

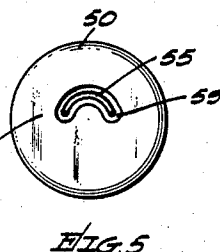
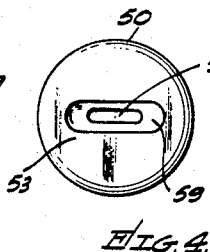
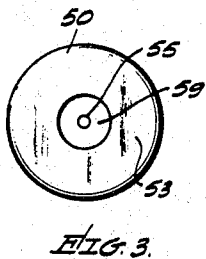
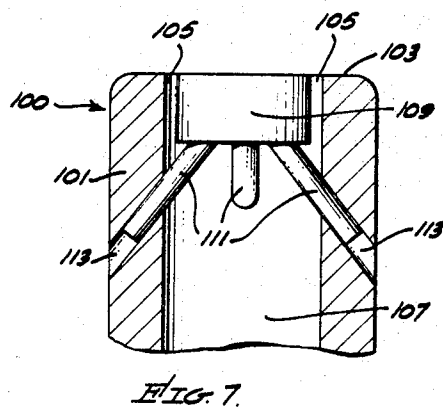
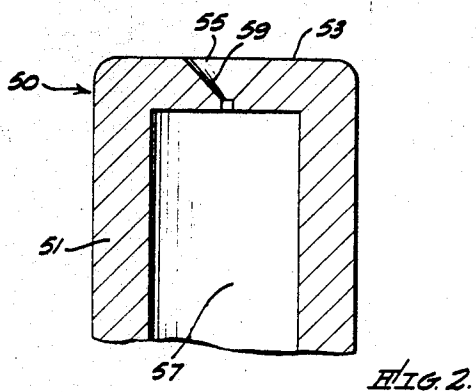
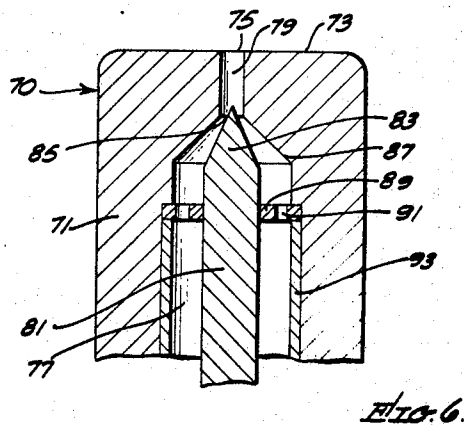
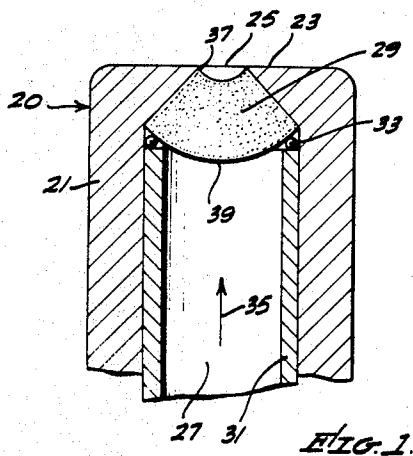
Oct. 28, 1969

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LIQUID-METAL ARC CATHODE WITH MAXIMIZED  
ELECTRON/ATOM EMISSION RATIO

3,475,636

Filed Nov. 14, 1967

3 Sheets-Sheet 1



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3 Sheets-Sheet 2

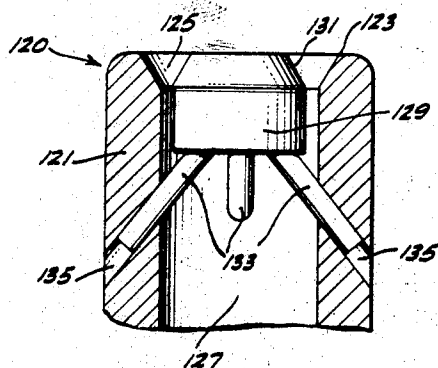


FIG. 8.

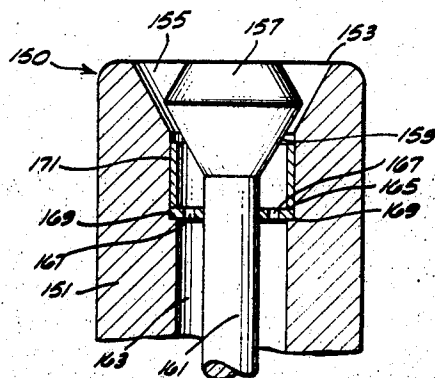


FIG. 9.

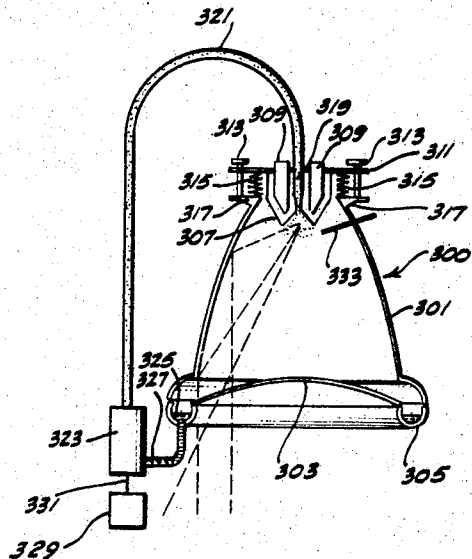


FIG. 11.

