The use of the electride form of 12CaO-7Al2O3 or C12A7, as a low work function electron emitter in a hollow cathode discharge apparatus is described. No heater is required to initiate operation of the present cathode, as is necessary for traditional hollow cathode devices. Because C12A7 has a fully oxidized lattice structure, exposure to oxygen does not degrade the electride. The electride was surrounded by a graphite liner since it was found that the C12A7 electride converts to its eutectic (CA+C3A) form when heated (through natural hollow cathode operation) in a metal tube.
References Cited

OTHER PUBLICATIONS


* cited by examiner
FIG. 3
Baseline Configuration

- NCC @ 12.7 mm w/o B-field
- NCC @ 25.4 mm w/o B-field
- NCC @ 38.1 mm w/o B-field

Cathode Flow Rate (sccm)

FIG. 8
1

12CAO-7AL2O3 ELECTRIDE HOLLOW CATHODE

CROSS-REFERENCE TO RELATED APPLICATIONS

The present application claims the benefit of U.S. Provisional Patent Application No. 61/816,593 for “C12A7 Electride Hollow Cathode,” by Lauren P. Rand et al., which was filed on 26 Apr. 2013, the contents of which is hereby specifically incorporated by reference herein for all that it discloses and teaches.

STATEMENT REGARDING FEDERAL RIGHTS

This invention was made with government support under Grant No. F30602-06-C-0023 awarded by the Air Force Electronic Systems Center, Nong05GH75H awarded by the NASA Goddard Space Flight Center and NNX11CD55 awarded by the NASA Lyndon B. Johnson Space Center. The government has certain rights in the invention.

FIELD OF THE INVENTION

The present invention relates generally to hollow cathode discharge apparatus and, more particularly to the use of 12CAC0-7AL2O3 electrode material as a low work function electron emitter in a hollow cathode discharge apparatus.

BACKGROUND OF THE INVENTION


The calcium aluminate phase of 12CAO-7AL2O3 (C12A7), is one of several alumina-lime phases found in common alumina-based cements. C12A7 has a naturally formed nanostructure, in which subnanometer-sized cages form a three-dimensional crystal lattice. See, e.g., Y. Toda et al. (2007), “Work Function of a Room-Temperature Stable Electride [Ca24Al28O64]4+(4e—),” Advanced Materials, 19(21), 3564-3569. The unit cell consists of twelve cages. Although this cage structure is similar to those found in clathrate phases of ice and in zeolites, there is a difference in that the unit cell of C12A7 is positively charged; that is, there are four fewer electrons on the atoms that comprise the framework cage of C12A7 than are needed to neutralize the cage. The positive charge is counteracted by two atomic oxygen ions (O—) that are clathrated (floating) within two of the twelve subcages. New properties can be imparted to C12A7 if the free oxygen ions are substituted with anions like O2— and H—, and when four electrons are substituted for the two O2— ions to form C12A7 electride, the only inorganic electride known to be stable at high temperature. See e.g., S. Matsuishi et al. (2003), “High-Density Electron Anions in a Nanoporous Single Crystal: [Ca24Al28O64]4+(4e—). Science, 301, 626-629; and S. Kim et al. (2007), “Fabrication of room temperature-stable 12CAO 7AL2O3 electride: a review,” Journal of Material Science, 18, S5-S14. The stability of the C12A7 electride is attributable to the unique cage structure as well as the fully oxidized nature of the lattice.

The work functions of current state-of-the-art hollow cathode insert materials lanthanum hexaboride (LaB6) and cerium hexaboride (CeB6) are near 2.7 eV, while the work function of barium-impregnated porous tungsten (Ba—W) is near 2.1 eV (D. Goebel et al. (2007), “LaB6 Hollow Cathodes for Ion and Hall Thrusters,” Journal of Propulsion and Power,” 23(3), 552-558. LaB6 and CeB6, are generally heated to approximately 1900 K to obtain sufficient levels of emission, while Ba—W is heated above 1300 K. See e.g., D. Goebel et al., supra. These temperatures require well-made heaters and good thermal insulation. Ba—W cathodes, while operating at lower temperatures, are more susceptible to both poisoning and high rates of evaporation if operated at high current. See. e.g., D. Goebel et al., supra. By contrast, the work function of C12A7 electride has been measured in field emission tests to be as low as 0.6 eV, due to its unique charged lattice structure. See, e.g., S. Kim et al. (2006), “Synthesis of a Room Temperature Stable 12CAO.7AL2O3 Electride from the Melit and Its Application as an Electron Field Emitter,” Chem. Mater., 18(7), 1938-1944; and J. F. Medvedeva et al. (2009), “Electronic band structure and carrier effective mass in calcium aluminates, Physical Review B, 76, 155107-1-155107-6; and Y. Toda et al. (2004), “Field Emission of Electron Anions Clathrated in Subnanometer-Sized Cages in [Ca24Al28O64]4+(4e—),” Advanced Materials, 16(8), 685-689.

