United States Patent

Eckhardt

[54] **OFFSWITCHING OF LIQUID METAL ARC SWITCHING DEVICE BY INTERNAL CURRENT DIVERSION TO AN AUXILIARY ELECTRODE**

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Attorney—W. H. MacAllister, Jr. et al.

[57] **ABSTRACT**

An enclosed vessel containing one or more anodes, a main cathode, one or more auxiliary cathodes, and means for maintaining a low pressure in the tube comprises a liquid-metal arc switching device. The main cathode is fed with a metal which is liquid at convenient temperatures, so that limited quantities of the metal are present and available on the cathode for arcing. The interior of the vessel is maintained at a low background pressure so that, during nonconduction, vacuum space insulation is provided between the anodes and the cathodes. Arc initiation is accomplished by any convenient initiator, and the arc runs upon the small amount of liquid metal fed at an appropriate rate to the main cathode. For arc extinction, at least one auxiliary cathode is positioned within the envelope.
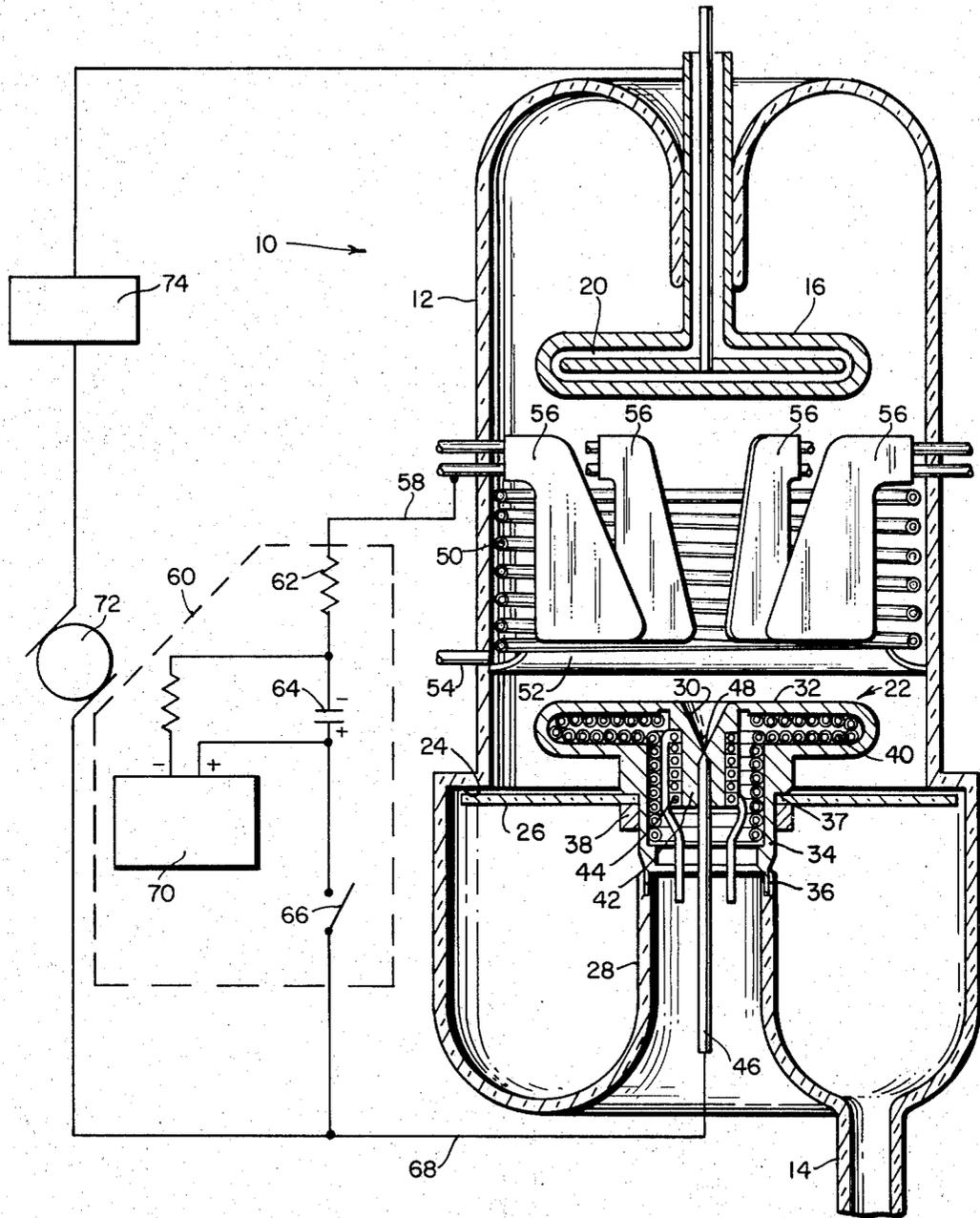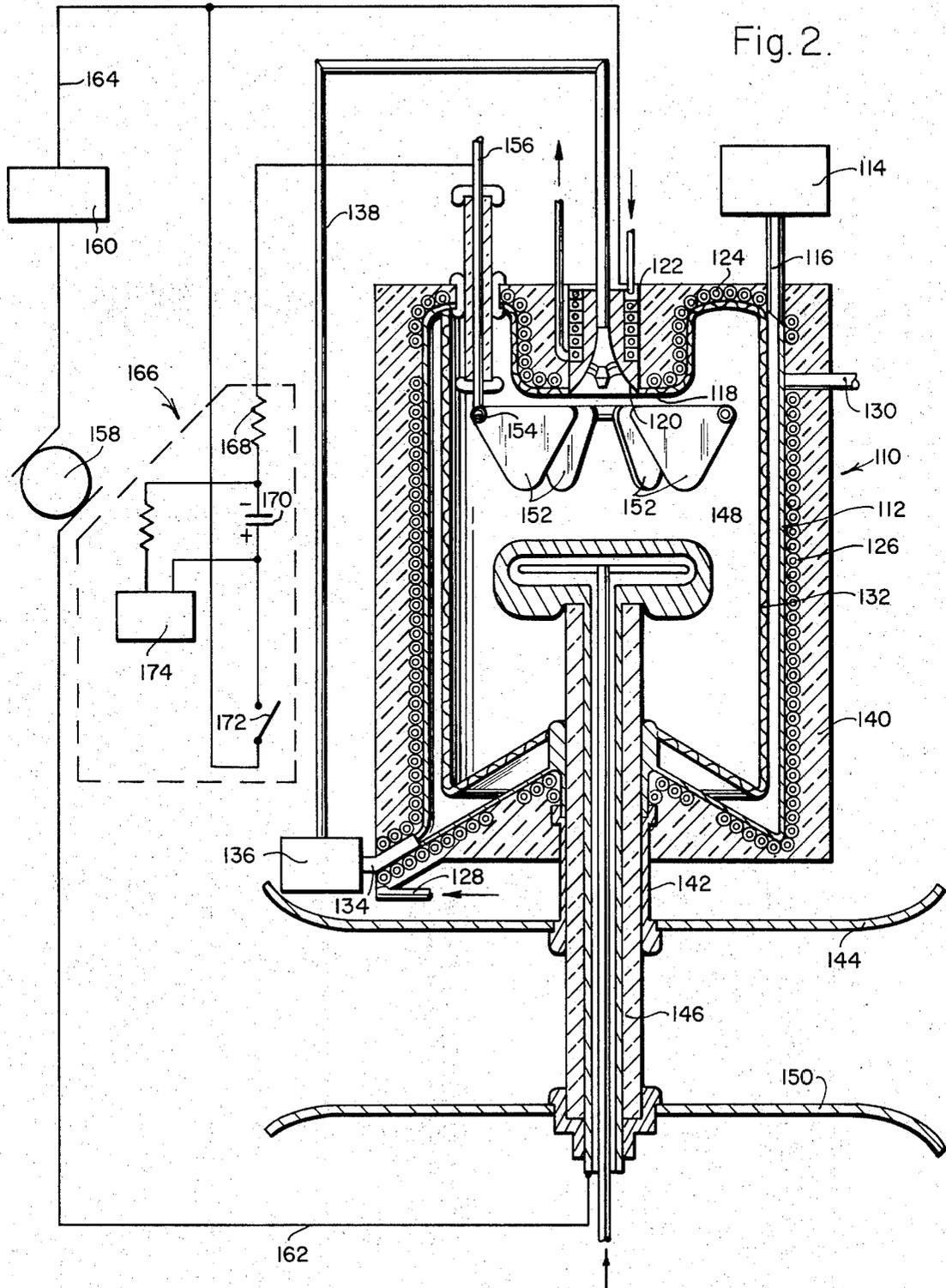
16 Claims, 2 Drawing Figures
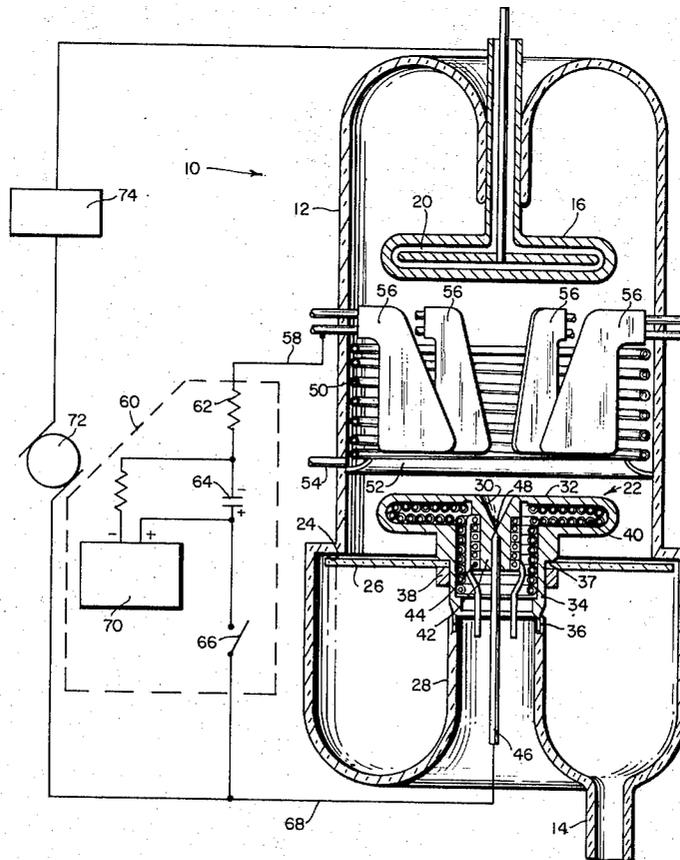
Fig.1.

