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Dell et al.

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[54] **ELECTROLYTIC CELL FOR METAL PRODUCTION**

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[52] **U.S. Cl.** **204/244**; 204/245; 204/247

[51] **Int. Cl.** **C22d 3/02**

[58] **Field of Search** 204/67, 64, 243 R–247

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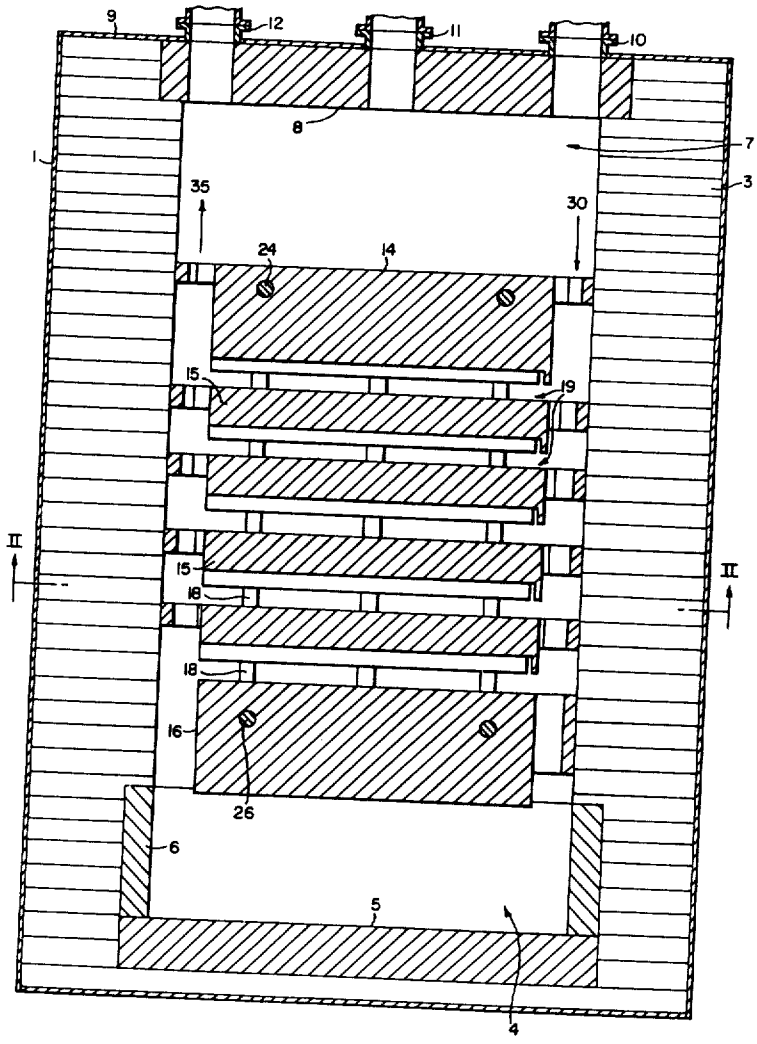
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[57] **ABSTRACT**

Metal such as aluminum is produced electrolytically from the metal chloride dissolved in molten solvent of higher decomposition potential, in a cell which includes an anode, at least one intermediate bipolar electrode and a cathode in superimposed relationship defining inter-electrode spaces, with bath flow through the inter-electrode spaces effecting removal therefrom of metal produced, and permitting accumulation of metal by settling from the outflowing bath.