SUMMARY OF THE INVENTION

Embodiments of the present invention overcome the disadvantages and limitations of prior art by providing a hollow cathode discharge apparatus which does not require an external heater.

Another object of embodiments of the present invention is to provide a hollow cathode discharge apparatus which does not require an external heater, and which is resistant to degradation when exposed to oxygen relative to state of the art hollow cathodes.

Additional objects, advantages and novel features of the invention will be set forth in part in the description which follows, and in part will become apparent to those skilled in the art upon examination of the following, or may be learned by practice of the invention. The objects and advantages of the invention may be realized and attained by means of the instrumentalities and combinations particularly pointed out in the appended claims.

To achieve the foregoing and other objects, and in accordance with the purposes of embodiments of the present invention, as embodied and broadly described herein, hollow cathode discharge apparatus, hereof, includes: a metal tube.
having a first end and a second end, an outside surface and an inside surface; a gas source for flowing gas into the first end of the tube; a metal end cap having an orifice with a chosen diameter adapted to attach to the second end of the tube, such that the gas exits the tube through the orifice; a tubular graphite liner having an outer surface, a first open end and a second end, adapted to be inserted into the metal tube, and in electrical contact therewith, with the second end thereof disposed in the vicinity of the end cap; a 12CaO-7Al2O3 electride material disposed inside of the tubular graphite liner in the vicinity of the metal end cap; a keeper element disposed outside of the tube in the vicinity of the end cap; and a first direct current source in electrical contact with the keeper and the tube for initiating and maintaining an electric discharge in the gas between the electrode material and the keeper without the electrode material being initially heated.

In another aspect of the present invention and in accordance with its objects and purposes, the hollow cathode discharge apparatus, hereof, includes: a metal tube having a first end and a second end, an outside surface and an inside surface; a gas source for flowing gas into the first end of the tube; a metal end cap having an orifice with a chosen diameter adapted to attach to the second end of the tube, such that the gas exits the tube through the orifice; a tubular graphite liner having a first closed end and a second open end adapted to be inserted into the metal tube such that gas can flow between the graphite liner and the inside surface of the metal tube, the second end of the insert being disposed in the vicinity of the end cap; wherein the metal tube is dimpled in the region of the first end of the graphite liner for holding the liner in position in the tube, and for making electrical contact therewith, a 12CaO-7Al2O3 electrode material generated in the tubular graphite liner and filling the insert to about the second end thereof; a keeper element disposed outside of the tube in the vicinity of the end cap; and a first direct current source in electrical contact with the keeper and the tube for initiating and maintaining an electric discharge in the gas between the electrode material and the keeper without the electrode material being initially heated.

Benefits and advantages of the present invention include, but are not limited to, providing a hollow cathode discharge apparatus which does not require an external heating element, and has a low work function electron emitter material which resists degradation in the presence of oxygen and other gases.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated in and form a part of the specification, illustrate the embodiments of the present invention and, together with the description, serve to explain the principles of the invention. In the drawings:

FIG. 1a is a schematic representation of a side view of an embodiment of the hollow cathode apparatus of the present invention illustrating the cathode barrel, graphite liner and keeper, while FIG. 1b shows a schematic representation of a side view of a second embodiment of the cathode barrel and graphite liner suitable for smaller hollow cathodes.

FIG. 2 is a schematic representation of a circuit employed for initiating and maintaining a discharge in the hollow cathode apparatus illustrated in FIG. 1, hereof, with the closed keeper being replaced with an external wire keeper.

FIG. 3 is a graph of the anode voltage as a function of time over the course of four runs during the preparation of an insert.

FIG. 4 is a graph of the barrel temperature as a function of time over the course of four runs during the preparation of an insert.

FIG. 5 is a graph of the anode voltage as a function of discharge current for an electrode hollow cathode with an iodine propellant at a constant flow rate of 13 sccm.

FIG. 6 is a graph of the anode voltage as a function of mass flow rate for an electrode hollow cathode with an iodine propellant.

FIG. 7 is a schematic representation of a side view of the apparatus illustrated in FIG. 1, hereof, illustrating the addition of a neutral confinement cylinder and permanent magnets for generating an axial magnetic field.

FIG. 8 is a graph of the peak emission current of the cathode as a function of flow rate for different cylinder lengths, compared to the baseline configuration without the cylindrical extension.

