electrically biased via the biasing source 108, making them electrically attractive to positive ions emitted from the cathode 18; (2) the substrates 12 are rotated at a particular rotational speed; (3) the power supply 114 is set to establish an arc having a particular magnitude of current and voltage, but no arc is initiated; (4) the vacuum pumps 32,34 establish and maintain a particular vacuum pressure of gas within the vessel 14; and (5) coolant is cycled through



1 the cooling passages 28,30 within the vessel 14 and contactor 20.
2 Specific process parameters will depend upon factors such as the
3 substrate material, the material to be coated, and the desired
4 characteristics of the coating, etc.

5 Once the aforementioned steps have been completed, the arc
6 initiator 116 is brought into and out of contact with the evaporative
7 surface 36 of the cathode 18, causing an arc to jump between the arc
8 initiator 116 and the evaporative surface 36. The arc initiator 116 is
9 subsequently moved a distance away from the cathode 18, preferably
10 radially outside of the substrates 12. Once the arc initiator 116 is no
11 longer proximate the cathode 18, the arc jumps between the cathode 18
12 and the deflector shields 112 electrically connected to the vessel 24 (or
13 directly between the cathode 18 and the vessel 24).

14 The magnetic field generator 74 positioned in the contactor 20
15 drives the cathode spot along the evaporative surface 36 of the cathode
16 18. To be more specific, each side magnet 84 produces a magnetic
17 field that permeates the cathode 18 and runs substantially parallel to the
18 cathode evaporative surface 36. FIGS. 7 and 8 show an approximation
19 of where the magnetic field lines are believed to run and vector 124
20 represents the magnetic field extending between the cathode end
21 surfaces 38,40. The direction of the magnetic field vector 124 depends
22 upon the orientation of the side magnet 84 poles, and all side magnets
23 84 are oriented in like manner. A vector 126 representing the electric
24 arc, in contrast, extends away from the evaporative surface 36 in a
25 substantially perpendicular direction. Together, the magnetic field and
26 the electric current of the arc create a force (the Hall effect) on the arc
27 that causes the arc to travel a distance around the circumference of the
28 cathode 18. The dwell time of the arc at any particular cathode spot is
29 inversely related to the Hall effect force; i.e., an increase in the Hall
30 effect force, causes a decrease in the dwell time. A person of skill in

1 the art will recognize that decreasing the dwell time reduces the
2 occurrence of macro-particles which can adversely effect the uniformity
3 and surface finish of the deposited coating.

4 The individual magnetic fields of the side magnets 84, in close
5 circumferential proximity to one another, collectively force the arc to
6 circle the cathode evaporative surface 36 along an arc path 122 (see
7 FIG.2). The number of side magnets 84, the relative spacing of
8 magnetic fields emanating from side magnets 84, and the intensity of
9 those magnetic fields can be adjusted to satisfy the application at hand.
10 In some applications, however, it is advantageous to further include a
11 center magnet 86. The magnetic field of the center magnet 86 appears
12 to influence the geometry of the magnetic fields emanating from the
13 side magnets 84. As a result, the arc path 122 around the
14 circumference of the cathode 18 is moved axially away from the side
15 magnets 84. Hence, the center magnet 86 can be used to move the
16 axial position of the arc path 122. FIG.7 shows an approximation of
17 how the magnetic field lines from the side magnets 84 and center
18 magnet 86 are believed to interact. An arc path 122 proximate the
19 axial midpoint of the cathode 18 helps maintain the arc away from the
20 contactor 20 (or between both contactors 20), thereby minimizing
21 undesirable wear on the contactor 20. An arc path 122 (and
22 consequent erosion geometry) proximate the axial midpoint also helps
23 increase the efficiency of the coating process by maximizing the
24 amount of material that can be eroded from a particular cathode 18.

25 The energy delivered by the arc causes the material at the
26 cathode spot to vaporize, thereby liberating atoms, molecules, ions,
27 electrons, and particles from the cathode 18. The biased substrates 12
28 attract the ions, causing them to accelerate toward the substrates 12.
29 The ions strike the exterior surface of the substrates 12, attach, and
30 collectively form a coating of the cathode material.