9 Claims, 4 Drawing Figures



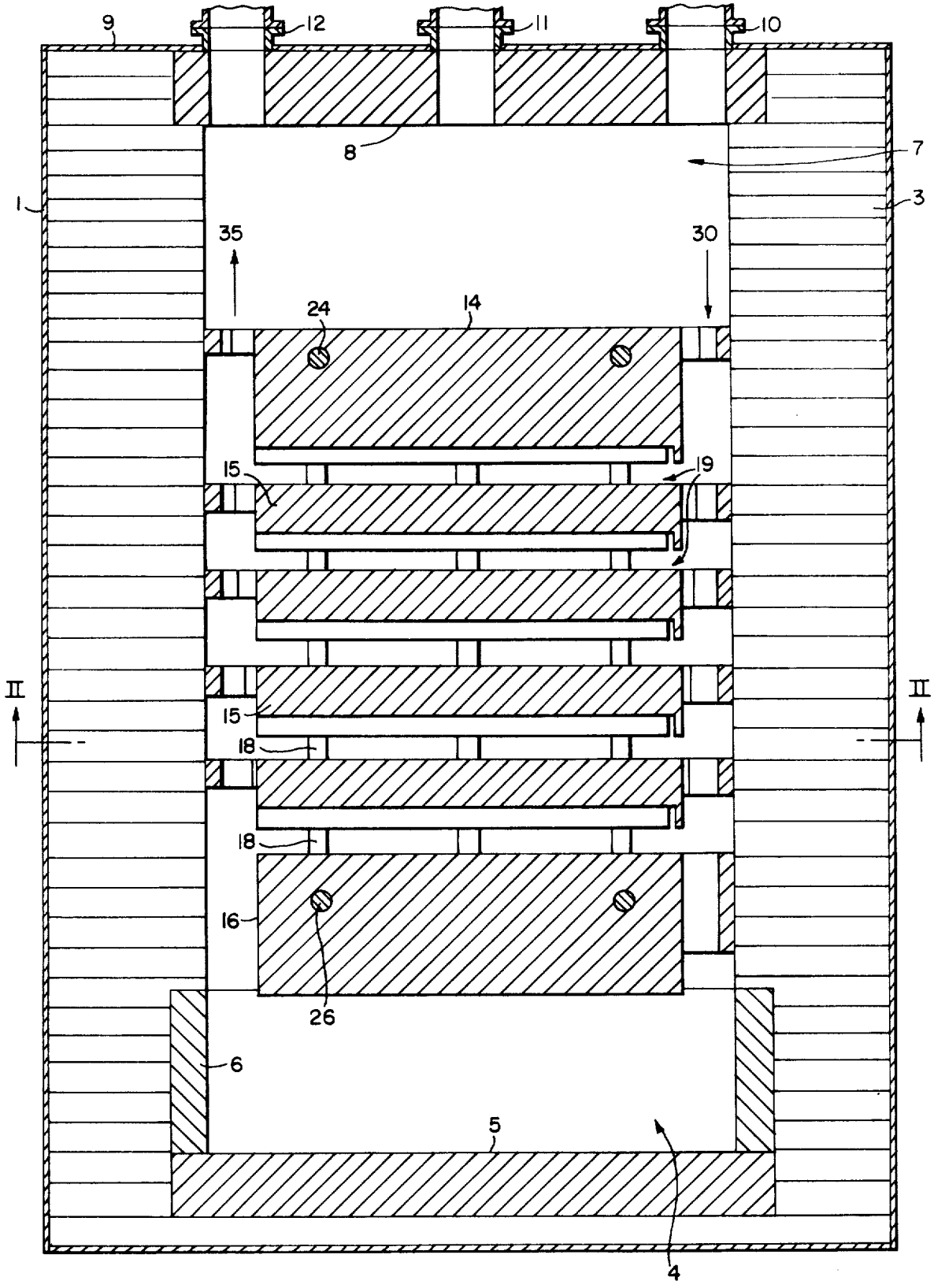


FIG.1.

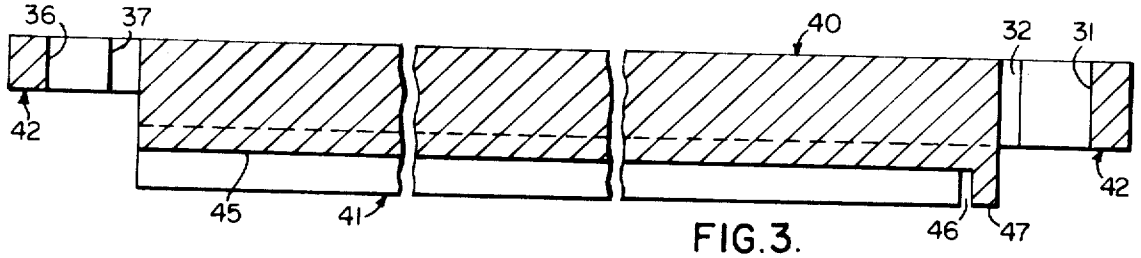


FIG.3.