FIG. 9 is a graph of the increase in peak emission current when an axial magnetic field is applied, compared with a baseline configuration without magnetic fields.

FIG. 10 is a graph of the peak emission current capability of the cathode with an axial field strength of 100 Gauss and the neutral confinement cylinder at various positions relative to the downstream face of the keeper.

DETAILED DESCRIPTION OF THE INVENTION

Embodiments of the present invention include the use of the electride form of 12CaO-7Al2O3, or C12A7, as a low work function electron emitter in a hollow cathode discharge apparatus. The low work function of C12A7 electrode derives from its unique structure, and permits a C12A7 cathode to operate theoretically at ~400 K. No heater is required for initiating the operation of the cathode, as is necessary for traditional hollow cathode devices, thereby eliminating these components and reducing the weight of fieldable hollow cathode devices.

Without the need for a heater the hollow cathodes of the present invention can be significantly smaller in diameter when compared to existing cathodes. Additionally, cathodes capable of providing small current emission (<100 mA) may be fabricated for micro-propulsion applications since electron or cathode emitters emit at lower temperatures than traditional emitters. In fact, 1/10 in. cathodes are anticipated in accordance with the teachings of the present invention.

In the assembly of the hollow cathode apparatus hereof, a sliver of C12A7 electrode is placed into a graphite tube. When small hollow cathodes having outside diameters ≤3.5 mm are desired, a graphite cup used also to prepare the electride, as will be described hereinafter, was placed within the hollow cathode with the open end of the cup placed near to the orifice of the hollow cathode. In both embodiments, graphite was used since it was found that the C12A7 electrode would convert to its eutectic (CA+C3A) form when heated (through natural hollow cathode operation) in a metal (tantalum) tube. The graphite provides an anionic template, as it does during the original C12A7 formation process, as also will be described hereinbelow.

A. Preparation of C12A7 Electride:

Two precursors (CaCO3 and Al2O3) were mixed in a 12:7 stoichiometric ratio and ground with a mortar and pestle to reduce the particle size and help facilitate a solid-state reaction. The powders used were 150 Mesh Type 507C aluminum oxide from Sigma Aldrich and 99.9% pure calcium carbonate from Fisher Scientific. The mixture was placed in a graphite crucible, fabricated from EDM-5 fine-grained graphite obtained from Ohio Carbon Blank, Inc. The carbon crucible
was found to be necessary for the successful formation of C12A7 electride. Although the exact mechanism is unknown, it is thought that the carbon crucible is needed to supply carbon anions to occupy the subcages and permit the forma-
tion of the lattice, which then evacuate upon cooling leaving
behind their electrons (S. Kim et al., supra). A graphite plate
was secured over the top of the crucible with tantalum wire to
keep the molten precursors from flowing out of the crucible
during the heating process due to surface tension.

The furnace and crucible were placed in a vacuum cham-
ber, and the temperature raised to 1700° C. over the course of
about 2 h, at which point the furnace power was abruptly
turned off and the furnace and crucible were allowed to cool
radiatively to the water-cooled vacuum chamber walls. The
crucible cooled to below the recrystallization temperature of
about 1000° C. in less than 30 min. The chamber was gener-
ally not vented for at least 16 h after the power supply had
been shut off, in order to give the furnace and crucible time
to cool before exposure to atmosphere. As an alternative, the
electride could be cooled more rapidly, limited by undesirable
fracturing of the material, by introducing an inert gas into the
furnace, thereby permitting convective cooling to occur. The
resulting electride was metallic-looking, conductive, and
bonded to the graphite. Positive identification was obtained
using EPR, x-ray photoelectron spectroscopy (XPS), and x-ray
diffraction crystallography (XRD). Using a diamond-
coated blade, slivers consisting almost entirely of C12A7
electride were cut from the graphite crucible for use in the
hollow cathode, as will be described hereinbelow. The result-
ing pieces were approximately 1.9 mm wide and 12.7 mm
long. Because C12A7 electride has a fully oxidized lattice
structure, exposure to oxygen and other gases present in labo-
ramory air were found not to have a deleterious effect on the
anode.

In the second embodiment, electrode-filled cups about 6
mm long having outer diameters of about 2.6 mm, inner
diameters of about 2 mm, and a 5 mm long hollow cavity,
were generated. As will be discussed in more detail herein-
below, these cups with electrode filling were placed inside Ta
hollow cathodes with the electrode filling placed in the vicin-
ity of a Ta orifice plate.

B. Hollow Cathode:

Initial electrode hollow cathode prototypes utilized a
graphite hollow cathode tube with an orifice plate at one end
thereof. This was done because the electrode could be melted
directly on the inner surface of the graphite hollow cathode
tube. The precursors were mixed and put directly in the tube,
and the entire tube was then placed in the vacuum furnace and
heated according to the procedure described hereinbelow.