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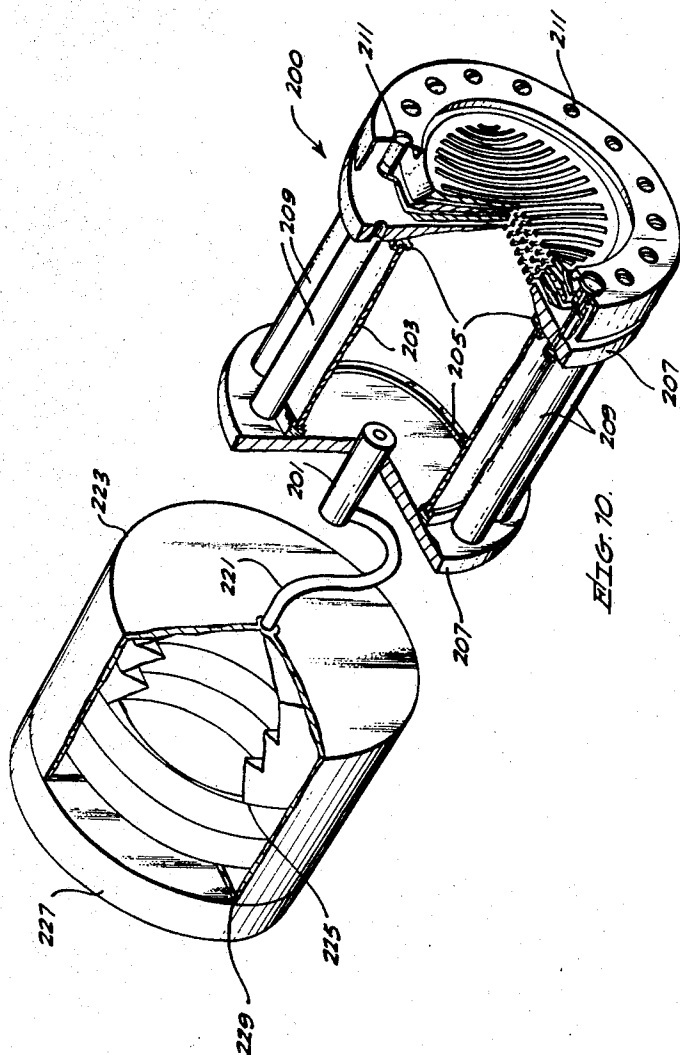
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3 Sheets-Sheet 3



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3,475,636

## LIQUID-METAL ARC CATHODE WITH MAXIMIZED ELECTRON/ATOM EMISSION RATIO

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Continuation-in-part of application Ser. No. 476,810, Aug. 3, 1965. This application Nov. 14, 1967, Ser. No. 699,276

Int. Cl. H01j 1/02

U.S. Cl. 313—29

17 Claims

### ABSTRACT OF THE DISCLOSURE

A forced-flow gravity-independent liquid-metal arc cathode includes a pool-keeping structure and is provided with passageway means for feeding liquid metal to the pool-keeping structure. The pool-keeping structure includes lateral sides which define the pool area and locate the liquid-metal pool so that it is accessible for arcing. The liquid metal wets the sides. Electrons are emitted from the liquid metal by operating the cathode in the liquid-metal pool arc mode with the arc spot at the juncture of the pool and wetted sides. This cathode is useful, for example, in electron bombardment ion sources, as the neutralizer cathode for ion beams, as a long-life light source, and for use in high voltage, high current rectifiers, switching devices, and circuit breaking devices.

The invention described herein was made in the performance of work under a NASA contract and is subject to the provisions of Section 305 of the National Aeronautics and Space Act of 1958, Public Law 85-568 (72 Stat. 435; 42 U.S.C. 2457).

### CROSS REFERENCE

This application is a continuation-in-part of patent application Ser. No. 476,810, and now abandoned filed Aug. 3, 1965, by Wilfried O. Eckhardt, entitled "Liquid-Metal Arc Cathode."

### BACKGROUND

This invention relates to a liquid-metal arc cathode and more particularly to a novel type liquid-metal arc cathode emitting electrons and metal atoms in gas discharge or vacuum devices.

The oldest and most widely used cathode device used to date is the thermionic cathode. This type of cathode is probably best known for its use as the electron emitter in electron vacuum tubes. However, it has now been incorporated as a source of electrons in electron bombardment ion sources for space propulsion devices. In this regard, reference may be made to an article entitled "An Ion Rocket with Electron Bombardment Ion Source" by H. R. Kaufman in NASA Technical Note D-585, January 1960. Another application of this type of cathode is as a neutralizer for ion beams in space propulsion engines (thrusters).

Although they have been used extensively in recent years, cathodes of the type described in the above-referenced article have been found to have the disadvantage of experiencing deleterious effects from considerable ion bombardment. The result of this bombardment is that even the best thermionic emitters developed to date for thruster applications, for example, have a useful life time which is shorter than desired for presently contemplated electric-propulsion missions. The problem arises from the difficulty in keeping the discharge voltage below the sputtering threshold of the materials used for the cathodes. Another disadvantage characteristic of many thermionic cathodes is that they are either destroyed or deactivated

on being exposed to the normal atmosphere while in operation or even just after operation.