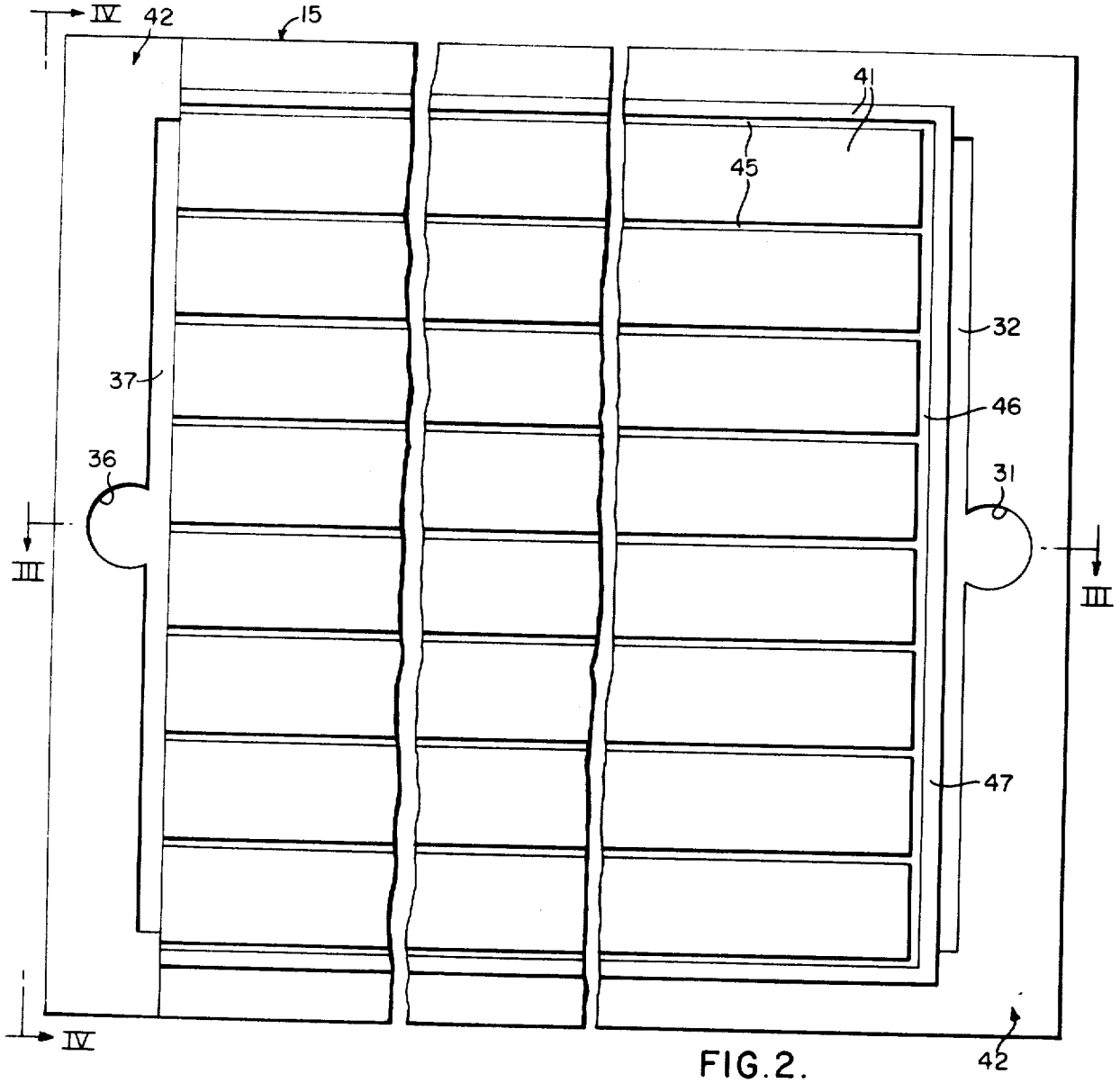


FIG.2.

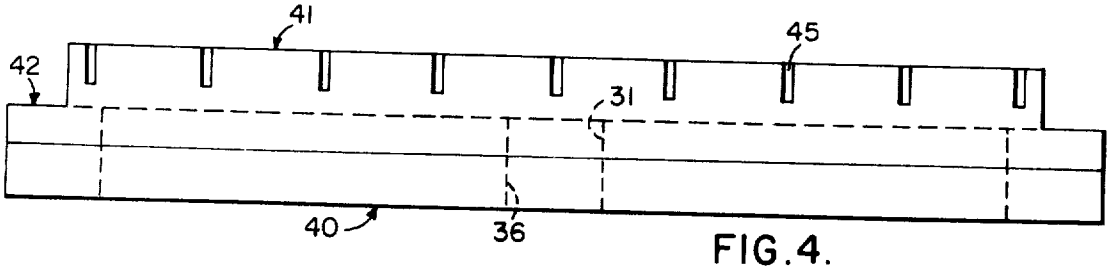


FIG.4.

ELECTROLYTIC CELL FOR METAL PRODUCTION

CROSS REFERENCE TO RELATED APPLICATION

This is a division of application Ser. No. 178,650, filed Sept. 8, 1971, now U.S. Pat. No. 3,822,195.

BACKGROUND OF THE INVENTION

This invention relates to a cell and process for producing metal such as aluminum from the metal chloride dissolved in a molten solvent, by electrolyzing the chloride-solvent bath in a cell which includes an anode, at least one intermediate bipolar electrode, and a cathode in superimposed spaced relationship defining inter-electrode spaces, with selectively directed bath flow through the inter-electrode spaces. While the invention may be employed for producing other metals, such as magnesium, zinc or lead, it is particularly applicable to producing aluminum.