The resulting cathode typically had several solidified ele-
ctrone droplets attached to the graphite at uncontrollable inter-
vals along the inside of the barrel, with the electrode droplet
furthest downstream often being as much as 1.27 cm
upstream of the orifice end of the tube. Since models predict
that the majority of electron emission in a hollow cathode will
occur in the first few millimeters of the insert, the upstream
position of the electrode was much less effective. The result-
ing operation was unstable due to discharge often extingu-
ishing. Anode voltage was observed to vary, perhaps, due in
part to the dominant emission site changing between the
multiple electrode droplets. Additionally graphite is suscepti-
able to arcing, which occurred frequently and eventually
resulted in severe erosion of the orifice plate.

To improve the stability of the cathode and decrease arcing,
a tantalum tube was used in place of the graphite barrel. The
tantalum barrel was capped with a thoriated tungsten orifice
plate having an orifice. Rather than melt the electrode precur-
sors directly onto the inner surface of the barrel, the precur-
sors were heated in a graphite crucible, and the resulting
electride was broken into pieces. Several pieces were inserted
into the tantalum tube near the thoriated tungsten orifice plate,
with the result that the discharge could be run for greater than
seven hours. The operation was unstable as was typified by
large fluctuations in anode voltage, perhaps, due to the move-
ment of emission sites between the different electrode pieces,
such that differing dominant sources of current might be
reflected in the anode voltage because emission from an elec-
tride piece further upstream in the barrel would require higher
voltage. It was also found that electride material that came in
direct contact with the tantalum tube would convert to a non-
conductive and non-emitting phase, which resulted in the
cathode becoming more difficult to start and operate.

These problems were overcome by placing an electride
sliver into a graphite liner that was subsequently placed inside
the tantalum tube in the vicinity of the thoriated tungsten
orifice plate or cap. After performing conditioning oper-
ations, which will be described in more detail hereinbelow, the
cathode was found to start readily and operate stably. In the
second embodiment, electride was formed within a graphite
cup that was subsequently placed within a tantalum hollow
cathode having an orifice. The sidewall of the tantalum tube
was slightly crimped to prevent the graphite cup from moving
within the tantalum tube, and to keep the electrode near to the
orifice plate, while permitting gas to flow between the interi-
or surface of the tantalum tube and the outer surface of the
graphite cup.

Reference will now be made in detail to the present
embodiments of the invention, examples of which are illus-
trated in the accompanying drawings. In the FIGURES, similar
structure will be identified using identical reference char-
acters. It will be understood that the FIGURES are for the
purpose of describing particular embodiments of the inven-
tion and are not intended to limit the invention thereto. Turn-
ing now to FIG. 1a, a schematic representation of a perspec-
tive side view of an embodiment of hollow cathode apparatus,
10, of the present invention, showing barrel, 12, fabricated
from a 6.3 mm diameter cylindrical tantalum tube having
circular thoriated tungsten orifice plate or cap, 14, with or-
ifice, 15, having a thickness of 0.635 mm an orifice diameter of
0.76 mm, adapted to close off the downstream end thereof
such that gas passes through orifice 15. Cap 14 may be welded
to the top of barrel 12. Different orifice sizes have been used,
and result in different operating conditions. The downstream
1.9 cm of the tantalum barrel was surrounded with 10 layers
of radiation shielding, 16, fabricated from 0.0127 mm thick
tantalum foil. As stated, unlike traditional cathodes, no heater
was incorporated in the design.

As mentioned hereinabove, to maintain the electrode in its
conductive form, an anionic template, such as fine-grained
EDM-3 graphite tube or liner, 18, having circumferential lip,
20, at circular end, 21, closest to orifice plate 14 and open at
the other end, 22, thereof, was inserted into hollow cathode
barrel 12. A single sliver of C12A7, 24, was placed in graphite
liner 18 near the downstream end thereof. Liner 18 was 2.54
cm long with an inner diameter of 2.54 mm, an outer diameter
of 5.08 mm. Lip 20, having an inner diameter of 1.905 mm,
was found to keep electride 24 from contacting orifice plate
14. The largest effective diameter for lip 20 has not been
investigated. Liner 18 was wrapped with single layer of tan-
talum foil, 26, to improve electrical contact and then inserted
into a tantalum cathode barrel. Optionally, an electrical wire,
28, may be attached to tantalum foil 26 and directed upstream
in tube 16 from graphite liner 18. Enclosed cylindrical keeper,
30, having 2.54 mm orifice, 32, in circular end-plate, 33,
disposed 1.27 mm downstream from barrel orifice plate 14 was placed around cathode barrel 12. Gas source, 34, supplies chosen gases to barrel 12. In order to save gas, when it is desirable to pulse the cathode discharge on and off, gas source 34 may also be turned on and off. A circular flange, 37, or other attachment to keeper, 30, permits keeper 30 to be mounted to chosen surfaces, as desired.