1 FIG.2 shows an eroded cathode 18 in phantom, substantially
2 symmetrical about the arc path 122. In the embodiment which includes
3 apparatus 94 for rotating the magnetic field generator 74, rotation of
4 the magnetic field generator 74 within the contactor 20 helps promote
5 uniform axial and circumferential erosion of the cathode 18. The
6 rotation distributes the magnetic contribution of each side magnet 84
7 around the circumference of the cathode 18 as a function of time. It
8 must be emphasized, however, that rotation of the magnetic field
9 generator 74 is not required to create a circling arc. As stated above,
10 the individual magnetic fields of the side magnets 84 collectively force
11 the arc to circle the cathode evaporative surface 36.

12 Referring to FIG.1, when a coating of sufficient thickness has
13 been deposited on the substrates 12, the power supply 114 is turned off
14 and the arc extinguished. The vessel 14 is purged with inert gas and
15 brought to ambient pressure. The contactor 20 is actuated out of
16 contact with the cathode 18 and the platter 48 is removed from the
17 vessel 14. The substrates 12 are subsequently removed from the platter
18 48 and new substrates 12 attached. The loaded platter 48 is then
19 inserted back into the vessel 14 in the manner described earlier and the
20 process repeated.

21 Although this invention has been shown and described with
22 respect to the detailed embodiments thereof, it will be understood by
23 those skilled in the art that various changes in form and detail thereof
24 may be made without departing from the spirit and the scope of the
25 invention. In one example, means for cooling the contactor 20 may be
26 used other than that disclosed in the Best Mode. In another example, a
27 power supply 114 that simulates direct current, such as one having an
28 LCR circuit or other rectifying means, may be used in place of a D.C.
29 power supply 114. In another example, the Best Mode discloses one or



- 1 both contactors 20 as actuatable. In some cases, however, it may be
2 acceptable to have stationary contactors 20.

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I claim:

1 1. An apparatus for applying material by cathodic arc vapor
2 deposition to a substrate, comprising:
3 a vessel;
4 means for maintaining a vacuum in said vessel;
5 a disk-shaped cathode, positioned inside said vessel, having a
6 first end surface, a second end surface, and an evaporative surface
7 extending therebetween;
8 means for selectively sustaining an arc of electrical energy
9 between said evaporative surface and an anode; and
10 means for driving said arc around said evaporative surface,
11 wherein said means for driving said arc is positioned in close proximity
12 to said cathode, and said means for driving said arc produces a
13 magnetic field that permeates said cathode;
14 wherein said arc of electrical energy extending between said
15 cathode and said anode liberates a portion of said cathode which is
16 subsequently deposited on the substrate located inside said vessel.

1 2. An apparatus according to claim 1, wherein said means for
2 sustaining an arc of electrical energy between said cathode and said
3 anode comprises:
4 a power supply, having a positive lead and a negative lead;
5 wherein said negative lead of said power supply is electrically
6 connected to cathode, and said positive lead is electrically connected to
7 said vessel, thereby making said vessel act as said anode; and
8 wherein said cathode is electrically insulated from said vessel.

1 3. An apparatus according to claim 1, wherein said means for
2 driving said arc around said evaporative surface comprises:
3 a ferromagnetic center piece;





4 a magnetic field generator, attached to said ferromagnetic center
5 piece, wherein said magnetic field generator produces a magnetic field
6 having a portion that runs substantially parallel to said evaporative
7 surface of said cathode.

1 4. An apparatus according to claim 3, wherein said magnetic field
2 generator, further comprises:

3 a plurality of magnets, wherein each magnet is attached to a
4 side surface of said ferromagnetic center piece, and said magnets are
5 uniformly spaced around said ferromagnetic center piece.

1 5. An apparatus according to claim 4, wherein said magnets are
2 permanent magnets.