Commercial production of aluminum is presently effected by electrolyzing a bath of alumina dissolved in a molten halide composed essentially of sodium fluoride, aluminum fluoride and calcium fluoride. In this process, commonly known as the Hall process, carbon anodes are employed which are gradually consumed by the oxygen produced on the anode surfaces, and this represents a considerable economic loss attendant upon such operations. The bath is maintained at temperatures over 900°C. Power efficiency is limited by the practical necessity of maintaining an anode-cathode distance of at least about 1¼ inches (from carbon anode to the underlying layer of molten aluminum which is the effective cathode surface), in order to reduce intermittent shorting and loss of current efficiency caused by undulations of the aluminum layer induced by magnetic fields.

The present invention is directed particularly to the use of aluminum chloride as the source material for aluminous metal. Since electrolytic reduction of aluminum chloride does not produce oxygen, and since it may be electrolyzed at appreciably lower temperatures than alumina, two inherent economic limitations of the conventional Hall process are avoided. Although the possibilities of achieving these and other advantages attendant the use of aluminum chloride as a source material in the electrolytic reduction of aluminum have long been recognized and avidly sought, commercial realization thereof has been precluded by numerous other unsolved problems attendant upon the use of this source material in such a process.

Among the problems to be overcome by a commercially viable process for producing aluminum from aluminum chloride by electrolysis are the achievement of high power efficiency, desirably through relatively high current efficiency and relatively low voltage, without an economically defeating back reaction of the chlorine and aluminum produced. While the prior art has recognized the possibility of achieving some of the desired advantages hereinbefore mentioned, especially through the use of cells employing bipolar electrodes, it is noted that such suggestions generally disclosed the use of such electrodes in vertical position, or in a position inclined at a substantial angle, so that metal produced on each cathode surface settled by gravity to the bottom of the cell through each inter-electrode space, while the chlorine produced on each anode surface rose out of each inter-electrode space, i.e., moved in a direction counter to the settling aluminum.

SUMMARY OF THE INVENTION

This invention may be briefly described as a process and apparatus for the electrolytic production of metal such as aluminum from the metal chloride in a cell which includes an anode, at least one intermediate bipolar electrode, and a cathode in superimposed, spaced relationship defining inter-electrode spaces therebetween. In its broad aspects, the process comprises electrolyzing bath composed essentially of the metal chloride dissolved in molten solvent of higher decomposition potential in each inter-electrode space to produce chlorine on each anode surface thereof and metal on each cathode surface thereof, and establishing and maintaining a flow of bath through each inter-electrode space to effect removal therefrom of metal produced, this flow being such that it sweeps metal therewith out of each inter-electrode space. Desirably the bath flow is selectively directed into, across and out of each inter-electrode space, by utilization of the chlorine produced as the lifting gas in a gas lift pump which lifts the lighter bath upwardly while permitting heavier molten metal swept from each inter-electrode space to settle in a direction counter to that of the chlorine-pumped bath. In the practice of such process, additional metal chloride may be incrementally or continuously fed into the bath, and the bath as so maintained may be continuously recycled through the inter-electrode spaces. Still other aspects of the invention include novel structure and structural inter-relationships for the cell and electrode components to complement and enhance the operational efficiency of the mode of operation just described.

Among the advantages of the invention are the avoidance of metal accumulation, whether as a pool or as substantial droplets or the like, on the cathode surfaces, thus permitting minimal anode-cathode spacing, less than three-fourth inch, with consequent reduced cell resistance. This means less heat generation and improved voltage efficiency, with attendant economic advantages, especially in large multi-electrode cells. The absence of substantial accumulation of metal on the cathode surfaces also means there is, in effect, no metal layer on such surfaces to be distorted by magnetic flux and no problem of variation in effective anode-cathode distance as is the case when metal layers of variable depth may accumulate. The chlorine produced continually passes out of the inter-electrode spaces as it performs its pumping action, thus also reducing cell resistance that might otherwise be contributed by the presence of a substantial accumulation of chlorine on the anode surfaces. The opportunity herein afforded to employ close anode-cathode spacing surprisingly leads to an overall improvement in current efficiency as well as in voltage efficiency, despite the close proximity of chlorine and aluminum in narrow inter-electrode spaces. The chlorine appears to remove aluminum oxide formed from impurities and to promote aluminum particle coalescence without causing substantial re-chlorination of the metal. Also, it has been observed surprisingly that with the employment of close anode-cathode spacing, e.g. less than three-fourth inch, the attack on carbonaceous cathode surfaces that is otherwise caused by the presence of reduced alkali metal in the bath is minimized. Still further advantages flow

from the low heat generated and the reduced operating temperatures that may be employed.

While achieving the various advantages referred to above may not alone render the electrolytic reduction of aluminum from aluminum chloride a commercially viable reality, the advances herein disclosed provide an answer to fundamental problems of long standing which have impeded progress in this field and, as such, represent marked contributions to the desired attainment of the ultimate and long standing objective of providing an economically feasible and commercially viable process for the production of aluminum from aluminum chloride.