FIG. 1b is a schematic representation of a side view of a second embodiment of hollow cathode barrel 12 and liner 18. The keeper, insulator and mounting elements have been removed for clarity, but are necessary to complete the hollow cathode. Unlike liner 18 of FIG. 1a, which is open at bottom end 22, liner 18 in FIG. 1b has a closed bottom end 22 and an open downstream end, 21. Electrode 24 is generated in a graphite cup having a graphite cap, in accordance with the procedure described in Section A, hereinabove. When the electrode synthesis is complete, the cup is cut down in length such that its open end 21 is close to the level of electrode material 24 formed in the cup, producing thereby liner 18. Because of the smaller diameter 3.5 mm) of liner 18, the surface tension of the electrode both forms a cone at a 45° angle in the region of the open end 21 of liner 18, and does not flow or migrate out of liner 18 when heated by the electric discharge, although open end 21 of liner 18 is placed close to orifice plate 14.

Tube 12 is dimpled in two or more locations, 35a,b, both to make electrical contact with insert 18, and to hold liner 18 within tube 12. Liner 18 has an outside diameter smaller than the inside diameter of tube 12, such that gas can pass around liner 18 and exit tube 12 through orifice 15 in orifice plate 14, and participate in the discharge.

FIG. 2 is a schematic representation of a circuit employed for initiating and maintaining a discharge in hollow cathode apparatus 10. An external tantalum wire keeper, 36, was occasionally used in place of closed keeper 30 for ease of access to the cathode and for viewing the discharge. The wire keeper was also used for preparing the cathode for regular service, as will be explained in more detail hereinbelow. In that configuration, the wire was bent into a circle approximately 6.3 mm in diameter, and placed approximately 1.27 mm downstream from orifice plate 14. Stainless steel ring anode, 38, having an outer diameter of 5 cm, a length of 24 cm, and a thickness of 0.38 mm, was disposed 3 cm from thoriated tungsten orifice plate or cap 14 thereof to measure the operating temperature of the cathode using reader, 48. When enclosed graphite keeper 30 was installed, temperature was not measured.

Cathode testing was conducted in a diffusion pumped vacuum chamber, not shown in the FIGURES, having a base pressure of approximately 6x10^-5 Torr. The chamber pressure was 2x10^-7 Torr when about 4 sccm of xenon, a common mass flow rate used to test the hollow cathodes, was introduced into barrel 12 from gas source 34.

Unlike traditional cathodes, the discharge start-up procedure does not involve a lengthy conditioning or heat-up process. There were two procedures by which the discharge electrode cathode was initiated. One involved setting the mass flow rate and increasing the keeper voltage until a discharge was initiated by an arc discharge between keeper 30 or 36 and cathode barrel 12, which ignited the cathode discharge. With 50 sccm of xenon flowing, the discharge typically started with 400 V on keeper 30 or 36. Alternatively, a high voltage could be applied to keeper 30 or 36, while the mass flow rate was increased until the cathode started. With 1000 V on the keeper, the discharge commenced with approximately 25 sccm of xenon. The later procedure was used more frequently to conserve gas. At startup, the cathode immediately coupled to the anode to within the response time of the display on the power supply which was less than about 0.2 s. It should be pointed out that unsuccessful attempts were made using these start-up procedures on an identical cathode without the electrode/graphite liner insert. The ignition time of less than about 0.2 s is useful for operating the cathode in pulse mode. As an illustrative example, one could operate the cathode for a period of time on the order of seconds followed by the discharge and flow rate being "off" for a chosen period of time.

Reproducible cathode operation is defined as duplicated anode voltages and barrel temperatures at a given set point. For the following data, reproducible operation was defined as an anode voltage constant and repeatable within ±3 V, and an operating temperature constant and repeatable within ±50° C. It was found that the first two or three times an insert was operated, the cathode generally exhibited initially high and decreasing anode voltages and barrel temperatures. After three or four runs, the anode voltages and barrel temperatures at different set points became approximately constant. FIGS. 3 and 4, respectively, illustrate this progression for a single insert over the course of four runs, and operation was deemed reproducible between the third and fourth run. The abrupt shutdown at the end of conditioning runs 1, 2 and 3 were followed by a period sufficient to return the cathode to about room temperature. This time period was typically 2-3 h, but occasionally as long as 16 h if the shutdown occurred at the end of the day. The conditioning run following an abrupt shutdown and cool down time resulted in lower temperatures and anode voltages on the subsequent run that were not possible to achieve without the abrupt shutdown and cool down process.