Fig. 2.

OFFSWITCHING OF LIQUID METAL ARC SWITCHING DEVICE BY INTERNAL CURRENT DIVERSION TO AN AUXILIARY ELECTRODE

BACKGROUND

This invention relates to the field of liquid-metal arc rectifiers and liquid-metal cathode switching devices.

Mercury arc rectifiers are well-known in the art. They suffer from numerous problems, which problems primarily stem from the fact that a large mercury pool is present in the device, and this large mercury pool maintains, through evaporation, a fairly high background pressure within the rectifier vessel. In commercial devices, the pool temperature is kept as low as is practical and as is consistent with arc operation, in order to maintain this background pressure as low as is possible. However, despite this, at the pool temperature usually found in such devices, there is sufficient mercury vapor within the tube that deionization is slow upon voltage reversal. This, in turn, causes arcing back from the anode to the cathode, unless the rate of voltage rise is kept very low, which is highly objectionable regarding the circuit in which the device is used.

To overcome this limitation, state-of-the-art high voltage mercury tubes are provided with grading electrodes. These grading electrodes lead to another limitation: the current which can pass to one anode through such a set of grading electrodes is limited to such extent that for higher currents a number of parallel anodes and sets of grading electrodes are required. These limitations then lead to the need for complex multi-anode tubes (with current-dividing transformers to divide the current uniformly between parallel anodes) and grading electrodes with attendant voltage dividers.

The voltage holdoff properties of the conventional mercury pool liquid cathode devices are determined by a trade-off between the desired voltage holdoff, the peak current, the voltage drop across the arc, and voltage recovery rates. These conflicting requirements do not permit the device to be designed for high voltage holdoff and high current without the complex grading electrodes and the multiple anodes mentioned above.

Furthermore, the only prior art mercury arc rectifiers and switching devices capable of forced current interruption against a voltage persisting in the forward direction are those described in U. S. Pat. No. 3,586,904, granted June 22, 1971, entitled "Offswitching of Liquid-Metal Arc Switching Device by Auxiliary Arc Liquid-Metal Starvation," by W. O. Eckhardt. Compared with this auxiliary-arc method, the present offswitching method has the advantage of less time delay. All other prior art devices which accomplish offswitching fall into two classes. The first class is one wherein current diversion in the external circuit permits or causes offswitching of the switching device. Such external circuit current diversion is applicable for offswitching of most conventional devices. Examples are found in all types of switches, from mechanical switches to thyristors. In the second class of switching device, offswitching occurs within the switching device. There have previously been only three known kinds of devices which were capable of doing this. These three devices are transistors, high-vacuum electron tubes, and magnetically-switched gas-filled tubes using glow discharges or thermionic cathodes. The liquid-metal arc switching devices as disclosed here are capable of several different modes of operation leading to off switching. In all of these, the present structure has a reduced energy storage requirement, as compared to the first class of device described above. With respect to devices of the second class, the switching device of the present invention has a far superior conduction efficiency in high-power applications, or much higher power handling capability, or much longer life, or combinations of these properties.