BRIEF DESCRIPTION OF DRAWINGS

In the accompanying drawings, FIG. **1** is a sectional elevation of a cell for producing metal in accordance with the invention, the cell having a plurality of electrodes in superimposed relationship in the cell cavity.

FIG. **2** is an enlarged view taken along the line II—II of FIG. **1**, showing the underside (anode surface) of a bipolar electrode employed in the cell of FIG. **1**.

FIG. **3** is a vertical section of the bipolar electrode shown in FIG. **2**, the section being taken on the line III—III of FIG. **2**.

FIG. **4** is a left end view of the bipolar electrode shown in FIG. **2**, the orientation thereof being shown by the line IV—IV in FIG. **2**.

DETAILED DESCRIPTION OF THE INVENTION

Cell Structure

A preferred cell structure for producing aluminum in accordance with the principles of the invention is illustrated in the drawings. Referring particularly to FIG. **1**, the cell illustrated includes an outer steel shell **1**, which is lined with refractory sidewall and end wall brick **3**, made of thermally insulating, electrically nonconductive material which is resistant to molten aluminum chloride-containing halide bath and the decomposition products thereof. The cell cavity accommodates a sump **4** in the lower portion for collecting the aluminum metal produced. The sump bottom **5** and walls **6** are preferably made of graphite. The cell cavity also accommodates a bath reservoir **7** in its upper zone. The cell is enclosed by a refractory roof **8**, and a lid **9**. A first port **10**, extending through the lid **9** and roof **8**, provides for insertion of a vacuum tapping tube down into sump **4**, through an internal passage to be described later, for removing molten aluminum. A second port **11** provides inlet means for feeding aluminum chloride into the bath. A third port **12** provides outlet means for venting chlorine.

Within the cell cavity are a plurality of plate-like electrodes which include an upper terminal anode **14**, desirably an appreciable number of bipolar electrodes **15** (four being shown), and a lower terminal cathode **16**, all preferably of graphite. These electrodes are arranged in superimposed relation, with each electrode preferably being horizontally disposed within a vertical stack. The cathode **16** is supported at each end on sump walls **6**. The remaining electrodes are stacked one above the other in a spaced relationship established by interposed refractory pillars **18**. Such pillars **18** are sized to closely space the electrodes, as for example to space them with their opposed surfaces separated by less than three-fourth inch. In the illustrated embodiment, five inter-electrode spaces **19** are formed between opposed electrodes, one between cathode **16** and the lowest of the bipolar electrodes **15**, three between successive pairs of intermediate bipolar electrodes **15**, and one between the highest of the bipolar electrodes **15** and anode **14**. Each inter-electrode space is bounded by an upper surface of one electrode (which functions as an anode surface) opposite a lower surface of another electrode (which functions as a cathode surface), and the spacing therebetween, e.g. about one-half inch, is referred to herein as the anode-cathode distance (the electrode to electrode distance being the effective anode-cathode distance in the absence of a metal layer of substantial thickness). The bath level in the cell will vary in operation but normally will lie well above the anode **14**, thus filling all otherwise unoccupied space therebelow within the cell.

Anode **14** has a plurality of electrode bars **24** inserted therein which serve as positive current leads, and cathode **16** has a plurality of collector bars **26** inserted therein which serve as negative current leads. The bars **24** and **26** extend through the cell wall and are suitably insulated from the steel shell **1**.

As noted earlier, the sump **4** is adapted to contain bath and molten aluminum, and the latter may accumulate beneath the bath in the sump, during operation. Should it be desired to separately heat the bath and any metal in sump **4**, an auxiliary heating circuit may be established therein.

With reference now to FIGS. **2**, **3** and **4**, as well as FIG. **1**, the bath flow passages will now be described. A bath supply passage, flow into which is indicated by the arrow at **30**, generally extends from the upper reservoir **7** down along the right hand side (as viewed in FIG. **1**) of the superimposed electrodes, and such passage has fluid communication with each inter-electrode space **19**, and desirably with the sump **4**. This bath supply passage is compositely defined by a series of selectively sized and shaped openings in the sides of the electrodes. The general movement of bath will be downwardly from the right side of anode **14**, as seen in FIG. **1**, through a relatively wide opening in the edge of the anode **14**, thus passing into the space on the right hand side of the uppermost inter-electrode space **19**. The bath flows downwardly through the bath supply passage openings on the right hand side of the next electrode to the right hand side of the next inter-electrode space **19**, and so on. A portion of such bath may flow on through the openings on the right hand side of the cathode **16** into and through the sump **4**. In an exemplary construction, the bath supply passage through the marginal edges of the several electrodes may be formed by drilling round holes **31** and saw-cutting lateral slots **32**. In this case, the round holes **31** are conveniently of the same diameter in all of the bipolar electrodes **15** and in the cathode **16**, and such holes may conveniently accommodate insertion of a vacuum tapping tube when desired. In contradistinction therewith, the slots **32** are desirably widest in the highest bipolar electrode **15**, of decreasing size in the successively lower electrodes, and narrowest in the lowest bipolar electrode **15**. The slot may be omitted in the case of cathode **16**, if desired. FIG. **1** schematically shows a typical size gradation of such slots, while FIGS. **2**, **3** and **4** illustrate an opening **31** and slot **32** suitable for use in an intermediate bipolar electrode position. Thus, the described bath supply passage desirably has a downward size reduction suited to its function as a

