United States Patent

Eckhardt

[15] **3,659,132**

[45] **Apr. 25, 1972**

[54] **LIQUID-METAL ARC SWITCHING DEVICE AND PROCESS**

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[73] Assignee: **Hughes Aircraft Company,** Culver City, Calif.

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[21] Appl. No.: **51,868**

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 720,695, Apr. 11, 1968, abandoned.

[52] **U.S. Cl.** **313/32,** 313/34, 313/172, 313/173, 313/163

[51] **Int. Cl.** **H01j 13/00**

[58] **Field of Search** 313/32, 34, 163, 172, 173

[56] **References Cited**

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2,216,743	10/1940	Karlovitz et al.	313/34 X
2,345,397	3/1944	Hutchings	313/34 X

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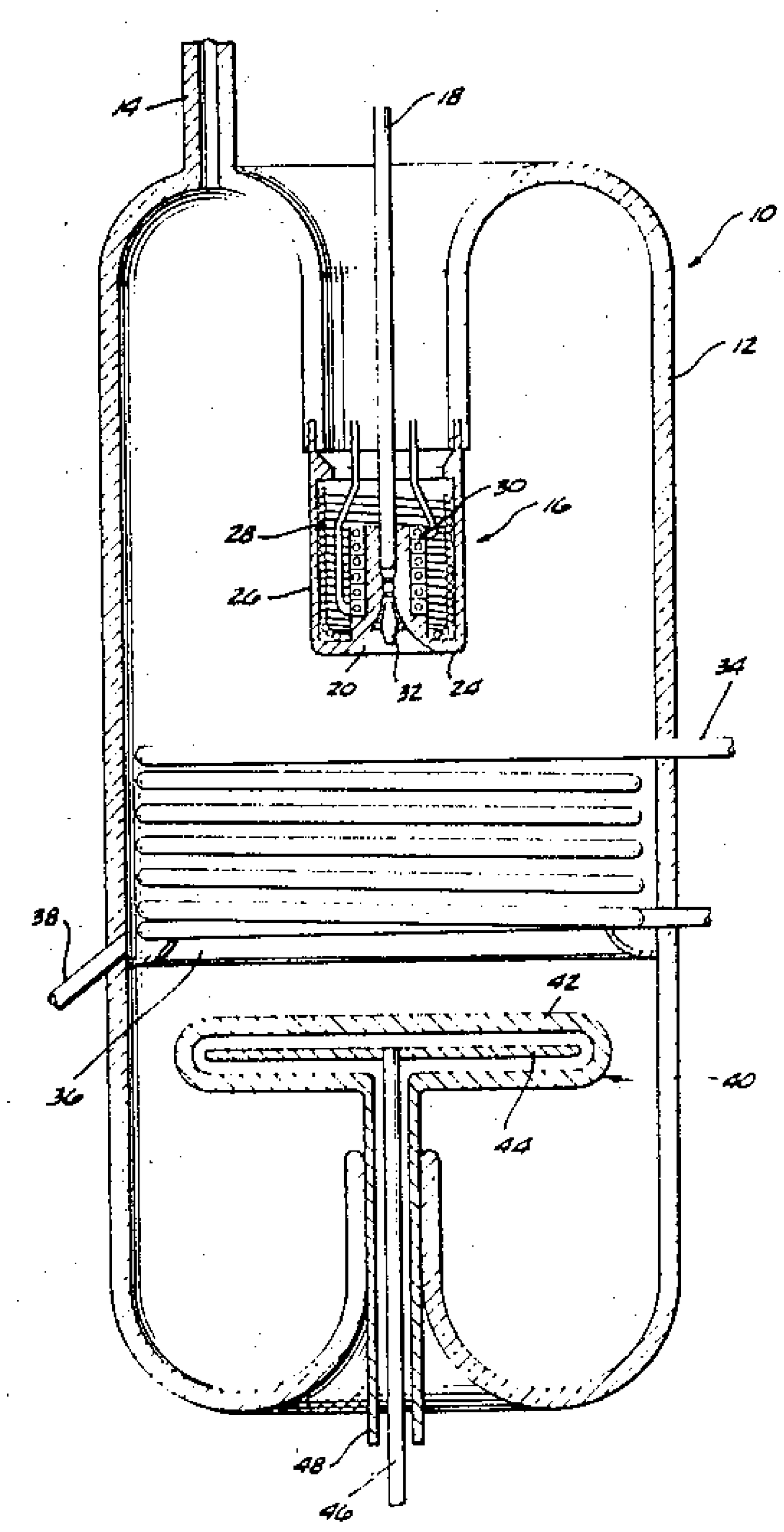
Attorney—James K. Haskell and Allen A. Dicke, Jr.