SUMMARY

In order to aid in the understanding of this invention, it can be stated in essentially summary form that it is directed to a switching device including an enclosing tube or vessel in which are located one or more anodes, a liquid-metal main cathode, one or more auxiliary cathodes, and means for maintaining a low pressure in the tube. The main cathode is fed with a low arc-voltage metal which is liquid at convenient temperature, so that a small quantity of this metal is available on the cathode to permit a current-carrying arc to run between the main cathode and the anode or anodes. When forced interruption of this current is desired, a connector is provided to the auxiliary cathode to make it negative with respect to the main cathode, in order to draw ions from the arc plasma, which ions impact the auxiliary cathodes and cause secondary electron emission. When this secondary electron current exceeds the amount emitted by the main cathode, the direction of the main cathode current is reversed. This current reversal causes extinguishment of the arc spots on the liquid-metal main cathode. This extinguishment offswitches the arc from the main cathode, which cuts off the ion supply to also cause offswitching from the auxiliary cathode.

Accordingly, it is an object of this invention to provide a liquid-metal arc switching device which is capable of offswitching by providing an electric discharge between an auxiliary cathode and the anode, resulting in offswitching of the main cathode-to-anode arc, followed by offswitching of the auxiliary cathode-to-anode discharge. It is a further object to provide a liquid-metal cathode switching device which accomplishes offswitching by main arc ion impingement upon one or more auxiliary cathodes to create secondary electrons which, in turn, produce a secondary discharge which permits offswitching of the main arc followed by offswitching of the auxiliary discharge. It is still another object to provide a switching device wherein auxiliary cathodes are incapable in themselves of producing sufficient electrons to support a discharge, but a discharge is produced between the auxiliary cathodes and the anode by impingement of ions from the main arc, causing the production of secondary electrons.

Other objects and advantages of this invention will become apparent from a study of the following portion of the specification, the claims and the attached drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a longitudinal section through a liquid-metal arc switching device having six auxiliary cathodes therein, and schematically showing the electric circuit in association therewith.

FIG. 2 is a longitudinal section through another liquid-metal arc switching device of a different configuration, also having six auxiliary cathodes therein, and with a schematic electric circuit shown in association therewith.

DESCRIPTION

Referring to FIG. 1 of the drawings, the liquid-metal arc switching device is generally indicated at 10. The term "switching device" is used to generally describe a device which is capable of initiating and/or interrupting current flow in a circuit. This includes circuits wherein the current reaches a natural zero by means independent of an exterior of the switch tube, as well as devices in which the current zero is accomplished by the switch tube by an increase in voltage thereacross by arc cessation. The first case includes rectification of alternating current, and the second case includes DC circuit breakers and forced commutators for converting DC to AC, as well as current-limiting AC circuit breakers. Thus, the device itself inherently interrupts current flow upon voltage reversal and can be operated to interrupt current without current or voltage reversal. For these reasons, the term switch device is used generally to define the scope of such devices.

The switch device 10 includes an envelope 12 which serves as a vessel or a tube within which the primary components of this switch device are located. Vacuum pump connection 14 is provided on the envelope 12 to either originally pump down the non-condensable gases after manufacture, whereupon it is sealed, or can be continuously pumped to maintain the desired low background pressure of non-condensable gases.

Anode 16 is positioned within the envelope and has an external connector which extends externally of the envelope for electrical connection. Anode 16 is shown as being in the shape of a flat circuit disc so that a maximum area is exposed to the electrically conducting plasma. Anode 16 is preferably provided with heat exchange passage 20. Flow of coolant through passage 20 controls the temperature of anode 16 to prevent extreme temperature excursions. Anode 16 is preferably maintained at a temperature above the condensation temperature of the liquid metal, hereinafter described, so that condensation does not occur thereon. Such condensation leads to arc-back situations, and is thus undesirable. Heating of the anode is caused by its absorption of the kinetic energy of the plasma particles, by the recombination energy of electrons and ions, and by the I^2R drop of the current flow through the anode material. Thus, at high currents, cooling fluid flow may be necessary through heat exchanger passage 20 to prevent the anode from reaching destructive temperatures. On the other hand, at low loads, heating fluid flow through heat exchange passage 20 may be necessary to maintain anode 16 above the liquid-metal condensation temperature. Heat exchange passage 20 is conventionally externally connected and is controlled by any convenient temperature-sensing means responding to the temperature of anode 16.

Envelope 12 is made at least partially of insulative material to provide electrical separation of the envelope walls between anode 16, condenser 50, and cathode 22. The envelope extends downwardly, as shown in the drawing, from anode 16 to below cathode 22. Offset 24 provides an internal offset adjacent which

insulating disc 26 is positioned. Envelope 12 continues downward below offset 24 as a cylindrical tube, and curves inward and upward to form tubular re-entrant section 28. Cathode 22 can be any of the cathodes described in W. O. Eckhardt U.S. Pat. No. 3,475,636.

Cathode 22 is made of a metal which is a high arc voltage material, as compared with the liquid metal used in connection with it. The term arc voltage is defined as arcing voltage in U.S. Pat. No. 3,475,636, and in *Proceedings of the Institute of Electrical Engineers*, Volume 110, No. 4, April 1963, pages 796–797, Section 4.6. Furthermore, the metal of the cathode structure must be compatible with the liquid metal. Cathode 22 has pool-retaining walls 30 against which the liquid metal is located and against which the arc runs, at the juncture or junctures between walls 30 and the liquid metal. Above the walls, cathode 22 has a front face 32, which is substantially in the form of a planar disc. Below the front face 32, cathode 22 extends downwardly in a reduced diameter tubular neck 34 which is sealed to tubular re-entrant section 28 of the envelope by means of an appropriate seal joint 36. In the embodiment shown, cathode 22 has a shoulder 37 positioned between the larger diameter front face and neck 34. Insulating disc 26 rests against this shoulder and is maintained in place by retainer 38. Other geometries of wall 30 than the one shown in the drawing can also be employed.