Thermionic, as well as various other types of cathodes, in conjunction with anodes and gas feed systems, are also used in plasma arc devices serving as high intensity light and heat sources. As one example of this application, reference may be made to U.S. Patent Ser. No. 3,136,915 for a High Energy Plasma Source, to W. Jaatinen et al. Also, an article in Z. Physik, vol. 132, p. 244 (1952) by K. Larche and his article in Z. Electrotechn., vol. 72, p. 427 (1951) may be referred to in this regard. The devices described utilize solid cathodes and have the disadvantage of very limited life of the cathode or associated anode or both, depending on the particular configuration.

Liquid-metal arc cathodes have also been either used or proposed for applications in the foregoing described devices and other applications such as in rectifiers and switches. In the use of this type cathode in very high voltage-high power level rectifier and switching devices, the fact that the amounts of metal evaporated from the cathode is not controllable is a distinct disadvantage because it may lead to frequent high voltage breakdown. For a more complete description of liquid-metal arc cathodes reference may be made to an article entitled "Kraftübertragung mit hochgespannten Gleichstrom," in De Ingenieur 67/2 nr. 44 dd. (Apr. 11, 1955) by Erich Uhlmann, and to a book entitled "The Arc Discharge" by H. de B. Knight, published by Chapman and Hall Ltd., London, 1960.

Another disadvantage that may be present in the use of conventional liquid-metal arc cathodes is that they are gravity dependent for their operation in order to keep the liquid metal in a confined cathode area. Furthermore, these devices are not self-protecting in their operation and in the event of a high current surge from a short circuit, for example, these devices may be permanently damaged.

### SUMMARY

The preferred structure of this liquid-metal arc cathode is one in which only sufficient liquid metal is exposed as is necessary for proper arc maintenance. This permits the arc chamber in which the cathode is positioned to be operated at a lower pressure, for liquid metal evaporation is minimized by a minimized area of the liquid metal presented to the low pressure in the arc chamber. This in turn results in a maximized electron/atom emission ratio and also results in a higher voltage standoff capability in the chamber when the arc is not running, due to the lower pressure and the lower number of evaporated liquid-metal atoms in the chamber atmosphere.

The liquid-metal pool which is accessible for arcing is defined by lateral walls in the pool-keeping structure. In one case, these lateral walls are the walls of a feed bore, and in another case, they are the divergent walls of the pool-keeping structure just beyond the feed bore so that equilibrium of liquid-metal position is obtained by balancing evaporation plus losses due to arc activity against feed rate. In addition to the fact that the pressure in the arc chamber can be kept lower than with conventional pool type cathodes, due to the restricted exposed area of the liquid metal, the present cathode may also be made to operate independently of gravitational or inertial forces because the pool is maintained in the pool-keeping structure by surface tension. Furthermore, this same effect permits the cathode to be used in any orientation in gravitational fields.

It is therefore an object of the invention to provide a liquid-metal arc cathode that replaces thermionic cathodes in electron bombardment ion sources with the advantage of longer cathode life and elimination of a phase separator in the expellant feed system of such devices when used

in space propulsion systems. It is another object of the present invention to provide a liquid-metal arc cathode that is not adversely affected by accidental exposure to the atmosphere even when in full operation. It is still another object of the invention to provide a liquid-metal arc cathode that can serve as a long-life neutralizer cathode for ion beams, with a life advantage over thermionic cathodes. It is yet another object of the present invention to provide a liquid-metal arc cathode that can serve as a long-life light source of very high brightness, with a life and brightness advantage over conventional plasma arc devices.

It is a further object of the present invention to provide a liquid-metal arc cathode that can serve in rectifying, switching, and circuit breaking devices for very high currents and voltages, with a reverse voltage standoff advantage over open pool mercury arc devices.

It is still a further object of the present invention to provide a liquid-metal arc cathode that is self-protecting, in that if current drawn from the cathode exceeds the value which the cathode can handle at the set feed rate, the arc will automatically extinguish without damage to the cathode. It is yet another object of the invention to provide a liquid-metal arc cathode that allows operation as a high intensity light source at a time average electron emission current density exceeding that of any other known high current cathode by orders of magnitude to permit very high power concentrations in the plasma which emits the light.

#### DESCRIPTION OF THE DRAWINGS

FIGURE 1 is a multi-orifice type liquid-metal arc cathode according to one embodiment of the invention;

FIGURE 2 is a divergent-nozzle type liquid-metal arc cathode according to a preferred embodiment of the invention;

FIGURES 3, 4 and 5 illustrate various divergent-nozzle shapes for the embodiment shown in FIGURE 2;

FIGURE 6 is a capillary bore type liquid-metal arc cathode according to another embodiment of the invention;

FIGURE 7 is an annular slit type liquid-metal arc cathode according to still another embodiment of the invention;

FIGURE 8 illustrates a divergent-nozzle variation of the annular slit type cathode of FIGURE 7;

FIGURE 9 is still another variation of the annular slit type cathode having an adjustable divergent nozzle orifice;

FIGURE 10 illustrates schematically (with a section broken away) the essential parts of a typical ion thruster design employing a forced-flow liquid-metal arc cathode according to the invention; and

FIGURE 11 is a schematic diagram of a high intensity mercury arc lamp incorporating a forced-flow liquid-metal arc cathode of the invention.

#### DESCRIPTION

As described previously, in the cathode of this invention electrons are emitted from a surface of liquid metal by operating the cathode in the liquid-metal pool arc mode. In a book by J. D. Cobine entitled "Gaseous Conductions," Dover Publications, Inc., New York, pp. 418-419 (1958), it is shown to be a fact that in mercury-pool rectifiers and ignitrons, the liquid-metal pool arc mode can be maintained with currents in the range from about 3 amps to more than  $10^4$  amps with free mercury surfaces, and down to 50 milliamperes by using a spot anchor (also called spot-fixer in the art), i.e., by immersing in the mercury surface a wetted piece of a refractory metal which has the effect of confining the arc spot to its mercury-covered edge.