vertical supply header for downwardly feeding bath from reservoir **7** into each of the inter-electrode spaces **19.**

In a similar manner, a bath return passage, flow from which is indicated by the arrow at **35,** provides for the upward transport of the bath material to the reservoir **7** after passage thereof through the inter-electrode spaces **19,** the flow being induced as described hereinafter by the gas lift pump effect of the chlorine gas internally produced, by electrolysis in the inter-electrode spaces **19.** The bath return passage generally extends upwardly along the left hand side (as viewed in FIG. **1**) of each inter-electrode space **19,** i.e., opposite the supply passage, and this bath return passage has fluid communication with each inter-electrode space **19** and desirably also communicates with the sump **4.** Such return passage is compositely defined by selectively sized and shaped openings in the sides of the electrodes, with a relatively wide opening in the edge of anode **14.** In an exemplary construction the bath return, gas lift passage through marginal edges of the several electrodes may be formed by drilling round holes **36** and saw-cutting lateral slots **37.** In this case, the round holes **36** are conveniently of the same diameter in all of the bipolar electrodes **15** and such holes may conveniently accommodate the taking of bath samples when desired. In contradistinction therewith, the slots **37** are desirably widest in the highest bipolar electrode **15,** of decreasing size in the successively lower electrodes, and narrowest in the lowest bipolar electrode **15.** FIG. **1** schematically shows a typical size gradation of such slots, while FIGS. **2, 3** and **4** illustrate an opening **36** and slot **37** suited for use in an intermediate bipolar electrode position. Thus the bath return, gas lift passage desirably has an upward size increase, i.e., it is preferably larger at the uppermost bipolar electrode levels than at the lowermost bipolar electrode levels and is generally increased in size from lower to higher levels to accommodate additional chlorine and bath flowing thereinto from successive inter-electrode spaces. The gas lift passage openings may be generally compositely sized to provide a passage area at each level of about 0.05 to 0.15 square inch per standard cubic foot per hour (SCFH) of chlorine passing therethrough (standardized at a pressure of 1 atmosphere and a temperature of 70°F).

The selective flow of gas and bath across each inter-electrode space **19** is desirably selectively directed by the configuration of its upper or anode surface, a preferred configuration being illustrated in FIGS. **2, 3** and **4.** Each bipolar electrode **15** has a flat cathode surface **40,** as does cathode **16,** which functions as the lower bounding surface of an inter-electrode space **19;** and each bipolar electrode **15** also has a transversely channelled anode surface **41,** as does anode **14,** which functions as the upper bounding surface of an inter-electrode space **19.** The anode surface of each electrode is preferably undercut or relieved around its perimeter **42,** in the side edge portions of which bath flow passage openings **31, 32** and **36, 37** are provided. Such relief operates to minimize electrolysis at the perimeter of the electrodes and thereby reduces any tendency toward short circuiting at the sides and edges of the cell.

Each anode surface includes a plurality of spaced rectangular slots or channels **45** which transversely extend to the relieved side edge of each electrode at the bath return-gas lift passage side thereof. Such slots operate to conduct chlorine upwardly away from the balance of the lower anode surface **41** and thereby effect removal of chlorine from a location within the minimum anode-cathode space to a location further from the aluminum produced on the cathode surface, with a concomitant minimizing of re-chlorination of the aluminum produced. The channels **45** do not extend to the relieved edge at the bath supply passage side but terminate in fluid communication with a common lateral connecting channel **46.** The lateral channel **46** is desirably located inboard of the bath supply passage and is defined in part by a downwardly depending marginal ledge **47** serving as a gas dam to obstruct, if not effectively prevent, back flow of chlorine gas into the bath supply passage **30.** Transverse and lateral channels, similar to channels **45, 46** as just described, are incorporated on the underside of each bipolar electrode **15,** and are also preferably included in the lower surface of anode **14.** By way of example, the anode surface of each electrode desirably has a total projected channel area which is substantial but constitutes less than half the total projected area of the anode surface. The slot area and depth is desirably chosen so as to readily direct the transport of chlorine away from the lowermost anode surface **41.**