Following the above operations, it was found that relatively low voltage on keeper 30, 36 was required to start the electrode cathode and there was no visible arc activity observed. The cathode did not appear to require an arcing event on the orifice to initiate operation, and the applied voltage on the keeper was not adequate to cause arcing between the cathode and keeper orifices. Of significance is that the C12A7 electrode, which has a low work function, appears to emit a sufficient number of electrons at room temperature to trigger the discharge initiation sequence that quickly transitions into the desired and sustained arc discharge between the electrode inside the cathode and the externally located electrodes.

As seen from FIG. 4, operating temperatures as low as 975° C. were measured on the outer surface of the downstream end of the cathode barrel. Under some operating conditions, temperatures of about 650° C. were measured. After an initial stabilization process, the operation leveled out or within a tenth of a volt on the current-limited anode, and was repeatable to within a few volts during subsequent operations (over a two month period, with 20 cathode restarts, 11 chamber vent-pump-down sequences, and an iodine exposure in which 0.1 g of iodine was flowed through the tantalum barrel at room temperature). An electrode insert has operated for more than 60 h, with no observed degradation. Additionally, there
Iodine has recently attracted interest as an alternative electric propulsion propellant, since it can be stored in low pressure tanks in the solid phase, eliminating the need for the large, high pressure storage solutions mandated by xenon. Iodine has an atomic mass similar to that of xenon with slightly larger ionization cross-sections (for both 1 and I2). The increased reactivity of iodine when compared to xenon was a concern, especially when the susceptibility to contamination of Ba—W hollow cathodes was considered; however the electride hollow cathode of the present invention has been observed to be resistant to contamination.

The iodine feed system to the cathode incorporated a heated iodine reservoir with a pressure transducer that could be used to quantify the approximate flow rate. All tubing between the reservoir and the cathode were heated to prevent iodine condensation. The reservoir was weighed after each day of operation, allowing for the development of a flow rate calibration curve from the measured reservoir pressure.

The cathode was tested in the diode configuration with a ring anode and enclosed graphite keeper described hereinabove, the constant 0.3 A of current collected by the keeper being added to the discharge current. The cathode discharge was initiated with iodine at room temperature with no heater. Almost 20 hours of operation with iodine was accumulated on a single C12AT electrode insert with no observable electrode degradation or contamination. The 20-hour duration involved eight restarts from room temperature as well as an exposure to atmosphere; no difficulty starting and operating the cathode was encountered. However, a black discoloration was observed on the outer surface of the tantalum cathode barrel, and the tantalum radiation shielding was also discolored and damaged, likely due to iodine reacting with the cathode structure materials to form iodine compounds. Tantalum is known to react with iodine to form tantalum pentatide (TaI5) above about 300°C. Using refractory metals such as tungsten or molybdenum for the barrel and radiation shielding material would most likely prevent corrosion, as they react with iodine at elevated temperatures.

A graphite barrel with flexible graphite or platinum radiation shielding might be used to overcome this problem. Graphite adsorbs and desorbs iodine with temperature fluctuations, but will not corrode or react. The cathode barrel and orifice plate could be fabricated from graphite, and the downstream end of the orifice plate covered with a platinum plate, which would prevent arcs from occurring between the graphite and the keeper during discharge initiation. Graphite erodes quickly and deforms into peaks and tendrils when subjected to arcing. Platinum will eventually corrode in the presence of iodine, although at a rate more than 150 times slower than that of tantalum. Alternatively, a graphite orifice plate might be used with a keeper power supply that incorporates arc suppression circuitry to avoid damage to the graphite.

The anode voltage as a function of discharge current was measured at a constant iodine flow rate of approximately 13 sccm. Data were recorded as the current was increased from 3 A to 15 A, and decreased from 15 A to 3 A over approximately one hour, and are shown in FIG. 5. The cathode performance at lower iodine flow rates was also investigated by slowly decreasing the temperature of the iodine reservoir in the feed system while the anode voltage was recorded, as shown in FIG. 6. The discharge current was kept constant at 3 A with additional 0.3 A collected by the keeper. The internal pressure of the cathode was estimated to be approximately one Torr; consequently, there is uncertainty regarding flow rate, especially at flow rates near 5 sccm where the increase in anode voltage was observed. It is believed that the actual flow rate is lower than 5 sccm, because cathode operation using xenon shows an increase in anode voltage at flow rates close to 1 sccm at a discharge current of 3 A.