[57] **ABSTRACT**

The electrical switch device has an envelope in which is mounted a force-fed liquid-metal cathode, an anode, a condenser which may or may not be subdivided for voltage grading purposes and, in the preferred embodiment, electrical shielding means for the condenser. The cathode is capable of very high electron-to-atom emission ratio. The required value for the electron-to-atom emission ratio is above 50 to 1. When arcing occurs from the liquid metal, a plasma jet of electrons, ions, and neutral particles is emitted from the arc spot. In addition, during arcing as well as non-arcing periods, some of the liquid metal evaporates from the cathode. This evaporation occurs into a much larger solid angle than that subtended by the plasma jet. The anode is mounted facing the cathode and it intercepts the plasma jet, thus permitting current conduction between anode and cathode with minimum voltage drop. The anode is kept at an elevated temperature, so that none of the ions and neutrals of the impinging plasma jet can remain condensed on it. They are immediately re-evaporated, including the ions after they have been neutralized. The condenser has a very much larger area than the exposed liquid metal area on the cathode, at least 100 times the exposed liquid metal area to dominate the equilibrium and it is kept at a low enough temperature to efficiently condense the liquid-metal vapor emitted by the cathode. With mercury used as the liquid metal, the condenser temperature is kept substantially below 0°, preferably at about −35° C, which is just above the melting point of mercury. The combination of the high electron-to-atom emission ratio of the cathode with the large, low temperature condenser results in an equilibrium background pressure (i.e., pressure outside the plasma jet) of at least as low as 10^{-3} Torr during arcing and lower than 10^{-4} Torr during non-arcing periods. This low background pressure, in turn, permits the essentially unperturbed propagation of the plasma jet between the cathode and the anode surface upon which it impinges. Such a discharge mode is commonly referred to as a "vacuum arc". The fact that the plasma jet is emitted only during arcing and that the pressure within the space surrounding this jet is kept low, results in the ability to hold off electric fields up to 50 kV per centimeter between anode and cathode immediately after cessation of arcing. Arcing may cease because of a zero in the current fed to the switching device, as in conventional arc devices, or it may cease due to depletion of the liquid metal available for arcing on the surface of the force-fed cathode. In the latter case, the current fed to the switching device is forcibly interrupted. The process employs these characteristics for switching.

21 Claims, 4 Drawing Figures



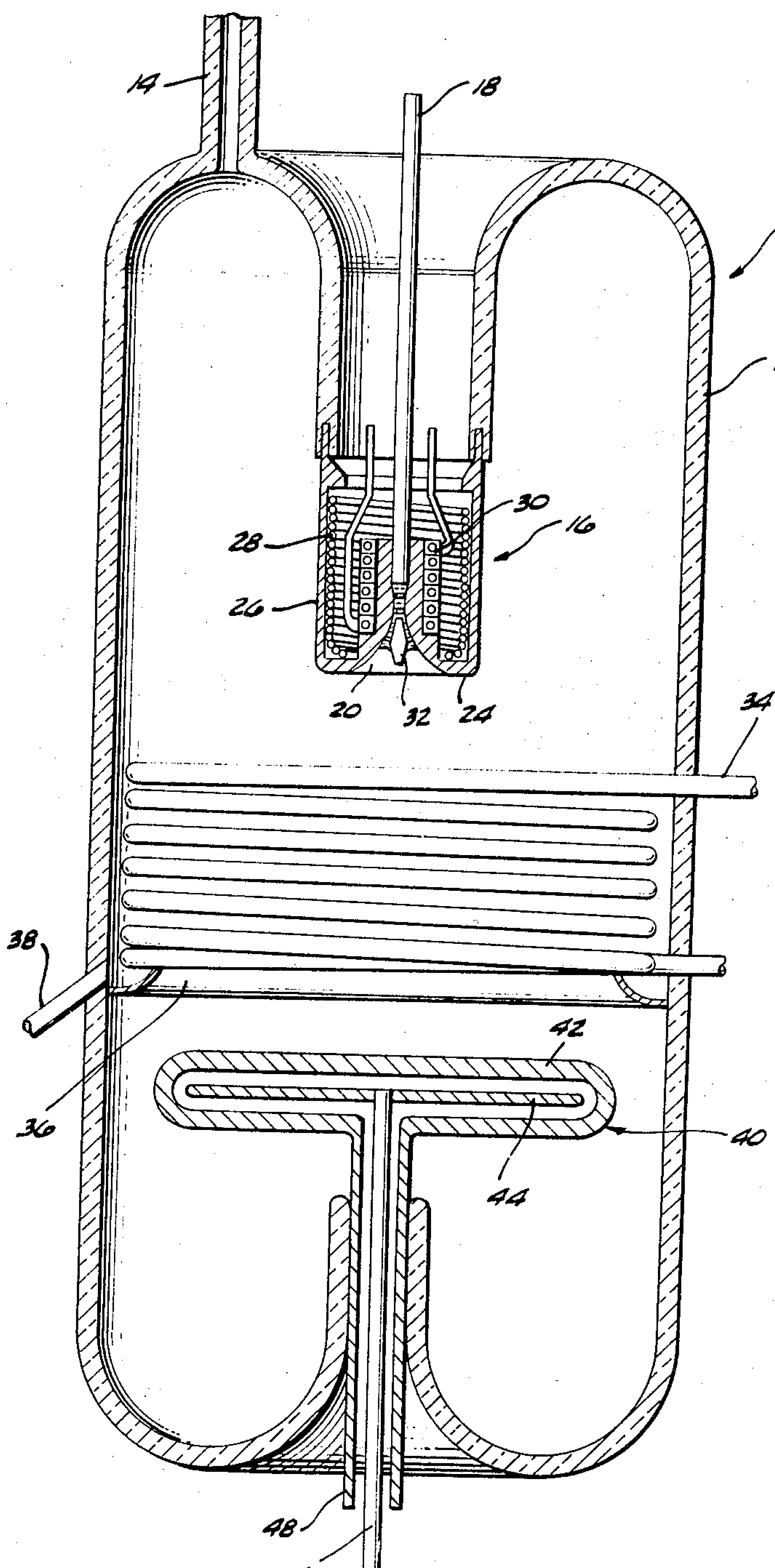


FIG. 1.