The Molten Bath

The electrolyte employed for producing aluminum in accordance with the subject invention normally will comprise a molten bath composed essentially of aluminum chloride dissolved in one or more halides of higher decomposition potential than aluminum chloride. By electrolysis of such a bath, chlorine is produced on the anode surfaces and aluminum on the cathode surfaces of the cell electrodes. The aluminum is conveniently separated by settling from the lighter bath, and the chlorine rises to be vented from the cell. In such practice of the subject invention, the molten bath is positively circulated through the cell by the buoyant gas lift effect of the internally produced chlorine gas, and aluminum chloride is periodically or continuously introduced into the bath to maintain the desired aluminum chloride concentration.

The bath composition, in addition to the dissolved aluminum chloride, will usually be made up of alkali metal chlorides, although, other alkali metal halides and alkaline earth halides, may also be employed. A presently preferred composition comprises an alkali metal chloride base composition made up of about 50–75% by weight sodium chloride and 25–50% lithium chloride. Aluminum chloride is dissolved in such halide composition to provide a bath from which aluminum may be produced by electrolysis, and an aluminum chloride content of about 1½ to 10 % **by weight of the bath will generally be desirable. As an example, a bath analysis as follows (in percent by weight) is satisfactory:** 53% NaCl, 40% LiCl, 0.5% $MgCl_2$, 0.5% KCl, 1% $CaCl_2$, and 5% $AlCl_3$. In such bath, the chlorides other than NaCl, LiCl and $AlCl_3$ may be regarded as incidental components or impurities. The bath is employed in molten condition, usually at a temperature above that of molten aluminum and in the range between 660° and 730°C, typically at about 700°C.

Process

The process for producing metal from metal chloride is exemplified by the process described in the following detailed description of preferred modes of operation of

the process as employed for producing aluminum in a bipolar electrode cell, it being understood that references to exemplary cell structure shown in the drawings should be taken as illustrative only. As described hereinabove, bath supplied from reservoir **7** through bath supply passage **30** is electrolyzed in each inter-electrode space **19** in a cell which includes, in superimposed, spaced relationship, an upper anode **14**, at least one intermediate bipolar electrode **15** and a lower cathode **16**, to produce chlorine on each anode surface thereof **41**, and aluminum on each cathode surface thereof **40**. The electrode current density may conveniently range from about 5 to 15 amperes per square inch, the practical operating current density suited to any particular cell structure being readily determined by observation of the operating conditions. The chlorine so produced is buoyant and its movement is employed to effect bath circulation, while aluminum is swept by the moving bath from the cathode surfaces and settles from the outflowing bath in a manner to be described hereinbelow. An induced flow of molten bath into, through and out of each inter-electrode space **19** is established which sweeps aluminum produced on each cathode surface **40** through and out of each inter-electrode space **19** in a direction concurrent with the flow of the bath. This sweeping action effectively prevents aluminum from coalescing in unduly large droplets or from building up into a substantial pool or layer thickness on the cathode surfaces, and the bath flow through each inter-electrode space may be maintained at a rate such that there is no substantial accumulation of aluminum therein. In any given installation, the practical velocity suited to any particular cell structure and anode-cathode spacing will be determined by observation of the operating conditions.

The molten bath exiting from each inter-electrode space **19** is effectively and positively pumped upwardly in the return passage **35**, preferably by employment of the gas lift effect thereon of chlorine produced and conducted from each inter-electrode space in the same general direction as the bath and buoyantly rising in the return passage **35**. This, in turn, induces the selectively directed, concomitant flow of bath through the inter-electrode spaces. Preferably the bath which is upwardly moving in the return passage **35** is delivered to the reservoir **7** above the anode **14**, where the chlorine may be conveniently vented from the bath (at port **12**) and the aluminum chloride content of the bath may be replenished (through port **11**).

While the bath is being upwardly displaced in the gas lift passage **35** as described above, aluminum swept thereinto from each inter-electrode space **19** is permitted to settle in a counter current direction therein and, surprisingly, most of the aluminum may so settle without undue re-chlorination of aluminum so produced, although some aluminum may be carried upwardly with the bath to be recirculated with the bath. Conveniently, the settling aluminum accumulates in a sump **4** below the cathode **16**, from which it may be tapped as desired. One practical method of removing molten aluminum is to use a vacuum tapping tube inserted into sump **4** through port **10** and the bath supply passage **30**.

As will now be apparent, the inclusion of a plurality of spaced transverse passages and associated lateral passage on the underside of anode surfaces not only accommodates the outward flow of chlorine produced without accumulation of a substantial amount of such chlorine on the lowermost anode surfaces **41**, but also selectively and unidirectionally directs and channels the flow of chlorine in a substantially unobstructed manner, minimizing or preventing back flow toward the supply passage **30**. The desired selectively directed chlorine flow toward the gas lift passage **35** may be established even against a flat anode surface, of course, by various means, such as temporary initial restriction of back flow in the supply passage.