In addition to emitting electrons at the arc spot, it has been found that the liquid-metal surface also emits atoms of the liquid metal. The effect of an arc spot terminating

on a liquid-metal surface is that atoms are removed from the surface at the arc spot (due to local heating and possibly by sputtering due to ion bombardment) at a rate, as indicated in the above-referenced book, to be for a conventional mercury-pool arc, approximately one atom per 8 emitted electrons.

In addition to this mechanism, evaporation from the inactive part of the cathode surface causes an additional efflux of atoms from the liquid. In several applications of the invention described above, it is desirable to keep the neutral efflux small. To this effect, it will be seen that the area of the exposed liquid-metal surface is kept small.

In order to minimize evaporation of atoms from the surface, the pool temperature must be kept as low as possible. To accomplish this, the liquid metal must wet the pool-keeping walls so that the arc spot operates at the juncture between the liquid metal and the walls. The heat flux from the arc spot does not pass through the pool of liquid metal, but directly into the mass of cathode structure, which can be cooled by any convenient means. Furthermore, in order to maintain the arc spot at the juncture, the pool-keeping wall angle must be such that the plane of the juncture must be above the free face of the liquid-metal pool.

In the various embodiments of the invention, it will be shown that the position of the liquid-metal surface is maintained in stable equilibrium by using a pool-keeping structure which allows the dynamic balance of the hydrostatic pressure (under which the liquid metal is kept by a suitable feed system) against the sum of arc forces, surface tension, and friction forces in the pool-keeping structure. For cathodes of the invention used within a gravitational field or under high accelerations, gravitational and inertial forces must be included in this equilibrium condition.

FIGURE 1 shows a multi-orifice pool-keeping cathode structure 20 having a heavy-walled side wall portion 21 and having a face 23. Central opening 25 is disposed in face 23. Opening 25 communicates with a passageway 27 disposed within the body of the structure 20, through a spherical sector-shaped porous plug 29. Porous plug 29 is retained in passageway 27 adjacent opening 25 by means of a tight-fitting metal sleeve 31 pressing an O-ring gasket 33 against the periphery of the porous plug 29. Cathode structure 20 may be fabricated from any material having high heat conductivity such as molybdenum or tungsten, for example, while the sleeve 31 may be fabricated from stainless steel, for example, and the O-ring 33 may be made from any suitable elastomer. Alternatively, liquid-cooling means can be used to control the temperature of a thin-walled side wall portion substituted for the heavy-walled structure shown. The porous plug 29, on the other hand, may be made from a refractory metal such as molybdenum or tungsten or from a ceramic compound such as alumina or a highly refractory dielectric such as diamond. If made of a refractory metal, the porous plug 29 may be sealed by electron beam welding it to member 21.

In porous-plug type cathodes such as cathode 20, a liquid metal such as mercury (not shown) is forced under pressure along the passageway 27 and through the porous body of the plug 29 in a direction indicated by the arrow 35. The spherical sector shape of the porous plug 29 combines a small face area 37 (as required, in certain applications, for a high ratio of electron to atom emission) with a large inlet area 39 (to minimize the possibility of clogging by impurities) while providing a uniform flow impedance over the entire inlet surface 39. In order to obtain an exposed mercury surface area of sufficiently small size, for the high ratio noted above (to keep atom evaporation low), the face 37 of the porous plug 29 is electron beam "washed" (i.e., a surface layer is melted to close the pores) everywhere except within a diameter slightly smaller than the intended active cathode

diameter. Another suitable method of pore closing can alternatively be used. Liquid metals other than mercury may also be used in the cathodes of the invention such as cesium or gallium, for example.

In operation of a multi-orifice cathode of the type shown in FIGURE 1, the liquid metal is made to wet the face 37 of the porous plug 29 and part of the surrounding area 23, and the arc is maintained on the wetted part of the surface. Wetting of the face of pool-keeping structures may be achieved by operating an electric arc on a liquid-metal globule such as mercury disposed on an area of the structure to be wetted. In this process, it is necessary to hold the globule in place either by suitable orientation in a gravity field or by constraining the motion of the globule through the use of a refractory metal probe. In the case of the nonmetallic porous plugs, the liquid metal may also be made to wet the porous material in order to hold the arc spot at the juncture between the pool-keeping wall and the liquid-metal pool.

When the liquid-metal pool is fairly small and wets the porous material, gravity independence is obtained because the adhesion and surface tension maintain the pool in place. Such small pools are desired, even in upright, gravity environments, in order to keep atom emission low.

The pool of liquid metal is restrained by the sides of the face 37 of the porous plug 29 which extend beyond the pool, where that portion of the concave spherical surface which extends laterally beyond the pool defines and restrains the pool. The arc is maintained at the juncture between the pool and the laterally extending face 37 extending therebeyond. In view of the fact that the exposed liquid-metal pool area increases when feed exceeds metal consumption, equilibrium is reached by the larger pool area presenting a larger evaporation area.