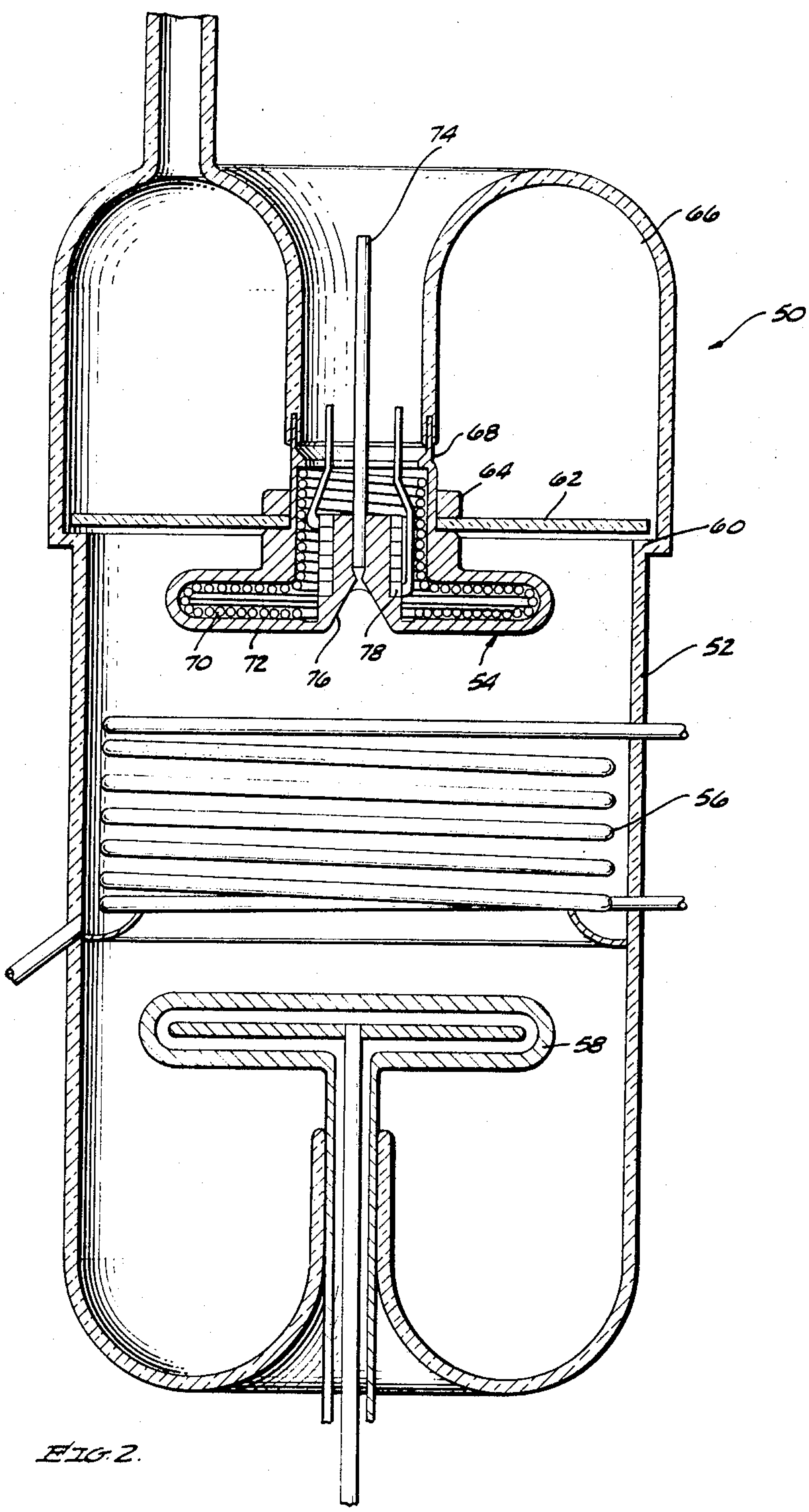


FIG. 2.