1 6. An apparatus according to claim 5, wherein each said magnet is
2 cylindrically shaped, having a first polar end and a second polar end,
3 said second polar end having a polarity opposite that of said first polar
4 end;

5 wherein said first polar end of each said magnet is are attached
6 to said ferromagnetic center piece.

1 7. An apparatus according to claim 6, further comprising:
2 a protective coating, said coating encasing said ferromagnetic
3 center piece and said magnets to inhibit corrosion of said ferromagnetic
4 center piece and said magnets.

1 8. An apparatus according to claim 6 further comprising:
2 a housing, in contact with one of said cathode end surfaces;
3 wherein said magnetic field generator is enclosed within said
4 housing.



- 1 9. An apparatus according to claim 8, further comprising:
2 means for selectively transferring thermal energy from said
3 housing;
4 wherein said means for transferring thermal energy selectively
5 transfers thermal energy from said housing.
- 1 10. An apparatus according to claim 6, further comprising:
2 a rotator, attached to said ferromagnetic center piece;
3 wherein said rotator rotates said ferromagnetic center piece and
4 attached magnetic field generator inside said housing.
- 1 11. An apparatus according to claim 10, wherein said rotator
2 comprises:
3 a drive motor, positioned outside said vessel;
4 a rod, attached to said ferromagnetic center piece, wherein
5 said rod extends outside said vessel and is selectively rotated by said
6 drive motor.
- 1 12. An apparatus according to claim 3, wherein said magnetic field
2 generator is an annular magnet, having an inner radial surface and an
3 outer radial surface, said outer radial surface having a polarity opposite
4 that of inner radial surface;
5 wherein said inner radial surface is attached to said
6 ferromagnetic center piece.
- 1 13. An apparatus according to claim 12, wherein a plurality of
2 magnet segments collectively form said annular magnet.
- 1 14. An apparatus according to claim 12 further comprising:
2 a housing, in contact with one of said cathode end surfaces;



3 wherein said magnetic field generator is enclosed within said
4 housing.

1 15. An apparatus according to claim 14, further comprising:
2 means for selectively transferring thermal energy from said
3 housing;
4 wherein said means for transferring thermal energy selectively
5 transfers thermal energy from said housing.

1 16. An apparatus according to claim 12, further comprising:
2 a rotator, attached to said ferromagnetic center piece;
3 wherein said rotator rotates said ferromagnetic center piece and
4 attached magnetic field generator inside said housing.

1 17. An apparatus according to claim 16, wherein said rotator
2 comprises:
3 a drive motor, positioned outside said vessel;
4 a rod, attached to said ferromagnetic center piece, wherein
5 said rod extends outside said vessel and is selectively rotated by said
6 drive motor.

1 18. An apparatus according to claim 3, further comprising:
2 a rotator, attached to said ferromagnetic center piece;
3 wherein said rotator rotates said ferromagnetic center piece and
4 attached magnetic field generator inside said housing.

1 19. An apparatus according to claim 18, wherein said rotator
2 comprises:
3 a drive motor, positioned outside said vessel;



4 a rod, attached to said ferromagnetic center piece, wherein
5 said rod extends outside said vessel and is selectively rotated by said
6 drive motor.

1 20. An apparatus according to claim 3 further comprising:
2 a housing, in contact with one of said cathode end surfaces;
3 wherein said magnetic field generator is enclosed within said
4 housing.

1 21. An apparatus according to claim 20, further comprising:
2 means for selectively transferring thermal energy from said
3 housing;
4 wherein said means for transferring thermal energy selectively
5 transfers thermal energy from said housing.

1 22. An apparatus according to claim 1, wherein said means for
2 driving said arc around said evaporative surface comprises:
3 a pair of magnetic field generators, each attached to a
4 ferromagnetic center piece;
5 wherein one of said magnetic field generators is positioned in
6 close proximity to said first end surface, and the other of said magnetic
7 field generators is positioned in close proximity to said second end
8 surface;
9 wherein each said magnetic field generator produces a magnetic
10 field having a portion that runs substantially parallel to said evaporative
11 surface of said cathode.

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