Steady-state operation of porous-plug type cathodes is obtained by adjusting the liquid-metal feed rate (through control of the feed pressure, see FIGURES 10 and 11) at a fixed discharge current so that about half the area of the porous area 37 is covered by liquid metal (not shown). This results in a stable equilibrium position of the liquid-metal surface. Thus, if the feed rate increases slightly at a fixed discharge current, the liquid-metal pool area on the porous area 37 will grow until evaporation from the enlarged liquid-metal surface area balances the increase in feed rate. The opposite is true if the feed rate decreases slightly.

One additional condition for the existence of a stable equilibrium between feed rate and evaporation rate arises from the fact that the arc spot changes its position very rapidly along the circumference of the exposed liquid-metal surface, spending approximately equal times at any portion of this circumference. Therefore, the density of thermal power flow into the exposed liquid-metal surface (and, consequently, its temperature and evaporation rate per unit area) will increase when the exposed liquid-metal surface area decreases. This means that the thermal conductance of the cathode structure 20 must be large enough to keep any change in surface temperature accompanying a change in surface area sufficiently small, so as to ensure that the total evaporation rate decreases when the exposed liquid-metal surface area decreases, or in other words, to ensure that the effect of a decrease of the exposed surface area is not overcompensated by a large increase in evaporation rate per unit area.

Instead of having a plurality of orifices of the embodiment of the invention as shown in FIGURE 1, various embodiments of the invention may be constructed utilizing a single orifice as can be seen from FIGURES 2 through 9.

With reference to FIGURE 2, there is shown a preferred embodiment of the invention comprising a single-orifice divergent-nozzle type liquid-metal arc cathode structure 50 having a heavy-walled side wall portion 51 and a pool-keeping structure having front face 53 in which is disposed a central conical pool-keeping opening 55.

The pool-keeping opening 55 communicates with passageway 57 disposed within the body of the structure 50 through a divergent-nozzle configuration 59. The walls of conical pool-keeping opening 55 extend on the sides of the liquid-metal pool to restrain it and define its frontal area. As in the embodiment shown in FIGURE 1, the cathode structure 50, as well as the other cathodes to be described, may be fabricated from any material with high heat conductivity such as molybdenum, for example.

In operation, liquid metal is fed from a pressure source upward through passageway 57 and then through the small orifice into the central conical pool-keeping zone of the orifice structure. The walls of the conical pool-keeping opening extend laterally of the pool. This results in a variable area of the frontal face of the liquid metal so that if more is fed than is removed by the previously described effects, the frontal face enlarges and more of the liquid metal evaporates. This establishes equilibrium. Furthermore, the conical walls of the pool-keeping opening 55 are laterally positioned with respect to the pool so that they define the pool area. Since they are conical, the angle of the walls with respect to the liquid-metal pool is favorable for limiting the pool size. It is necessary for the walls to be positioned with respect to each other at an angle less than 180° to properly restrain the mercury in position. The limiting angle is such that the plane through the juncture between the liquid metal and the walls is above the free face of the pool. This is critical to maintain the arc spot operating at the juncture. The conical walls in this embodiment have a total included angle of approximately 90°, as does the spherical sector pool-keeping surface of FIGURE 1, at its peripheral edges.

The plan views of FIGURES 3, 4 and 5 illustrate that the divergent pool-keeping surface may be circular as shown in FIGURE 3, fan-like as shown in FIGURE 4, or semicircular fan-like as shown in FIGURE 5. Although only these three orifice shapes are illustrated, it should be understood that many other shapes may be utilized, depending on the particular application where the cathode is to be used.

Another single orifice cathode structure is illustrated in FIGURE 6. Here there is shown a capillary-bore pool-keeping cathode structure 70 having a heavy-walled side wall portion 71 and having a frontal face 73 in which face there is disposed a central opening 75. The opening 75 communicates with a passageway 77 disposed within the body of the structure 70, by means of a pool-keeping capillary bore 79. This cathode may be fitted with an adjustable flow impedance member 81 having a pointed portion 83 to adjustably restrict the flow of liquid metal through the passageway 77 to bore 79 by an axial movement toward or away from the inlet opening 85 to the capillary bore 79. In order to provide a smooth flow transition from the passageway 77 to the capillary bore 79, it may be desirable to provide a sloping transition section 87 in the passageway 77 adjacent the pool-keeping bore 79. The adjustable member 81 may be retained in a coaxial position with respect to the opening 77 by means of a guide member 89 having a plurality of holes or openings 91 disposed therethrough. The guide member 89 may be retained in a fixed position in the passageway 77 by any conventional means such as a tight fitting metal sleeve 93.

The walls of pool-keeping bore 79 are parallel to each other. These walls define the space in which the liquid-metal pool is positioned, and limits its lateral size. In operation, the face of the liquid metal in pool-keeping bore 79 is below the frontal face 73 so that the pool is laterally restrained by the walls of bore 79. The frontal face of the liquid-metal pool is accessible for arcing, and the arc spot is active on the surface of the liquid-metal pool within bore 79. In this case, the area of the liquid-metal pool exposed to evaporation is not dependent upon the feed rate. On the question of maintaining feed equilibrium, the area function of the frontal face of the liquid-

metal pool subject to evaporation is not variable, and thus evaporation from the area viewpoint is not available, as it is in the structures of FIGURES 1 through 5. Other effects must be involved to maintain feed equilibrium in this case. Through suitable thermal design, the face of the liquid-metal pool restrained by the walls of bore 79 can be at a higher temperature when it is closer to frontal face 73, rather than closer to the point 83 of the adjustable flow impedance member 81. Thus, there is more evaporation from the pool when the feed rate is excessive and the pool approaches frontal face 73. Still another embodiment of a single-orifice liquid-metal arc cathode is that of an annular-slit cathode as shown in FIGURE 7. This figure illustrates an annular-slit cathode structure 100 having a heavy-walled side wall portion 101 and frontal face 103. In this face, there is disposed an opening 105 communicating with a passageway 107 disposed within the body of the structure 100. Coaxially disposed in the opening 105 is a disk 109 of a material which may be similar to that used for the side wall portion 101. The disk member 109 may be supported coaxially in the opening 105 by means of metal legs 111 passing through holes 113 in the side wall portion 101 of the structure 100 and into holes (not shown) in the disk member 109.