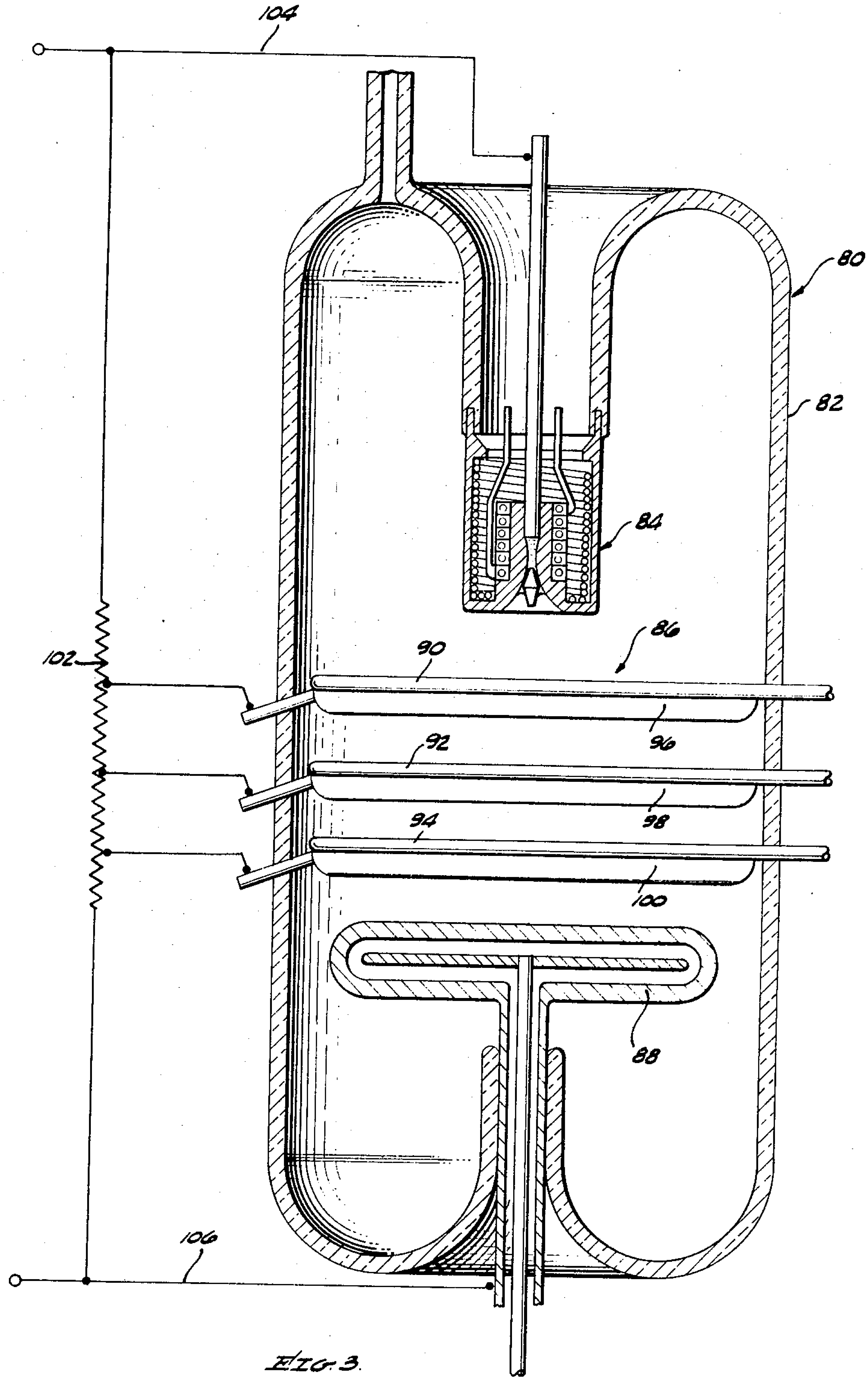
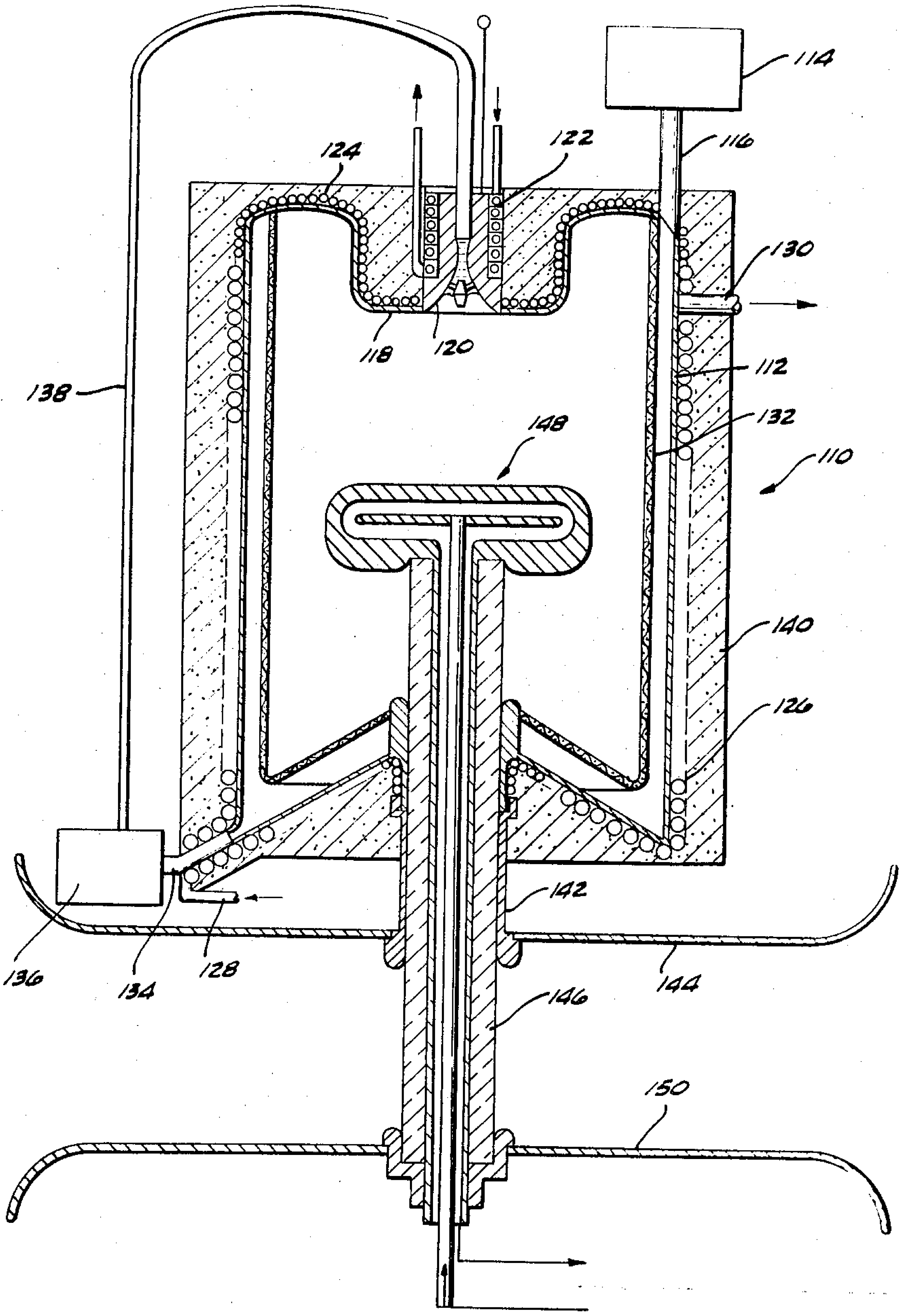


FIG. 3


114
116
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146
150

FIG. 4.

LIQUID-METAL ARC SWITCHING DEVICE AND PROCESS

CROSS REFERENCE

This application is a continuation-in-part of patent application Ser. No. 720,695, filed Apr. 11, 1968 now abandoned.