Heater 40 is located within the hollow interior of the cathode behind front face 32, and extends around the outer periphery, down inside of shoulder 37 and into neck 34 so that the entire exposed area of the cathode away from walls 30 can be controlled in temperature. The central portion of the cathode, below the recess formed by walls 30, extends downward to form neck 42, and heat exchanger 44 is positioned exteriorly of the neck. Both heater 40 and heat exchanger 44 have suitable connections extending downward within tubular re-entrant section 28 to permit external connection and temperature control. If desired, temperature sensors can be mounted so that accurate temperature determinations of the respective portions of the cathode 22 can be made.

The liquid metal required on the surface of the cathode structure for arcing can be provided either by feeding of metal in the liquid state or by intermediate vaporization and recondensation.

The term "liquid metal" is used to define those metals which are liquid at or just somewhat above room temperature. While called liquid metal, the metal is not necessarily in the liquid state when fed to walls 30 which define pool-keeping surfaces. Mercury is a convenient liquid metal, because it is normally liquid at room temperatures. Furthermore, it has a suitably low arc voltage. Thus, the arc preferentially strikes upon the liquid metal when the external surfaces of cathode 22 are formed of a relatively high arc voltage material. Additional materials which are suitable to act as the liquid metal fed to cathode 22 are exemplified by cesium, lithium, and gallium. If necessary, liquid-metal feed line 46, and associated equipment to provide the liquid metal thereto can be heated to maintain the liquidity or vapor state of the liquid metal.

As indicated, cathode 22, as well as anode 16, are preferably formed of high arc voltage materials. When

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mercury is employed as the liquid metal, molybdenum serves As a suitable material for the anode and cathode. Liquid-metal feed line 46 extends from a source of liquid metal of such nature as to provide the proper flow rate of liquid metal to cathode 22, as hereinafter described. Liquid-metal feed line 46 extends up through the re-entrant section 28, and in the example of the drawings, is connected centrally of cathode 22 to feed the liquid metal to the space defined between walls 30. If desired, a suitable flow restriction 48 can be positioned at the lower juncture of walls 30 with the opening therebelow connecting to feed line 46 to impede liquid-metal flow to the space defined between walls 30. When liquid metal is fed to the space in its liquid state, a porous flow restriction is desirable for it prevents an arc from extending down into the feed line when the pool between walls 30 is exhausted. However, when the liquid metal is fed in vapor form, a flow restriction in the form of a capillary passage is preferred, with the capillary somewhat larger than the passages through the porous mass employed in the example for liquid feeding.

Additionally, within envelope 12 condenser 50 is located. It serves as one means for continuously removing from the tube the metal vapor emitted by the cathode. Condenser 50 is suitably externally connected to maintain the desired temperature upon the condenser surface, as described below. When condenser 50 is maintained at a temperature to condense the metal to the liquid state, it is collected by trough 52, and can be recirculated to the cathode. In the case of recirculation of the liquid metal, it can be drained out through line 54, and an appropriate isolator will be required in the recirculation line.

Auxiliary cathodes 56 are also located within envelope 12. Since the plasma jet emerging from the main cathode 22 is substantially in the form of a solid cone having its apex on the main cathode, the auxiliary cathodes 56 are arranged as thin radial fins protruding into the plasma cone. The protrusion is slight enough that, during normal conduction of current from the main cathode 22 to the anode 16, auxiliary cathodes 56 do not substantially interfere with the operation. Six auxiliary cathodes 56 are illustrated. They are illustrated as being connected for cooling by the circulation of a suitable coolant therethrough, if desired. Each of the auxiliary cathodes 56 is connected to line 58 which, in turn, is connected to a source of electric current 60.

Source 60 comprises current-limiting resistor 62, capacitor 64, and control switch 66 connected in series. Switch 66 is connected through cathode line 68 to cathode 22. Capacitor charging power supply 70 is connected across capacitor 64 to charge the capacitor. Supply 70 is illustrated as feeding through a charging resistor, but may instead be an inherently current-limiting supply.

The normal connection to the switch device 10 comprises a series connection through cathode line 68, source of electric current 72, load 74, and anode 16. Through these connections, the switching device 10 controls the current from generator 72 through load 74. When switching device 10 is offswitched, the series connection is opened and load current ceases.

The pressure within envelope 12 is pumped down through a vacuum pump connection 14, before the

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device is put into use. In some cases, when the contents of the envelope have a minimum of out-gassing, the envelope can be sealed by closure of connection 14. In other cases, it may be desirable to keep the connection with a vacuum pump so that non-condensables can be pumped down when operation of the device so indicates.

The arc is initiated by any convenient means. No specific arc initiator is disclosed in the drawings, but those well-known in the art can be used. Examples of such are auxiliary electrode igniters, semiconductor igniters, and the like. Alternatively, a laser igniter directed onto the liquid-metal surface is suitable, as is an igniter which emits a puff of liquid-metal plasma into the space between the anode and the cathode to initiate arcing.

Presuming that a suitable voltage is applied across the anode-to-cathode space, and liquid metal is available on the cathode walls 30, the ignition of the device will cause conduction. The amount of liquid metal available on walls 30 for evaporation is kept purposely low so that the electron-to-atom ratio is high. As a consequence, the pressure in the envelope will remain relatively low, even during conduction. A typical pressure during non-arcing for mercury as the liquid metal is 5×10^{-6} Torr.

Heater 40 maintains the face of the cathode sufficiently hot that liquid-metal condensation cannot occur there. Similarly, the temperature of the pool-keeping walls 30 is controlled by heat exchanger 44. In cases where a liquid-metal pool is desired, heat exchanger 44 cools the pool-keeping walls to prevent excessive evaporation, especially in the case of high currents where the arc introduces a considerable amount of heat into the pool-keeping structure. In cases where the arc current is low, it may be necessary to heat the pool-keeping walls, especially in the case where the liquid metal is fed in vapor form to the walls 30. In such a case, the walls 30 are preferably slightly above the equilibrium condensation temperature of the liquid-metal vapor at that pressure. Thus, only transient condensation can occur. Transient condensation, in this sense, is a situation wherein superheated metal vapor deposits upon the wall in a thin film over a portion of the area, with such condensation occurring for a short time. However, since the surfaces are above the equilibrium condensation temperature, no condensation or droplets or masses of metal occurs. Instead, liquid metal is continuously deposited and evaporated off, and occupies only a portion of the wall area at any one time. This mode of operation is described in detail in U. S. Pat. No. 3,538,375: "Vapor-Fed Liquid-Metal Cathode," by W. O. Eckhardt.