The thermal design of cathode 100 is also such that the evaporation rate increases as the liquid-metal pool restrained in opening 105, between the parallel walls thereof, approaches face 103. By this means feed equilibrium is maintained in a manner similar to that described with respect to FIGURE 6.

Another annular-slit type cathode structure is shown in FIGURE 8. This embodiment is similar to the embodiment shown in FIGURE 7, in that an annular-slit configuration is provided. However, the embodiment of FIGURE 7 has a uniform cross section opening 105 which acts much like the uniform opening cross section (capillary bore 79) of the embodiment of FIGURE 6, whereas the cathode structure of FIGURE 8 incorporates the divergent-nozzle principle as described in FIGURE 2 in conjunction with the basic annular slit configuration shown in FIGURE 7. Accordingly, in FIGURE 8, there is shown a cathode structure 120 having a side wall 121 and a face 123 whereat there is disposed a sloping opening 125 communicating with a liquid-metal transporting passageway 127, which, in conjunction with a disk member 129 having an oppositely sloped upper surface 131, provides a divergent-nozzle annular-slit configuration. The disk member 129 may be supported coaxially within the opening 125 by leg members 133 passing through holes 135 in the side wall portion 121 of the cathode structure 120.

In this construction, the liquid-metal pool is positioned in the opening defined by the two truncated conical surfaces 125 and 131. Again, the area of the exposed face of the liquid-metal pool is dependent upon the amount fed, similar to the structures of FIGURES 1 through 5 so that equilibrium is established through the area exposed for evaporation. These truncated conical walls define the pool and are positioned laterally of the pool, and as is seen in FIGURE 8 having a total included angle in the order of 90° therebetween. This is a suitable angle for the maintenance of the pool in position.

Still another divergent-nozzle single-orifice cathode structure is shown in FIGURE 9. This embodiment provides the features of a divergent nozzle in conjunction with the ability to regulate the flow of liquid metal to the pool-keeping surface of the cathode. This embodiment comprises a single-orifice pool-keeping cathode structure 150 having a heavy-walled side wall portion 151 and a frontal face 153. Opening 155 is in the form of an annular divergent-nozzle slit and is defined by sloping surfaced disk member 157 disposed coaxially with respect to the opening 155. These truncated conical surfaces define opening 155. The disk member 157 is attached through a sloping transition section 159 to an adjustable rod 161 that is adapted to be moved in an axial direction either toward

face 153 to increase the flow of liquid metal or away from face 153 to restrict the opening 155 to decrease the flow. The position of the rod 161 coaxially with respect to an opening 163 in the structure 150 is provided by means of a guide 165 having holes or openings 167 therethrough. Guide 165 is retained in position against a shoulder 169 in the passageway 163 by a short sleeve 171.

In the single-orifice cathode described above, liquid metal such as mercury, for example, is forced through a capillary bore, an annular slit, a divergent nozzle or a combination of these.

The liquid metal is forced by the supply pressure to form a pool which is constrained by the walls of the bore, slit or divergent nozzle. These walls define the pool and thus are pool-keeping surfaces. These walls must provide lateral walls to define the pool area. In the illustrated cases, the walls preferably extend between an angular relationship wherein they are in the order of 90° with respect to each other to a position where the included angle is zero, i.e., where they are parallel to each other. The maximum permissible angle is dependent upon the wettability of the cathode material and the surface tension of the liquid metal so that the face of the pool does not project beyond the plane defined by the meniscus contact line with the pool-keeping surface. Under the circumstances, the pool can be maintained and the arc can operate on the pool at the juncture between the pool and the pool-keeping wall.

The wall of the orifice is wetted by the liquid metal whether or not gravity independence is required.

A stable equilibrium position of the liquid-metal surface exists for a divergent-nozzle configuration of suitable thermal design, because the area of the free liquid-metal surface increases if this surface shifts downstream and vice versa; therefore, the same mechanism applies here as discussed in connection with the porous plug embodiment. In the case of a uniform cross section configuration, such as the capillary-bore embodiment of FIGURE 6 and the annular-slit embodiment of FIGURE 7, the wetted state determines that the equilibrium of the liquid-metal surface position is stable. Because the pool-keeping surface of the orifice of the bore or slit is wetted, the same situation as in the porous plug case prevails, resulting in stable equilibrium.

Additionally, it may be desirable to sense the position of the free liquid-metal surface and to feed this information into a control circuit linking feed rate and discharge current. The required accuracy of the sensing is most stringent in the case of neutral equilibrium of the surface position. A sensor which is applicable to porous-plug as well as single-orifice type cathodes may consist of an annular thermo-couple junction (not shown) surrounding the porous face or orifice close to the intended downstream limit of the liquid-metal surface position. By proper thermal design of the cathode configuration, the temperature in this location can be made to increase if the liquid-metal surface shifts downstream, thereby generating the desired sensor output.