BACKGROUND

The invention relates to the field of liquid metal arc rectifiers and switches, such as mercury arc rectifiers.

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.

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 an anode, a cathode, and a condenser for maintaining a low pressure in the tube. The cathode is fed with a low arc-voltage metal which is liquid at convenient temperatures, so that a small quantity of this metal is available on the cathode so that a current-carrying arc runs between the cathode and the anode. The cathode is arranged so that, during arc activity, it emits a minimum amount of atoms and ions in relation to the required electron current. This enables the condenser to maintain the pressure in the tube relatively low during arcing and to quickly establish a vacuum of high insulative properties after arc cessation.

It is thus an object of this invention to provide an electrical high-voltage, high-current, single-gap switch device which has a small, force-fed liquid-metal cathode emitting a plasma jet and an anode structure positioned with respect to the cathode so that the anode structure has desirable electrical coupling with plasma jet emitted from the cathode. It is a further object to provide an enclosed switch device with the background pressure maintained therein at a sufficiently low level, such as 10^{-3} Torr or less, during arcing that the background does not substantially interfere with the plasma jet cone so that the plasma jet cone is not distorted before it interacts with the anode.

It is another object of this invention to provide an enclosed switch tube having an anode structure, a cathode, and a condenser, and arranged so that the condenser, optionally together with vacuum pumping devices, maintains the pressure within the tube at a sufficiently low level that the pressure in the tube does not interfere with the flow of neutrals and ions from an arc spot, so an anode structure can be positioned with respect to the plasma jet for maximum coupling with the plasma jet issuing from the arc spot or spots. It is a further object of this invention to provide a liquid-metal cathode which is fed with non-solid metal so that a small area of liquid metal is provided for arcing activity, which area defines the position of arcing activity and thus defines the apex of the plasma cone issuing from the liquid-metal area to accurately define the plasma cone position and thus permit anode positioning with respect to the plasma cone. It is a further object of this invention to provide a liquid-metal cathode which is fed with non-solid metal so that a small area of liquid metal is provided for arcing activity, such area of liquid metal being small enough and maintained at low enough temperature that the emission of neutral atoms is kept sufficiently small to permit the condenser to maintain the low background pressure required for the essentially unperturbed propagation of the plasma jet between the cathode and the anode upon which it impinges, the unperturbed propagation of the plasma jet characterizing the mode of gas discharge commonly referred to as a "vacuum arc." The area of liquid metal is also small enough and maintained at low enough temperature so that the emission of neutral atoms is kept sufficiently small to maintain in conjunction with the condenser a background pressure low enough to prevent electrical breakdown between the cathode and the anode. It is a further object of this invention to provide a liquid-metal arc switching device wherein the liquid metal has a low arc voltage and is fed to a cathode structure having a higher arc voltage so that arcing is restricted to the low arc voltage material and arcing tends to cease when the low arc voltage material available in the cathode structure becomes exhausted. 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 vertical sectional view along the axis of the first embodiment of the liquid-metal arc switching device, in accordance with this invention.

FIG. **2** is similar to FIG. **1**, showing a second embodiment thereof.

FIG. **3** is similar to FIG. **1**, but showing a third embodiment thereof.

FIG. **4** is similar to FIG. **1** and showing the fourth and preferred embodiment of the liquid-metal arc switching device of this invention.

DESCRIPTION

Referring to the drawings, the liquid-metal arc switching device is generally indicated at **10** in FIG. **1**, **50** in FIG. **2**, **80** in FIG. **3**, and **110** in FIG. **4**. 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 and 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 forced arc cessation. The first case includes rectification of alternating current, as well as inversion of dc to ac by natural commutation, and the second case includes dc circuit breakers and forced commutators for inverting 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 generically to define the scope of such devices.

The liquid-metal arc switching device of FIG. 1 is generally indicated at 10. It comprises a vessel 12 which is closed off so that a vacuum of appropriate value can be maintained therein. Vacuum pump connection 14 is provided on the envelope 12 to either originally pump down the original 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. The main part of the vessel 12 is made of electric insulation material, such as glass or ceramic. Alternatively, the vessel can be made of metal with suitable insulation separating the various parts thereof, which are at different potentials, as is hereinafter described.

Cathode 16 is a cathode of the nature shown in W. O. Eckhardt U. S. Pat. No. 3,475,636, the entire disclosure of which is incorporated herein by this reference. Any one of the cathode embodiments illustrated in that patent can be employed, or any other specific cathode configuration falling within the teachings of that patent is useful herein. An electron-to-atom emission ratio for satisfactory operation of the switch device is at least 50 to 1. The most desirable ratio is 100 to 1 and above. Cathode 16 is fed with liquid metal from a suitable supply line 18. The supply line 18 supplies liquid metal to a flow impedance which can either take the form of a porous plug, or of a narrow capillary flow control tube or any other flow impedance. The liquid metal is made to pass under pressure through this flow impedance and is delivered to pool-retaining walls 20 of the cathode. The arc then runs at the juncture between walls 20 and the liquid metal, the liquid metal being of low arc voltage material, as compared to the cathode wall material.

The external surface of cathode 16, including cathode wall 20, is made of high arc voltage material. The term arc voltage is defined as arcing voltage 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. A suitable low arcing voltage material is mercury. A suitable high arcing voltage cathode wall material is molybdenum or tungsten.

In order to prevent condensation of liquid metal on the front surface 24 and the side surface 26, heater coil 28 is provided. This heater coil maintains surfaces 24 and 26 at a temperature sufficiently high that the liquid metal does not condense thereon. This prevents the arc from running anywhere away from the liquid metal juncture to cathode wall 20.