As stated above, heat exchanger 40 keeps the remainder of the cathode above condensation temperature to prevent metal pools from forming thereon to prevent the arc from acting on any surface but the walls 30. In addition, the heating prevents metal condensation at the juncture between neck 34 and tubular re-entrant section 28, for arcing at this juncture would be destructive. Additionally, insulating disc 26 prevents any appreciable quantity of the metal vapor from reaching that juncture in order to prevent the destructive arcing.

Condenser 50 is positioned to condense metal vapor in order to prevent a buildup of vapor pressure within envelope 12. In the case of mercury, in order to maintain the metal vapor pressure within the tube in the absence of arcing below 10^{-5} Torr, when it is desired to retain the condensed mercury in the liquid state, the temperature of condenser 50 is maintained at about 240° K. When a lower pressure is desired, a lower condenser temperature can be used, resulting in solidification of the condensed mercury. In the latter case, the condenser can be periodically warmed to permit liquid mercury to drain out of the bottom of trough 52 through drain 54.

In operation, switch 66 is open, and the main circuit electron current passes from main cathode 22 to anode 16 and thence through load 74 and source 72. When offswitching is desired, switch 66 is closed. Thereupon, capacitor 64 supplies voltage which makes the auxiliary cathodes from several hundred to several thousand volts negative with respect to the main cathode 22. Capacitor 64 is capable of supplying, for a short time, a current which exceeds the main circuit current. Ions are extracted by the auxiliary cathodes from the plasma jet issuing from the spot on the main cathode 22. These ions bombard the auxiliary cathodes 56 to cause the emission of secondary electrons. Because the source 60 makes available for emission by the auxiliary electrode a current which exceeds the main circuit current, and because the source 60 also provides a sufficient driving voltage to actually inject this current into the plasma, the current flowing through the main liquid-metal cathode 22 momentarily reverses direction. This causes arc spot extinction on the liquid metal. With arc spot extinction, the plasma jet disappears, so that there is no further ion bombardment of the auxiliary cathodes 56. The switching device then reverts to high vacuum and all currents through the tube are interrupted.

From an understanding of this operation, it is important that the auxiliary cathodes 56 are of such shape, material, and thermal condition that no arc spot will form thereon. Molybdenum is a suitable metal, as discussed above. The shape illustrated in FIGS. 1 and 2, that of flat panels edgewise-directed toward the plasma jet, is preferred. This type of structure permits achievement of sufficient coupling with the plasma jet of the liquid metal cathode, while maintaining a high pumping speed for the condenser 50. The thermal design of the auxiliary cathodes 56 must be such that they are neither heated to thermionic emission temperature by the plasma jet nor kept so cold that liquid metal will condense on their surfaces.

In order to prevent the formation of arc spots on the metal surfaces of any of the electrodes 16, 22, and 56, the rate of voltage rise between these electrodes must be limited. An upper limit is on the order of 10 kilovolts per microsecond, when the electrodes are formed of molybdenum.

FIG. 2 illustrates liquid metal arc switching device 110. It comprises an envelope 112 which is in the form of a metal vessel. Vacuum pump 114 is connected to the vessel by means of pipe 116 to maintain the interior of the vessel at a sufficiently low pressure by removing the non-condensables. The upper wall of vessel 112 extends downward into the vessel to join the face of cathode 118. The pool-keeping walls 120 are the same

as those shown at 30 in FIG. 1 and in U.S. Pat. No. 3,475,636. Cooling coils 122 are provided to maintain the pool-keeping walls 120 at the appropriate temperature, either for the maintenance of a liquid pool against the pool-keeping wall, or to permit the transient condensation of vapor thereon, as previously described with respect to cathode 22. Normally, coils 122 will be cooling coils, in order to maintain the proper thermal equilibrium. Behind cathode face 118 and extending along the top of vessel 112 are heater coils 124. These heater coils prevent condensation of liquid metal to thus prevent the arc from running anywhere on the upper surface of the vessel away from the juncture between pool-keeping walls 120 and the liquid metal fed thereto.

The outer peripheral wall, as well as part of the lower wall of vessel 112, form the condenser surface by having cooling coils 126 secured thereto. These cooling coils are provided with a circulating coolant which has an inlet at 128 and an outlet at 130 to maintain the associated wall sufficiently cool to act as a condenser surface for the liquid metal vapor. The vessel can be at cathode potential, provided the screen 132, positioned interiorly of the condenser portion of the vessel wall is also close to or at cathode potential. More generally, the cathode could be isolated electrically from the vessel walls, and the vessel walls could be kept at an arbitrary or floating electrical potential, so long as the potential of screen 132 is close or equal to the potential of the vessel walls. Furthermore, screen 132 is heated to such a temperature that no liquid metal condenses on it. The purpose of screen 132 is to electrostatically shield the condenser walls of vessel 112 upon which liquid metal is condensing, so that virtually no electric field exists on the surface of the liquid metal condensed on the walls of vessel 112. By limiting the electric field, the formation of arcs to the condensed liquid metal is avoided, even when the wall potential is negative with respect to the anode potential.

Condensed liquid metal runs down the vessel side walls and bottom walls to liquid metal outlet 134. Liquid metal outlet 134 is connected to liquid metal pump 136, which may be of the type shown in H. J. King U.S. Pat. No. 3,444,816. When the condenser is at cathode potential, no isolator is necessary in the liquid metal return line 138 to the cathode, as shown in FIG. 2. However, should the condenser be at a different potential from the cathode and liquid metal recirculation is desired, a liquid feedline isolator, such as shown in H. J. King et al. U.S. Pat. No. 3,443,570, may be employed.

In addition to the single tubular cylindrical screen 132 shown, a plurality of concentric screens can be employed. Such plurality of concentric screens could be voltage-graded, if desired. Thermal insulation 140 surrounds the entire vessel 112, in order to maintain the different portions thereof at the desired temperatures.

Tubulation 142 extends from the bottom of the vessel. On its lower end, it carries corona shield 144. Insulator tube 146 is carried in vacuum tight connection within tubulation 142. An anode 148 is mounted through insulator tube 146. Anode 148 is identical to anode 16, except for its mounting. The lower end of the support tube of anode 148 carries corona shield 150 at anode potential.

Auxiliary cathodes 152 are mounted upon mounting ring 154. The auxiliary cathodes and mounting ring are supported to face main cathode 118 with the auxiliary cathodes individually comprising fairly flat plates positioned edgewise to the plasma jet which issues from the main cathode in operation. Thus, the auxiliary cathodes 152 are similar to the auxiliary anodes 56.