As a specific but not an exclusive example of an application of the forced-flow liquid-metal arc cathode, reference may be made to the Kaufman-type electron bombardment ion thruster of FIGURE 10. The ion thruster portion 200 is similar to the thrusters described in the Kaufman article referenced above and includes, in this example, a divergent-nozzle liquid-metal arc cathode 201 similar to the cathode described in FIGURE 2. The thruster 200 also includes a discharge-chamber anode 203 supported by insulators 205 attached to discharge-chamber end plates 207 which also function as magnetic pole pieces. Outside the discharge-chamber anode 203 parallel to the axis of the chamber are disposed permanent magnet bars 209. In order that the ions generated within the discharge chamber may be extracted efficiently, a permeance-density matched ion extraction system, comprising a plurality of specially perforated openings is attached to the end plate (magnetic pole piece) member 207 opposite

the cathode 201 by means of a plurality of suitable fasteners such as, for example, screws 211. It should be pointed out that the ion extraction system need not be the pervance-density matched type for proper operation of a thruster incorporating a cathode according to the invention. The operation of this type of ion thruster is thoroughly described in the referenced Kaufman article and will not be delineated here.

As previously described, the cathode 201 is provided with a forced-flow liquid-metal feed system and in this embodiment includes an expellant feed pipe 221 connected to the cathode 201 and to a pressure controlled mercury storage tank 223 which includes metallic bellows 225 and pressure controller 227 which controls the feed rate by adjusting gas pressure between the bellows 225 and the outer shell 229 of the storage tank 223.

The electrons required for the ionization of the expellant in a Kaufman-type electron bombardment ion source have heretofore been drawn from a thermionic cathode. The main obstacle which has heretofore blocked long cathode life in mercury electron bombardment ion thrusters is the difficulty in keeping the discharge voltage below the sputtering threshold of thermionic cathode materials as described previously. This problem does not exist when a forced-flow liquid-metal arc cathode is used. In this case, any liquid-metal atom sputtered from the liquid-metal cathode surface is replaced by the liquid-metal flow to the cathode. Furthermore, the liquid-metal atom efflux from the cathode provides the expellant which is subsequently ionized in the discharge and is required for the operation of the thruster. An additional important advantage of this scheme is the fact that it requires no phase separation in the expellant feed system. Finally, because the forced-flow liquid-metal arc cathode can be made independent of gravity as described above, it is suitable for operation of the thruster in a gravity-free environment such as free space.

In order to achieve a high expellant utilization in a Kaufman-type thruster, for example, the ratio of efflux of expellant atoms to electrons must be kept relatively small (typically between 0.1 and 0.05). To this effect, it is necessary to keep the evaporation from the inactive part of the liquid-metal surface small compared to the atom efflux from the active cathode spot. This requirement imposes a limitation on the size of the exposed liquid-metal surface area (cathode area)  $A_K$  and the cathode temperature  $T_K$  which can be expressed as follows: If  $p_x(T_K)$  is the expellant vapor pressure as a function of temperature,  $m_x$  the atomic mass of the expellant,  $e$  the electronic charge, and  $k$  is Boltzmann's constant, then in order to obtain an ion beam current  $I_B$  with an expellant mass utilization  $\eta_m$  the following inequality must hold:

$$A_K p_x(T_K) \cdot (2\pi m_x k T_K)^{1/2} \ll I_B / e \eta_m$$

From this relationship an upper limit may be obtained for the combination of cathode area and temperature permissible. Reference may also be made for details concerning the pervance-density matched ion extraction system to an article by W. O. Eckhardt, J. Hyman, Jr., G. Hagen, C. R. Buckey and R. C. Knechtli in the AIAA Bulletin 1, No. 1, p. 8 (1964) entitled "Research on Ion Beam Formation From Plasma Sources" and in another article by these authors entitled "Research Investigation of Ion Beam Formation from Electron Bombardment Ion Sources" printed in a Technical Summary Report, Contracts NAS 3-2511 and NAS 3-3564 (March 1964) available from NASA, Office of Scientific and Technical Information, Washington, D.C., Attention: AFSS-A.

Representative experimental results obtained with a Kaufman-type thruster of 20 cm. anode diameter, using a forced-flow liquid-mercury arc cathode of the divergent nozzle type shown in FIGURE 2, are as follows:

Expellant mass utilization—Up to 97%

Specific electrical power requirement for discharge—500 to 800 ev./ion

Discharge voltage—25 to 35 v.

Discharge current—2.5 to 30 a.

5 Ion beam current—250 to 800 ma.

Magnetic field—50 to 150 gauss

Electron to atom emission ratio for optimum thruster performance—15 to 20.

10 The use of the cathode invention in a high intensity liquid-metal arc lamp is shown in FIGURE 11. Hence there is shown a lamp body 300 comprising a parabolic reflector 301 mechanically supporting a quartz window 303 by means of an annular anode-cooling jacket member 305. Positioned at the focus point of the parabolic reflector 301 is a liquid-metal arc cathode 307 of the invention. The cathode is supported by a thermoelectric or liquid-cooling jacket structure 309 attached to plate 311. Plate 311 is adjustably positionable with respect to the focus point of the parabolic reflectors by means of focusing adjustment screws 313 and springs 315 seated on a lip 317 attached to the parabolic reflectors 301. A liquid-metal such as mercury is fed through passageway 319 in the cathode structure 307 by means of a recirculating line 321 connected to a pump and potential separator arrangement 323. Pump and potential separator 323 are connected to a reservoir area 325 for the liquid metal in the annular anode 305 by means of a feed line 327. The pump is regulated to provide a predetermined force feed of the liquid metal to the cathode 307 by means of a conventional feed rate controller 329 connected by a control cable 331 to the pump 323. An arc is struck from the surface of the liquid mercury in the area of the cathode 307 by means of an igniter electrode 333 supported adjacent the cathode 307 by the parabolic reflector 301.