The normal heat of running of the arc may, depending upon heat transfer characteristics and the arc current, cause the liquid metal adjacent to the cathode wall 20 to become too hot to maintain the desired high electron-to-atom emission ratio. For this reason, cooling coil 30 is provided.

In the drawing, cathode wall 20 is a surface of revolution which is larger in the downward direction to be divergent. The center can be provided with plug 32 so that an annular pool space is created between the plug and the wall. The annular pool provides a greater length of contact between the pool and the wall, with less area from which evaporation can occur. However, the cathode can be constructed without plug 32 so that the walls 20 define a divergent, substantially conical zone for the liquid metal. Any one of the configurations of cathode pool shown in W. O. Eckhardt U.S. Pat. No. 3,475,636 can be employed.

Furthermore, the liquid metal may be supplied as a liquid, as taught by U.S. Pat. No. 3,475,636, or may be supplied as a vapor which transiently condenses upon the cathode wall 20, as is taught by Wilfried O. Eckhardt, In U.S. Pat. No. 3,538,375 entitled "Vapor-Fed Liquid-Metal Cathode", the entire disclosure of which is incorporated herein by this reference. When such a structure is employed, the temperature of the liquid metal being fed in vapor form and the temperature of cathode wall 20 is controlled, so that transient condensation occurs, as is shown in that patent. Additionally, within the vessel 12, condenser 34 is located. It serves as the means for continuously removing from the vessel the metal vapor emitted by the cathode. Condenser 34 is suitably externally connected to maintain the desired temperature upon the condenser surface, as described below. A possible embodiment of condenser 34 is a cylindrical coil within the vessel 12, the coil extending around the axis of the vessel and the axis of the cathode 16. Condenser 34 is supplied with a sufficient quantity of coolant at a sufficiently low temperature to maintain by condensation the required low vapor pressure, as is hereinafter described in the operation of the switch device. Trough 36 is positioned below the condenser coils, in order to catch the liquid metal condensed thereon. Drain 38 carries the liquid metal out of the vessel, from where it may be recirculated to the cathode by means of a suitable pump.

Anode 40 has a face 42 directed toward the cathode. The anode is in axial alignment with the cathode, so that arcing can directly occur between the cathode and the anode. The front face 42 is illustrated as being a planar disc, but may be any structure which intercepts a substantial part of the electron flow in the plasma jet. In any event, the anode face is directly in line with and unobstructed with respect to cathode 16.

Anode 40 is hollow and has a baffle 44 therein. The space between the baffle and the front of the anode is supplied with heat exchanger fluid through tube 46. The heat exchanger fluid passes between the baffle and the face and down through support tube 48 to return to supply. Electrical connections are made on support tube 48 and on liquid metal supply line 18, or any other convenient electrical connection to the pool-keeping wall 20 and face 42. The heat exchange fluid supplied to anode 40 is such as to permit the anode to operate at a proper temperature, which is above the condensation temperature of the liquid metal. When the switching device is operating at low currents, or is not arcing, the heat exchange fluid may need to heat the anode 40 and, at high currents, may need to cool the anode 40. The temperature of operation of the anode is above the condensation temperature of the liquid metal, as previously described, to prevent liquid metal from condensing thereon and from generating potential sites for arcing when reverse voltage is applied, which would reduce the voltage holdoff properties of the switching device. If voltage reversal across the switch device cannot occur, as for example in certain dc circuit breaker applications, and if the conduction time of the switch device is short compared with the periods of non-conduction, then it is permissible and may be more economical to maintain anode 16 at the same temperature as the condenser described above. In such a case, the anode and condenser can be electrically connected. Any means known to those skilled in the art and capable of controlling the anode temperature in the manner described above is suitable, and is not limited to baffle and heat exchange fluid means described above. The internal conditions of switching device 10 and the characteristics of its operation are described below.

FIG. 2 illustrates liquid metal arc switching device 50 which has a vessel 52 and, positioned therein, cathode 54, condenser 56, and anode 58. The condenser and anode are identical to those described in FIG. 1. The vessel is virtually identical to the vessel 12, except that it has an offset shoulder 60 against which dielectric baffle plate 62 is positioned. Plate 62 is engaged against a shoulder on the cathode by clamp 64. The baffle plate closes off the upper chamber 66 from arcing, to completely eliminate the chance that an arc can strike on the junction 68 between the metal of the cathode body and the dielectric material of the vessel.

Cathode 54 includes a heater 70 to maintain the cathode face 72 above the condensation temperature of the liquid metal. Cathode wall 76 and the liquid metal fed through liquid metal supply line 74 and adjacent to said cathode wall 76 are controlled in temperature by means of heat exchange coil 78. The cathode 54 is identical to the cathode 16, except for the larger diameter of face 72, which constitutes an internally heated thermal guard ring preventing metal vapor condensation between pool-keeping walls 76 and the dielectric baffle plate 62. Cathodes 16 and 54 illustrate various alternative features. Cathode **16** has its internal plug **32**, which reduces the liquid metal volume and exposed area, while increasing the length of the junction between the pool-keeping walls and the liquid metal pool surface. The walls of plug **32** are also pool-keeping walls. Cathode **54** does not employ such a plug. Furthermore, cathode **54** has a thermal guard ring, while cathode **16** does not. Additionally, cathode **54** has dielectric shield **62**, while cathode **16** does not. Each of these features can be employed in any combination with the other features, and with the alternative condensers described with respect to FIGS. **1**, **3** and **4**. The operation of liquid metal arc switching device **50** is described below.

FIG. **3** illustrates a liquid metal arc switching device **80** which comprises an envelope **82** in which is positioned the cathode **84**, condenser **86**, and anode **88**. The envelope, cathode and anode are identical to these corresponding structures shown and described with respect to FIG. **1**.