Ring 154 is mounted upon conductor 156, which passes through the vessel in electrically insulated relationship thereto, but maintaining the vacuum integrity of the vessel. Power source 158 and load 160 are serially connected by lines 162 and 164 to the anode and cathode. Thus, currents generated at source 158 and employed at load 160 pass through the switching device 110 so that offswitching the device cuts off load current. Auxiliary source 166 is connected between conductors 156 and 162. The auxiliary power supply 166 is identical to the power supply 60 illustrated in FIG. 1. Thus, it contains serially connected current limiting resistor 168, capacitor 170, and switch 172. Capacitor-charging power supply 174 is connected across capacitor 170, in order to charge it.

The pressure within the vessel is maintained sufficiently low that, when arcing occurs, it occurs in the vacuum arc mode. The vacuum arc mode is broadly defined as an arc having electrons, positive ions, and neutrals supplied in a plasma jet by arc spots within a vessel having a background pressure sufficiently low that it does not substantially affect the trajectories of the atoms and ions in this plasma jet. In the vacuum arc mode, there must be negligible non-condensable gas present in the vessel. Thus, when the arc becomes extinguished, the pressure in the arc space returns to a sufficiently low value to provide high electric field holdoff. To maintain the pressure sufficiently low for vacuum arc mode of operation, the vessel must not contain large areas of liquid metal (or other material) available for evaporation into the atmosphere of vessel.

The background pressure in the vessel during non-arcing and during arcing is sufficiently low that the mean free path of the gas molecules or atoms of the background gas is large, compared with the greatest dimension of the arc. The vacuum arc is therefore dependent for the atmosphere in which it burns on the emission of metal vapor and plasma from its cathode spots in the form of a plasma jet. This plasma jet being essentially electrically neutral, because of the presence of a sufficient number of positive ions to substantially neutralize the electronic space charge, the discharge runs at a low arc voltage.

Current between the plasma jet and the anode is carried by the plasma electrons reaching the anode. Neutral metal vapor from the cathode condenses on the condenser, as well as ions reaching the condenser from the plasma jet.

Conditions in the vacuum arc plasma are characterized by the fact that the vacuum arc depends for its plasma on the metal vapor emitted from its own cathode spots, and that this plasma and metal vapor are emitted from the region of the cathode spots in the form of a jet. It is by these characteristics that the vacuum arc differs most markedly from the more common low pressure arc.

The pressure within the vessel is maintained sufficiently low that, when arcing occurs, it occurs in the

vacuum arc mode. As discussed above, the vacuum arc mode is broadly defined as having electrons, positive ions, and neutrals supplied by the arc spot, and the background pressure within the vessel is sufficiently low that it does not substantially affect the trajectories of the atoms and ions emitted from the arc spots.

To provide the vacuum arc conditions described above, the pressure in the background volume outside of the plasma jet should not exceed about 10^{-3} Torr or less. A condenser temperature of about $-10°$ C or less is necessary, when mercury is used as the liquid metal, depending on current. A preferred condenser temperature for mercury is about $-35°$ C, which corresponds to just-liquid mercury on the condenser surface, and permits to attain a pressure as low as 5×10^{-6} Torr during non-arcing.

The arc is initiated by any convenient means, including those well-known in the art, such as auxiliary electrode igniters, semiconductor igniters, and the like. A laser igniter directed onto the liquid-metal surface is suitable. Alternatively, an igniter which emits a puff of plasma into the space between the anode and the cathode to initiate arcing can also be used. Plasma puffers are well-known. One is described in detail in an article by Winston H. Bostick, entitled "Plasma Motors," at pages 169 through 178 in the proceedings of the *CONFERENCE ON EXTREMELY HIGH TEMPERATURES*, edited by Fischer and Mansur and published by Wiley, 1958. Other suitable igniters are described in *GASEOUS CONDUCTORS*, by James D. Cobine, Dover Publications, New York, 1941, particularly at pages 421–426. Once the arc is initiated, a conical plasma jet is emitted from the liquid metal cathode. This plasma jet contains electrons, ions, and neutral particles. The jet issues forth from the arc spots on the liquid metal. The anode is positioned in such relationship with the plasma jet cone that it intercepts electrons, ions, and some of the neutral particles. The anode is positioned in such a relationship with the plasma jet that it intercepts a sufficient fraction of the jet to provide good electrical coupling to the jet. The anode is shown as being in the shape of a flat circular disc so that a maximum area is exposed to the electrically conducting plasma. The anode in each embodiment is preferably hollow so that its temperature can be controlled by means of a circulating liquid or of a heat pipe to prevent extreme temperature excursions. The anode is preferably maintained at a temperature above the condensation temperature of the liquid metal, so that condensation does not occur thereon. Such condensation leads to arc-back situations under voltage reversal and is thus undesirable. Heating of the anode is caused by its absorption of the kinetic energy of the plasma particles, by the recombination energy of electrons and ions, and by the I^2R drop of the current flow through the anode material. Thus, at high currents, cooling may be necessary to prevent the anode from reaching destructive temperatures. On the other hand, at low loads, heating may be necessary to maintain the anode above the liquid-metal condensation temperature. A heat exchanger is conventionally externally connected to the anode and is controlled by any convenient temperature-sensing means responding to the temperature of the anode. The anode heat exchanger structure shown in the drawings is exemplary. Any well-known heat exchanger structure can be employed.

The condenser rapidly captures the metal vapor emitted by the cathode and scattered by the anode so that the background pressure inside of vessel 112 remains low. Furthermore, the small liquid metal area adjacent to the pool-keeping wall is sufficiently small and maintained at sufficiently low temperature that the evaporation therefrom does not adversely affect the pressure inside the vessel, this pressure being maintained sufficiently low that vacuum arc conditions are maintained, that there is no substantial interference with the plasma jet, and that low enough pressure can be maintained to prevent breakdown. Electrons are extracted from the plasma cone and captured on the anode to thus cause current conduction.

One advantage of vacuum arc operation, as defined above, is that, as a result of being able to employ a high electron-to-atom emission ratio cathode in conjunction with the condensing means, faster hold-off voltage recovery rates (i.e., rates substantially in excess of 1–2 kV/μ second) and higher hold-off voltages are possible following higher conduction currents than are possible in any other existing single gap, single anode switching device. A further advantage of operation in the vacuum arc mode is that, when arcing ceases, the jet of particles from the arc spot is rapidly captured on the condenser so that the space between the anode and the cathode very quickly returns to vacuum conditions wherein the vacuum has high insulative value. This also favors rapid application of reverse voltage without conduction, at a rate of voltage rise substantially in excess of 1–2 kV/μ second.