**EXAMPLE 2**

Neutral Confinement Cylinder (NCC)

Improved confinement of the cathode neutral which normally escape away from the keeper orifice was observed by wrapping a stainless steel foil around the graphite keeper, thereby creating a cylindrical extension. Electromagnets have also been used to generate an axial magnetic field at the keeper face, 100, and 150 Gauss. Permanent magnets were used to generate an axial magnetic field at the keeper face, as illustrated in FIG. 7. Three field strengths were tested: 75, 100, and 150 Gauss. Permanent magnets were stacked around the base of the keeper in four stacks with four magnets per stack. This generated 100 Gauss at the keeper face, with field lines being aligned with the orifice and slowly diverging in the downstream region. Clearly, other types of permanent magnets can be employed in various configurations, to achieve similar results. Electromagnets have also been used with similar results.
The required keeper voltage for cathode ignition was found to be reduced with the application of an axial magnetic field. Further increases in magnetic field above 100 Gauss provided limited improvement. The 100 Gauss configuration was chosen as a compromise between maximum current emission and system mass. The total weight of the magnets to generate 100 Gauss was 0.13 kg. Voltage-Current curves were measured at various flow rates to determine the impact of an applied magnetic field on the electron emission capability of the cathode. In addition to the significant improvement in maximum electron emission for a given flow, the discharge voltage has been found to be reduced, indicating easier extraction of the cathode electrons. FIG. 9 is a graph of the peak emission current increase when going from the baseline configuration to the applied magnetic field configuration. As may be observed from FIG. 9, the emission current increases for all flow rates tested. While the applied magnetic field improves the electron emission capability for all flow rates, use of the NCC favors higher flow rates with minimal improvement below about 2 sccm.

**EXAMPLE 4**

**Magnetic Field+Neutral Confinement Cylinder Combination**

FIG. 10 is a graph of the peak emission current capability of the cathode with an axial field strength of 100 Gauss and various lengths of the NCC. The optimum length was found to be about 25.4 mm. The improvement observed when combining the two configurations (B-field and NCC) is approximately the sum of their individual improvements discussed hereinabove. The slopes of the trend lines for the various NCC lengths with the 100 Gauss field strength lies between the slopes of the standalone B-field configuration and the standalone NCC configuration. It should be noted that with the NCC having a length of 30.5 mm and a diameter matching that of the keeper diameter, results in a sharp drop in emission current capability compared to a length of 25.4 mm.

The foregoing description of the invention has been presented for purposes of illustration and description and is not intended to be exhaustive or to limit the invention to the precise form disclosed, and obviously many modifications and variations are possible in light of the above teaching. The embodiments were chosen and described in order to best explain the principles of the invention and its practical application to thereby enable others skilled in the art to best utilize the invention in various embodiments and with various modifications as are suited to the particular use contemplated. It is intended that the scope of the invention be defined by the claims appended hereto.

What is claimed is:

1. A hollow cathode discharge apparatus, comprising:
   - a metal tube having a first end and a second end, an outside surface and an inside surface;
   - a gas source for flowing gas into the first end of said tube;
   - a metal end cap having an orifice with a chosen diameter adapted to attach to the second end of said tube, such that the gas exits said tube through the orifice;
   - a tubular graphite liner having an outer surface, a first open end and a second end, adapted to be inserted into said metal tube, and in electrical contact therewith, with the second end thereof disposed in the vicinity of said end cap;
   - a 12CaO-7Al2O3 electrode material disposed inside of said tubular graphite liner in the vicinity of said metal end cap;

   a keeper element disposed outside of said tube in the vicinity of said end cap; and
   - a first direct current source in electrical contact with said keeper and said tube for initiating and maintaining an electric discharge in the gas between said electrode material and said keeper without said electrode material being initially heated.

2. The discharge apparatus of claim 1, further comprising an electrode or plasma anode disposed outside of said keeper; and a second direct current source for initiating and maintaining an electric discharge in the gas between said electrode material and said anode.

3. The discharge apparatus of claim 1, wherein said first direct current source is pulsed on and off.

4. The discharge apparatus of claim 3, wherein said gas source is pulsed on and off in synchronization with the on and off condition of said first direct current source.

5. The discharge apparatus of claim 1, wherein said metal tube is chosen from tantalum, tungsten, and molybdenyum, and alloys thereof.

6. The discharge apparatus of claim 1, wherein said metal tube is chosen from titanium, nickel and steel, and alloys thereof.

7. The discharge apparatus of claim 1, wherein said gas comprises xenon.

8. The discharge apparatus of claim 1, wherein said metal end cap is chosen from tantalum, tungsten, and molybdenyum, and alloys thereof.