Condenser **86** comprises a plurality of separate condenser structures, with three electrically-separate coils illustrated at **90**, **92**, and **94**. These coils have an open center to permit the arc to operate between the anode and cathode. They may each be of a single, circular loop around the axis of the switch device **80**, or may have additional loops, preferably in helical turns along the axis. Each of the condenser coils has a corresponding trough **96**, **98**, and **100**, respectively. Each of the troughs has a suitable outlet to permit the draining of the condensed liquid metal.

Resistor **102** is connected between line leads **104** and **106**, which are respectively connected to the cathode and the anode. Taps on resistor **102** are connected to the three condenser coils illustrated, so that the condenser is electrically graded in voltage between the cathode and anode, in accordance with the mechanical separation from the cathode and the anode. Such voltage grading prevents insulation breakdown when the device is non-conducting, to distribute the difference in voltage between the anode and the cathode along the length of the insulative envelope. This voltage grading is purely electrostatic, i.e., there are no grids attached to the grading rings which could impress on the entire tube cross section the potential of the rings, even in the presence of a substantial plasma density. Such grids would have the disadvantage of limiting the current which can be passed through the discharge column.

FIG. **4** 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 cathode face **118**. The pool-keeping walls **120** are the same as those shown in FIGS. **1** and **3**. 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 **16**. 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, be 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 electric 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. However, should the condenser be at a different potential from the cathode and liquid metal recirculation is desired, as shown in FIG. **4**, 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 **40**, except for its mounting. The lower end of the support tube of anode **148** carries corona shield **150** at anode potential.

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 the 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. More complete discussion of the vacuum arc is found in the PROCEEDINGS OF THE INSTITE OF ELECTRICAL ENGINEERS, Volume 110, No. 4, April 1963, pages 793–802. In this specification, arc voltage and arcing voltage are interchangeably used. 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 area at least 100 times the liquid metal pool area and 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 attainment of 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 spot 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 **16** 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 **16** in each embodiment is preferably hollow so that the temperature of anode **16** can be controlled by means of a circulating liquid or of a heat pipe 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 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 anode **16** 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 anode **16**. 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 **18** remains low. Furthermore, the small liquid metal area adjacent to 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 to 2 kilovolts per microsecond 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, 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 to 2 kilovolts per microsecond or even more. This makes the electrical switch device **10** of great utility for high voltage rectification, controlled rectification, and inversion, particularly at high currents.

The cessation of arcing can occur in operation by the change in polarity applied to the terminals. Additionally, cessation of arcing can be made to occur by stopping the flow of liquid metal to the liquid-metal pool. Thus, the device is useful for dc switching for, when it is desired that current be stopped, the liquid-metal flow is stopped to starve the pool and thus cause cessation of arcing. The material of the cathode around the pool is of such high arc voltage that the arc is extinguished rather than transferred to this material, when the rate of voltage rise does not exceed 10 kilovolts per microsecond. To maintain stable current flow in the device under the desired condition of high electron-to-atom emission ratio at the 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. Additionally, each embodiment of the electrical switching device can act as an overcurrent fault protector. When liquid metal in an amount proportional to normal current, up to a predetermined maximum feed rate of liquid metal, is fed to the cathode to supply normal current needs, when a fault occurs which draws a larger amount of current, the liquid-metal pool rapidly becomes exhausted because of its small volume. When the pool is exhausted, arcing stops so that excessively high fault currents can be interrupted. Of course, modulated feeding of the liquid metal produces controlled forced current interruption when the current starves the pool.

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 cathode (and scattered by 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 1,000 A, and the cathode emits 100 electrons per atom, a suitable condenser area is 1,500 cm^2.

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 trough through the drain.

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.

I claim:

1. An electrical switch device, said electrical switch device comprising:

a vessel;

an anode within said vessel, a cathode within said vessel and a condenser having a condenser surface within said vessel;

said cathode having a high arc voltage material pool-keeping wall, means for feeding a lower arc voltage metal in other than the solid state to a position adjacent said wall so that liquid metal is on said wall, temperature control means adjacent said wall for controlling the temperature of said wall to minimize evaporation of the lower arc voltage material adjacent said wall so that the electron-to-atom emission ratio of said lower arc voltage material during arcing is at least 50 to 1;

said condenser: (a) having a sufficiently large condensation surface area with respect to the liquid metal area on said cathode, and (b) being positioned with respect to said cathode and said anode, and (c) said cathode, said anode and said condenser being operated for causing an electric discharge between said cathode and said anode in the vacuum arc mode wherein an arc spot is formed on the liquid metal on said wall from whence is ejected a plasma jet containing electrons ions and neutral particles, and (d) said condenser is maintained at a suffiently low temperature to capture substantially all of the neutral particles and ions emitted from the arc spot to permit maintenance of the background pressure within said vessel during arcing sufficiently low that the atmosphere in said vessel does not substantially interfere with the plasma jet so that discharge in a vacuum arc mode is maintained.

2. The electrical switch device of claim **1** wherein said anode is positioned directly in the plasma jet to intercept a substantial amount of the electron flow in the plasma jet for good electrical coupling with the plasma jet.

3. The electrical switch device of claim **2** wherein said electrical switch device has an axis passing centrally through said cathode and said anode, and the plasma jet is ejected substantially along said axis.

4. The electrical switch device of claim **3** wherein said anode has a face on said axis and said face extends laterally with respect to said axis, said face being sufficiently large to intercept a substantial portion of the electrons in the plasma jet.

5. The electrical switch device of claim **4** wherein said anode has heat exchanger means therein for exchanging heat with respect to said anode, coupling means connected to said heat exchanger means for circulating heat exchange fluid through said heat exchange means in said anode.