Offswitching is accomplished by charging condenser 170 to a sufficient value that, once switch 172 is closed, the auxiliary cathode 152 is made negative with respect to the main, liquid-metal cathode 118. This extracts ions from the plasma jet extending from the arc spots on the liquid-metal cathode, which ions bombard the auxiliary cathode 152 to produce the emission of secondary electrons. Because the combination of capacitor 170 and resistor 168 makes available for emission by the auxiliary cathode 152 a current which exceeds the main circuit current, and because this source also provides a sufficient driving voltage to actually inject this current into the plasma, the current flowing through the liquid-metal cathode momentarily reverses its direction. This causes arc spot extinction on the liquid-metal cathode. With extinction, the plasma jet disappears, and the vessel reverts to a high vacuum. With the disappearance of the plasma jet, there are no more ions available to cause secondary electron emission from the auxiliary cathode, and all currents through the tube are interrupted.

Again, it is important that the auxiliary cathode be of such shape, material composition, and thermal condition that no arc spot can form on it.

To maintain stable current flow in the device under the desired condition of high electron-to-atom emission ratio at the main cathode, it is desirable to operate at approximately constant electron-to-atom emission ratio. To obtain this effect, the feeding of the liquid metal must be proportional to the arc current. When the average current is constant, the liquid metal can be fed at a constant rate.

The pressure within the envelope is pumped down through a vacuum pump connection, before the device is put into use. In some cases, when the contents of the envelope have a minimum of out-gassing, the envelope can be sealed by closure of connection. In other cases, it may be desirable to keep the connection with a vacuum pump so that non-condensables can be pumped down when operation of the device so indicates.

In the case of mercury, the condenser temperature is kept substantially below 0° C, and a preferred condenser temperature is about −35° C, this being just above the melting point of mercury and permitting the maintenance of a background pressure as low as 5×10^{-6} Torr during prolonged non-arcing periods. In order to maintain a background pressure of 10^{-3} Torr or less during arcing, the condenser surface area must be such that, when the total flux of metal vapor emitted by the main cathode (and scattered by the auxiliary cathode and the anode) is distributed over the condenser area, the particle flux in front of the condenser corresponds to the desired pressure. For example, if the liquid metal is mercury, the discharge current is 1,500 Angstroms, and the cathode emits 100 electrons per atom, a suitable condenser area is 1,500 cm².

When a lower pressure than that corresponding to the melting point of the liquid metal is desired, a lower condenser temperature can be used, resulting in solidification of the condensed metal. In the latter case, the condenser can be periodically warmed to permit liquid metal to drain out of the bottom of the vessel through the drain.

Moreover, the offswitching concept disclosed here is not limited to devices using *liquid*-metal arc cathodes. It is equally applicable to arc devices using *solid*-metal cathodes, such as vacuum relays and triggered vacuum gaps. In conventional design of such devices, the end of a rod-shaped cathode faces the end of a rod-shaped anode. Such solid-cathode vacuum arc devices are not normally capable of offswitching substantial currents against a persisting voltage in the forward direction, but by interposing one or more auxiliary cathodes between the anode and main cathode and providing an electrical connection as described above, these devices can be operated to offswitch their full conduction current. Examples of suitable shapes for the auxiliary cathodes are those shown in FIGS. 1 and 2. The disadvantage of a solid-cathode arc device, compared with a liquid-cathode arc device is, of course, the limitation on the total charge which can be conducted through the device before its insulators become shorted out by recondensed cathode material.

While the offswitching mode described above (where no arc spot is permitted to form on the auxiliary cathode) is the preferred one because of its high switching speed, the device disclosed here is capable of offswitching even when an arc spot does form on the auxiliary cathode. Two cases can be distinguished:

1. If a small amount of liquid metal has condensed on the auxiliary cathode, an arc spot may form on it under ion bombardment from the main cathode jet when switch 66 (or 172, respectively) is closed to initiate offswitching. Current transfer from the main cathode to the auxiliary cathode will then take place as usual, but electron emission from the auxiliary cathode will not cease automatically when the main cathode jet disappears. Nevertheless, electron emission from the auxiliary cathode will terminate, depending on which of the

following conditions occurs first, when either (a) the capacitor 64 (or 170) has been charged to essentially the full open-circuit voltage of source 72 (or 158) in the opposite polarity of the original charge, or when (b) the condensed liquid metal has been consumed by the arc spot on the auxiliary cathode, provided the rate of voltage rise across the switching device is limited (as stated previously) to prevent transfer of the arc spot to the base metal of the auxiliary cathode.

2. If the maximum current density for secondary electron emission from the auxiliary cathode ($\leq 20A/cm^2$) is exceeded, e.g., during an attempt to offswitch an overload current in the main circuit, an arc spot may form on the base metal of the auxiliary cathode. Here, too, current transfer from the main cathode will take place, and the spot on the auxiliary cathode will extinguish when capacitor 64 (or 170) has been charged to essentially the full open-circuit voltage of source 72 (or 158), as just described for case (1a).

If the offswitching ability of the device is to be preserved only when condition (1b) occurs, but abandoned in cases (1a) and (2), the voltage rating of capacitor 64 (or 170) may be kept substantially below that of source 72 (or 158). This can be accomplished by paralleling the capacitor with a spark gap which limits the voltage to a level only slightly above that of power supply 70 (174).

If, on the other hand, it is desirable to use a smaller auxiliary-cathode surface area than that determined by the current-density limit for secondary electron emission, while the rating of capacitor 64 (or 170) for the full main-circuit source voltage is not objectionable and some reduction in switching speed can be tolerated, then the interruption modes (1a), (1b), or (2) may be used in normal operation of the switching device, rather than only under overload or other fault conditions.

This invention having been described in its preferred embodiment, it is clear that it is susceptible to numerous modifications and embodiments within the ability of those skilled in the art and without the exercise of the inventive faculty. The disclosures of each of the patents and publications referred to above are incorporated in their entirety in this specification by this reference.

What is claimed is:

1. An electric switching device comprising:
an enclosing vessel, an anode, a liquid metal cathode, and a condenser within said vessel, feed means for feeding liquid metal to a surface on said cathode, means for maintaining a subatmospheric pressure within said vessel, cooling means for cooling said condenser so that arcing from the liquid metal on the cathode produces a substantially conical plasma jet, said anode being positioned to intercept at least a portion of said plasma jet, the improvement comprising:
an auxiliary cathode positioned within said vessel adjacent the plasma jet;
power supply means connected between said liquid metal cathode and said auxiliary cathode for impressing a negative potential on said auxiliary cathode with respect to said liquid metal cathode to extract ions from said plasma jet to cause secondary electron emission from said auxiliary cathode

at least equal to the original liquid metal cathode-to-anode current to cause quenching of the arc from said liquid metal cathode to said anode to stop conduction therebetween.