9. The discharge apparatus of claim 8, wherein said metal cap comprises thoriated tungsten.

10. The discharge apparatus of claim 1, wherein said metal end cap is welded to said metal tube.

11. The discharge apparatus of claim 1, further comprising a heat shield on the outside surface of said metal tube.

12. The discharge apparatus of claim 1, wherein the second end of said graphite insert has a circumferential graphite lip.

13. The discharge apparatus of claim 1, wherein said keeper comprises a wire keeper.

14. The discharge apparatus of claim 1, wherein said keeper comprises a cylindrical graphite keeper having an orifice, a chosen outer diameter, and an outer face, enclosing a portion of said tube in the region of said end cap.

15. The discharge apparatus of claim 14, further comprising a conducting cylinder having a chosen length and an inner diameter equal to the outer diameter of said graphite keeper, in electrical contact with said keeper for extending the length of said graphite keeper from the outer face thereof, thereby preventing gas molecules from expanding at high zenith angles from the orifice of said keeper.

16. The discharge apparatus of claim 1, further comprising at least one magnet or electromagnet for generating an axial magnetic field in the region of the orifice of said keeper.

17. The discharge apparatus of claim 15, further comprising at least one magnet or electromagnet for generating an axial magnetic field in the region of the orifice of said keeper.

18. The discharge apparatus of claim 1, further comprising a metal foil wrapped around the outside surface of said graphite liner for providing electrical contact between said tube and said graphite liner.

19. A hollow cathode discharge apparatus, comprising:
   - a metal tube having a first end and a second end, an outside surface and an inside surface;
   - a gas source for flowing gas into the first end of said tube;
   - a metal end cap having an orifice with a chosen diameter adapted to attach to the second end of said tube, such that the gas exits said tube through the orifice;

   a 12CaO-7Al2O3 electrode material disposed inside of said tubular graphite liner in the vicinity of said metal end cap;
a tubular graphite insert having a first close end and a second open end adapted to be inserted into said metal tube such that gas can flow between said graphite insert and the inside surface of said metal tube, the second end of said insert being disposed in the vicinity of said end cap; wherein said metal tube is dimpled in the region of the first end of said graphite insert for holding said insert in position in said tube, and for making electrical contact therewith;  
a 12CaO-7Al₂O₃ electride material generated in said tubular graphite insert and filling said insert to about the second end thereof;  
a keeper element disposed outside of said tube in the vicinity of said end cap; and  
a first direct current source in electrical contact with said keeper and said tube for initiating and maintaining an electric discharge in the gas between said electride material and said keeper without said electride material being initially heated.

20. The discharge apparatus of claim 19, further comprising an electrode or plasma anode disposed outside of said keeper; and a second direct current source for initiating and maintaining an electric discharge in the gas between said electride material and said anode.

21. The discharge apparatus of claim 19, wherein said first direct current source is pulsed on and off.

22. The discharge apparatus of claim 21, wherein said gas source is pulsed on and off in synchronization with the on and off condition of said first direct current source.

23. The discharge apparatus of claim 19, wherein said metal tube is chosen from tantalum, tungsten and molybdenum, and alloys thereof.

24. The discharge apparatus of claim 19, wherein said metal tube is chosen from titanium, nickel and steel, and alloys thereof.

25. The discharge apparatus of claim 19, wherein said gas comprises xenon.

26. The discharge apparatus of claim 19, wherein said metal end cap is chosen from tantalum, tungsten, and molybdenum, and alloys thereof.

27. The discharge apparatus of claim 26, wherein said metal cap comprises thoriated tungsten.

28. The discharge apparatus of claim 19, wherein said metal end cap is welded to said metal tube.

29. The discharge apparatus of claim 19, further comprising a heat shield on the outside surface of said metal tube.

30. The discharge apparatus of claim 19, wherein the second end of said graphite insert has a circumferential graphite lip.

31. The discharge apparatus of claim 19, wherein said keeper comprises a wire keeper.

32. The discharge apparatus of claim 19, wherein said keeper comprises a cylindrical graphite keeper having an orifice, a chosen outer diameter, and an outer face, enclosing a portion of said tube in the region of said end cap.

33. The discharge apparatus of claim 32, further comprising a conducting cylinder having a chosen length and an inner diameter equal to the outer diameter of said graphite keeper, in electrical contact with said keeper for extending the length of said graphite keeper from the outer face thereof, thereby preventing gas molecules from expanding at high zenith angles from the orifice of said keeper.

34. The discharge apparatus of claim 19, further comprising at least one magnet or electromagnet for generating an axial magnetic field in the region of the orifice of said keeper.

35. The discharge apparatus of claim 33, further comprising at least one magnet or electromagnet for generating an axial magnetic field in the region of the orifice of said keeper.