6. The electrical switch device of claim **1** wherein said cathode has an outer surface away from said pool-keeping wall, heat exchange means adjacent said cathode outer surface for maintaining said cathode outer surface at a sufficiently high temperature to prevent condensation of lower arc voltage metal on said outer surface, to prevent arcing from said outer surface.

7. The electrical switch device of claim **6** wherein said anode is positioned directly in the plasma jet to intercept a substantial amount of the electron flow in the plasma jet for good electrical coupling with the plasma jet.

8. The electrical switch device of claim **7** wherein said electrical switch device has an axis passing centrally through said cathode and said anode, and the plasma jet is ejected substantially along said axis.

9. The electrical switch device of claim **8** wherein said anode has a face on said axis and said face extends laterally with respect to said axis, said face being sufficiently large to intercept a substantial portion of the electrons in the plasma jet.

10. The electrical switch device of claim **9** wherein said anode has heat exchanger means therein for exchanging heat with respect to said anode, with coupling means connected to said heat exchanger means for circulating heat exchange fluid through said heat exchange means in said anode.

11. The electrical switch device of claim **1** wherein an axis extends through said vessel centrally through said cathode and said anode, the plasma jet passing generally in the direction of said axis from said cathode to said anode, said anode having an anode face facing said cathode and extending laterally with respect to said axis, said anode face being sufficiently large to intercept substantially all the electrons in said plasma jet for good electrical coupling, said condenser being positioned around said axis between said anode and said cathode and substantially outside of the plasma jet.

12. The electrical switch device of claim **11** wherein said vessel has a substantially cylindrical wall intermediate said anode and said cathode, with its cylindrical wall having an axis substantially coinciding with said axis of said switch device, said condenser being positioned adjacent said cylindrical wall, and comprising at least one coil of heat exchange passage for carrying coolant through it.

13. An electrical switch device, said electrical switching device comprising:

a vessel;

an anode within said vessel, a cathode within said vessel, and a condenser having a condenser surface within said vessel;

said vessel having an axis extending substantially centrally therethrough and through said cathode and toward said anode, said anode having an anode face facing said cathode and extending laterally with respect to said axis, said anode face being sufficiently large to intercept substantially all the electrons in a plasma jet;

said vessel having a wall intermediate said anode and said cathode, said vessel wall being said condenser surface and being away from said axis, said vessel wall being a metallic wall, a heat exchange passage secured to said metallic wall for the carrying of coolants for the cooling of said metallic condenser wall;

said cathode having a high arc voltage material pool-keeping wall, means for feeding a lower arc voltage metal in other than the solid state to a position adjacent said pool-keeping wall so that liquid metal is on said pool-keeping wall, temperature control means adjacent said wall for controlling the temperature of said pool-keeping wall to minimize evaporation of the lower arc voltage material adjacent said pool-keeping wall so that the electron-to-atom emission ratio of said lower arc voltage material during arcing is at least 50 to 1;

said condenser: (a) having a sufficiently large condensation surface area formed by said condenser wall with respect to the liquid metal area on said cathode and (b) being positioned with respect to said cathode and said anode, and (c) said cathode, said anode and said condenser being operated for causing an electric discharge between said cathode and said anode in the vacuum arc mode wherein an arc spot is formed on the liquid metal on said pool-keeping wall from whence is ejected a plasma jet containing electrons, ions, and neutral particles generally along said axis, and (d) said condenser is maintained at a sufficiently low temperature to capture substantially all of the neutral particles and ions emitted from the arc spot to permit maintenance of the background pressure within said vessel during arcing suffiently low that the atmosphere in said vessel does not substantially interfere with the plasma jet so that discharge in a vacuum arc mode is maintained.

14. The electrical switch device of claim 13 wherein said anode has a face on said axis and said face extends laterally with respect to said axis, said face being sufficiently large to intercept a substantial portion of the electrons in the plasma jet.

15. The electrical switch device of claim 14 wherein said anode has heat exchanger means therein for exchanging heat with respect to said anode, coupling means connected to said heat exchanger means for circulating heat exchange fluid through said heat exchange means in said anode.

16. The electrical switch device of claim 12 wherein a screen is positioned between said condenser and said axis so that neutral particles passing from the plasma to said condenser wall pass through said screen, said screen being maintained at a temperature above the vaporization temperature of the lower arc voltage metal in order to prevent condensation of lower arc voltage metal thereon.

17. The electrical switch device of claim 16 wherein said anode has a face on said axis and said face extends laterally with respect to said axis, said face being sufficiently large to intercept a substantial portion of the electrons in the plasma jet.

18. The electrical switch device of claim 17 wherein said anode has heat exchanger means therein for exchanging heat with respect to said anode, coupling means connected to said heat exchanger means for circulating heat exchange fluid through said heat exchange means in said anode.

19. The process of switching electric current comprising the steps of:

discharging electrons and atoms in a plasma jet in the vacuum arc mode between a liquid metal pool on a cathode and an anode by (a) maintaining the electron-to-atom emission ratio of the cathode at least 50 to 1 and (b) maintaining the background pressure outside of the plasma jet at least as low as 10^{-3} Torr during arcing by (c) maintaining a condenser adjacent the arc with an area at least 100 times the liquid metal pool area on the cathode at a sufficiently low temperature to condense the neutral particles; and

stopping electric current conduction by causing arc cessation.

20. The process of claim 19 further including the step of:

coupling the plasma jet emitting from the cathode to the anode by positioning the anode in the plasma jet stream so that substantially all of the electrons in the plasma jet impinge upon the anode.

21. The process of claim 20 wherein condensation is accomplished by:

positioning a condenser around the plasma jet to receive ions and neutrals reflected from the anode.

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