2. The switching device of claim 1 wherein said auxiliary cathode comprises a plurality of flat panels positioned substantially parallel to the flow direction of the plasma jet.

3. The switching device of claim 2 wherein said flat panels have edges intercepting the edge of the plasma jet cone.

4. The switching device of claim 1 wherein said liquid metal cathode and said anode face each other and said condenser surrounds the space between said facing liquid metal cathode and anode.

5. The switching device of claim 4 wherein said auxiliary cathode is positioned between said liquid metal cathode and said anode.

6. The switching device of claim 5 wherein said auxiliary cathode comprises a plurality of flat panels positioned substantially parallel to the flow direction of the plasma jet.

7. The switching device of claim 6 wherein said flat panels have edges intercepting the edge of the plasma jet cone.

8. The switching device of claim 1 wherein said auxiliary cathode is connected to be maintained at a temperature above the condensation temperature of the liquid metal and below the electron emission temperature of the material of said auxiliary cathode.

9. The switching device of claim 7 wherein said auxiliary cathode is connected to be maintained at a temperature above the condensation temperature of the liquid metal and below the electron emission temperature of the material of said auxiliary cathode.

10. The method of offswitching a liquid metal arc switching device having an enclosing vessel, with an anode, a liquid metal cathode, and a condenser within the vessel and arranged so that the pressure within the vessel is sufficiently low during arcing that a substantially conical plasma jet issues from an arc spot on the liquid metal cathode toward the anode, and which vessel contains a secondary cathode adjacent the plasma jet, comprising the steps of:
causing a liquid metal arc between the liquid metal cathode and the anode by applying a potential therebetween and causing current to flow therebetween while maintaining the background pressure sufficiently low by cooling of the condenser to cause an arc between the cathode and the anode in the form of a substantially conical plasma jet; and
offswitching said switching device by applying sufficient potential to the auxiliary cathode with respect to the liquid metal cathode to extract sufficient ions from the plasma jet to impinge on the auxiliary cathode to cause secondary electron emission from the auxiliary cathode flowing to the anode at least equal to the original current flowing between the liquid metal cathode and the anode to extinguish the arc from the liquid metal cathode to cause cessation of the plasma jet and consequent cessation of current flow from the liquid metal cathode to the anode and to cause cessation of secondary emission electron flow from the auxilia-

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ry cathode to the anode to offswitch the switching device.

11. An electric switching device comprising:

an enclosing vessel for maintaining a subatmospheric pressure within said vessel;

an anode within said vessel;

a main cathode within said enclosing vessel, said anode and said cathode being connectable for conduction of electricity therebetween in a metal arc mode wherein a plasma jet extends from an arc spot on said main cathode toward said anode during conduction, the improvement comprising:

an auxiliary cathode positioned within said vessel adjacent the plasma jet;

power supply means connected between said main cathode and said auxiliary cathode for impressing a negative potential on said auxiliary cathode with respect to said main cathode to extract ions from the plasma to cause secondary electron emission from said auxiliary cathode at least equal to the original main cathode-to-anode current to cause

quenching of the arc from said main cathode to said anode to stop conduction therebetween.

12. The switching device of claim 11 wherein said auxiliary cathode comprises a plurality of flat panels positioned substantially parallel to the flow direction of the plasma jet.

13. The switching device of claim 12 wherein said flat panels have edges intercepting the edge of the plasma jet.

14. The switching device of claim 13 wherein said auxiliary cathode is connected to be maintained at a temperature below the electron emission temperature of the material of said auxiliary cathode.

15. The switching device of claim 11 wherein said auxiliary cathode is positioned between said main cathode and said anode.

16. The switching device of claim 15 wherein said auxiliary cathode is connected to be maintained at a temperature below the electron emission temperature of the material of said auxiliary cathode.

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UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,699,384   Dated October 17, 1972

Inventor(s) Wilfried O. Eckhardt

It is certified that error appears in the above-identified patent
and that said Letters Patent are hereby corrected as shown below:

In the "Abstract," line 3, after "pressure in the," delete
"tube" and insert --vessel--. (Amendment dated 7/31/72)
At the end of the "Abstract," after "envelope." insert --When
the auxiliary cathode is made more negative than the main cathode,
ions are extracted from the plasma which emanates from the arc
spots on the main cathode. The extracted ions impinge upon the
auxiliary cathode to cause secondary electron emission. Thus,
when the auxiliary cathode is made sufficiently more negative than
the main cathode, the reverse current flowing between the auxiliary
cathode and the main cathode will exceed the main circuit flowing
between the main cathode and the anode, and this will cause
extinguishment of the arc spots on the liquid-metal main cathode.
When these spots are extinguished, the source of plasma has
disappeared, and hence ion emission from the plasma and consequent
secondary electron emission from the auxiliary cathode are
terminated, leading to offswitching of the device.-- (page 2,
lines 1 through 16.)
Column 2, line 26, delete "connector" and insert --connection--.
(Amendment dated 7/31/72)
Column 3, line 4, before "exterior" delete "an" and insert --and--
(Amendment 7/31/72)
Column 3, line 38, delete "circuit" and insert --circular--
(Amendment 7/31/72)
Column 5, line 2, after "serves" delete "As" and insert --as--.
Column 6, line 51, before "droplets" delete "or" and insert
--of-- (Amendment 7/31/72)
Column 9, line 7 before "56" delete "anodes" and insert
--cathodes--. (Amendment 7/31/72)
Column 9, line 18, delete "162" and insert --164--
(Amendment 7/31/72)
Column 11, lines 19 and 20, delete "1-2 kV/μ" and insert
--1 to 2 kilovolts per micro-- (Amendment 7/31/72)
Column 11, line 30, delete "1-2 kV/μ" and insert --1 to 2
kilovolts per micro-- (Amendment 7/31/72
Column 12, line 21, after "discharge current is" delete "1,500";
and insert --1,000-- (Page 27, line 28)

Page 1 of 2

UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,699,384   Dated   October 17, 1972

Inventor(s) Wilfried O. Eckhardt

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

Column 12, line 29, delete "Angstroms" and insert --amperes-- (Amendment 7/31/72)
Column 13, line 28, Delete "(174)" and insert --(or 174)--. (Amendment 7/31/72

Signed and sealed this 8th day of May 1973.

(SEAL)
Attest:

EDWARD M.FLETCHER,JR.
Attesting Officer

ROBERT GOTTSCHALK
Commissioner of Patents