From the foregoing, it will be seen that a forced-flow liquid-metal arc cathode is provided which may advantageously replace thermionic cathodes in many applications, and conventional pool cathodes in other applications, and which is not affected adversely by exposure to the atmosphere and which, if desired, is gravity independent.

45 In practicing this invention, any materials may be substituted for those specifically described which have the same characteristics or will perform the same function. Although several specific embodiments have herein been illustrated, it will be appreciated that other organizations of the specific arrangement shown may be made within the spirit and scope of the invention.

Accordingly, it is intended that the foregoing disclosure and the drawings shall be considered only as illustrations of the principles of this invention and are not to be construed in a limiting sense.

55 What is claimed is:

1. A liquid-metal arc cathode comprising a cathode structure having a liquid-metal pool zone therein, connection means on said liquid-metal arc cathode to connect said liquid-metal arc cathode to a source of liquid metal under pressure, the improvement comprising:

60 said liquid-metal pool zone having walls defining the lateral bounds of a liquid-metal pool within said pool zone, said liquid-metal pool zone being sufficiently small to permit a liquid-metal pool within said pool zone to be gravity independent, said walls being wettable by the liquid metal, said pool zone being positioned in said arc cathode so that the liquid-metal pool in said pool zone is accessible for arcing at the juncture of said walls and the liquid metal.

65 2. The liquid-metal arc cathode of claim 1 wherein at least one restricted flow opening is positioned in said liquid-metal arc cathode for conducting liquid metal into said liquid-metal pool zone.

70 3. The liquid-metal arc cathode of claim 2 wherein

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said restricted flow opening is formed as a part of said cathode.

4. The liquid-metal arc cathode of claim 2 wherein said restricted flow opening is a capillary bore.

5. The liquid-metal arc cathode of claim 4 wherein said cathode has a face, said capillary bore has walls intersecting said face, and said capillary bore walls adjacent said face are said pool zone defining walls which form said liquid-metal pool zone so that the liquid-metal pool is positioned between said walls when the liquid metal is participating in arcing.

6. The liquid-metal arc cathode of claim 5 wherein said capillary bore has an adjustable opening therein for adjustably delivering liquid metal between said passageway and the pool-keeping zone of said capillary bore.

7. The liquid-metal arc cathode of claim 2 wherein: said walls defining said pool-keeping zone are divergent walls, and said restricted flow opening is a capillary bore connecting said pool-keeping zone so that the liquid metal under pressure is communicated through said capillary bore into said pool-keeping zone having divergent walls;

said walls defining said pool-keeping zone being thermally connected so that at substantially constant arc current atom evaporation decreases when pool area decreases.

8. The liquid-metal arc cathode of claim 7 wherein said walls diverge at such an angle that the juncture of the liquid metal which wets the walls and the walls define a plane which lies above the free face of the liquid-metal pool.

9. The liquid-metal arc cathode of claim 7 wherein said divergent walls are substantially formed as a spherical section.

10. The liquid-metal arc cathode of claim 7 wherein said divergent walls are formed substantially of the surface of a truncated cone.

11. The liquid-metal arc cathode of claim 7 wherein said divergent walls are substantially formed as the surfaces of first and second adjacent truncated cones to form an annular liquid-metal pool zone.

12. The liquid-metal arc cathode of claim 2 wherein said at least one restricted flow opening is formed in a porous plug having a plurality of restricted flow openings therethrough.

13. The liquid-metal arc cathode of claim 2 wherein a passageway is connected to said restricted flow opening and a source of liquid metal under pressure is connected to said passageway so that a gravity independent reservoir of liquid metal is formed in said liquid-metal pool zone defined by said walls.

14. The liquid-metal arc cathode of claim 13 wherein flow control means is connected to said source of liquid metal to maintain said liquid-metal pool in said liquid-metal pool zone defined by said walls.

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15. The liquid-metal arc cathode of claim 1 wherein said cathode structure has a face, and wherein said walls defining said liquid-metal pool zone terminate at said face; said cathode structure being thermally arranged so that as liquid metal in the pool zone moves between said walls toward said face, the temperature of the liquid metal increases to increase liquid-metal evaporation, to substantially maintain pool position equilibrium along said walls while the cathode is operating as a liquid-metal arc cathode.

16. A liquid-metal arc cathode comprising:

a cathode structure having passageway means disposed therein to receive a liquid metal under pressure, the improvement comprising:

divergent liquid-metal pool-keeping walls positioned in said cathode to define the position of a liquid-metal pool zone between said walls so that liquid metal in the pool zone is accessible for arcing, and conducting means between said liquid-metal pool zone and said passageway means, said walls being wettable by the liquid metal,

feed means for feeding liquid metal to said pool zone through said conducting means to maintain a liquid-metal pool in said pool zone sufficiently small so that the atom to electron emission ratio of the liquid-metal pool in said zone is at least as low as 0.1 when said cathode is arcing into a space at subatmospheric pressure.

17. The liquid-metal arc cathode of claim 16 wherein the plane defined by the juncture of the walls and the liquid metal is positioned above the free face of the liquid metal.

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