The present invention as applied to aluminum, it will be observed from the foregoing description, provides both process and apparatus for producing aluminum from aluminum chloride with substantially no consumption of anode carbon by evolved oxygen, with lower heat input and lower temperatures than encountered in the Hall process, and with high power efficiency made possible by the opportunity to employ cell design and operating conditions in which there is low cell resistance and yet minimal re-chlorination of the aluminum produced. Thus, it will be seen that the subject invention provides a significant contribution to obtaining the long sought economic advantages in producing aluminum from aluminum chloride.

As earlier indicated, the invention may be employed for producing other metals and alloys. For example, the cell and process described in detail herein may be employed to produce magnesium. In such case the bath may be composed of magnesium chloride dissolved in molten halide of higher decomposition potential. A suitable low density composition is one made up of at least about 80% by weight, preferably about 85%, lithium chloride and at least about 1½% by weight, preferably about 15%, magnesium chloride. From such a bath, magnesium metal is produced in the manner generally described with reference to producing aluminum. If a small amount of aluminum chloride is also present, the metal produced may also contain some aluminum.

What is claimed is:

1. A cell for producing metal comprising

an anode, at least one intermediate bipolar electrode and a cathode in superimposed, spaced relationship defining inter-electrode spaces, each bounded by an anode surface and a cathode surface, for electrolyzing bath composed essentially of metal chloride dissolved in molten solvent,

a bath supply passage extending downwardly to each inter-electrode space,

a gas lift passage extending upwardly from each inter-electrode space at a location spaced from the bath supply passage for receiving chlorine, bath and metal from the inter-electrode space, said gas lift passage being adapted upon electrolysis of bath in each inter-electrode space to cause flow of bath out of the inter-electrode space, and thus induce concurrent outward flow of metal swept therewith, and to pump bath upwardly by employment of the gas lift effect of the chlorine produced and conducted to said passage, and to permit metal flowing into said passage to settle therein,

in which cell the flow of bath down through the supply passage, through the inter-electrode spaces, and back up through the gas lift passage may be maintained by the flow of chlorine produced, while metal produced may settle in a direction counter current to the gas lift.

2. A cell according to claim 1 in which the minimum distances between opposed anode and cathode surfaces are less than three-fourth inch.

3. A cell according to claim 1 in which said bath supply passage extends from a location above said anode.

4. A cell according to claim 1 provided with a sump below said cathode, with which said gas lift passage communicates, for accumulation of metal produced.

5. A cell according to claim 1 in which each said anode surface has spaced channels therein for receiving and directing flow of chlorine toward and into said gas lift passage, said spaced channels communicating with said gas lift passage but not with said bath supply passage, whereby back flow of chlorine into said bath supply passage is obstructed, said spaced channels being recessed from the minimum anode-cathode space, thereby to effect removal of chlorine from a location within the minimum anode-cathode space to a location further from the metal produced on the cathode surface.

6. A cell according to claim 1 in which said gas lift passage is larger at the anode level than at the lowermost bipolar electrode level, and is generally sized from lower to higher levels to have an area of about 0.05 to 0.15 square inch per standard cubic foot per hour of chlorine passing therethrough, to accommodate upward flow of chlorine and bath from the inter-electrode spaces.

7. A cell according to claim 1 in which an upper zone for bath, located above said anode, is provided with outlet means for venting chlorine therefrom and inlet means for replenishing the metal chloride content of the bath.

8. In a cell for producing aluminum by the electrolytic reduction of aluminum chloride in a molten halide bath,

a plurality of substantially horizontal electrodes disposed in superimposed, vertically spaced relationship defining inter-electrode spaces,

means defining a first passage for molten bath disposed in fluid communication with said inter-electrode spaces for conducting bath into said spaces from a source thereof,

means defining a second passage disposed in fluid communication with said inter-electrode spaces and remote from said first passage for conducting bath from said spaces to said source thereof,

said means providing for upwardly displacing molten bath by gas lift effect in said second passage and inducing a flow of bath from said first passage into and through said inter-electrode spaces and into said second passage, whereby substantial accumulation of aluminum in the inter-electrode spaces may be prevented.

9. In a cell as set forth in claim 8 including channel means disposed on the upper anode surfaces of the defined inter-electrode spaces to selectively direct chlorine internally produced in said inter-electrode spaces into said second passage for upwardly displacing molten bath by gas lift effect, said channel means including channels recessed from the minimum anode-cathode space, thereby to effect removal of chlorine from a location within the minimum anode-cathode space to a location further from the metal produced on the cathode surface.

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