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[54] **LOW TEMPERATURE REMOVAL AND
RECOVERY OF HYDROGEN HALIDES
USING AN ELECTROCHEMICAL
MEMBRANE**

[75] Inventor: **Jack Winnick**, Atlanta, Ga.
[73] Assignee: **Georgia Tech Research Corp.**, Atlanta,
Ga.
[*] Notice: This patent is subject to a terminal dis-
claimer.

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C25B 9/00
[52] U.S. Cl. **205/618**; 205/619; 205/763;
205/765; 204/245; 204/246
[58] Field of Search 205/763, 765,
205/618, 619; 204/245, 246

[56] **References Cited**

U.S. PATENT DOCUMENTS

4,246,081	1/1981	Winnick	204/130
4,738,760	4/1988	Marianowski et al.	204/130
4,762,596	8/1988	Huang et al.	204/60
4,859,292	8/1989	Appleby	204/60
5,411,641	5/1995	Trainham, III et al.	204/59
5,618,405	4/1997	Winnick	205/763

OTHER PUBLICATIONS

The Recovery of Chlorine from Hydrogen Chloride, Part 1:
New Method Using a Molten Salt as the Electrolyte, S.
Yoshizawa, Z. Takehara, Y. Ito and K. Oka, Journal of
Applied Electrochemistry 1 (1971) 245-251.

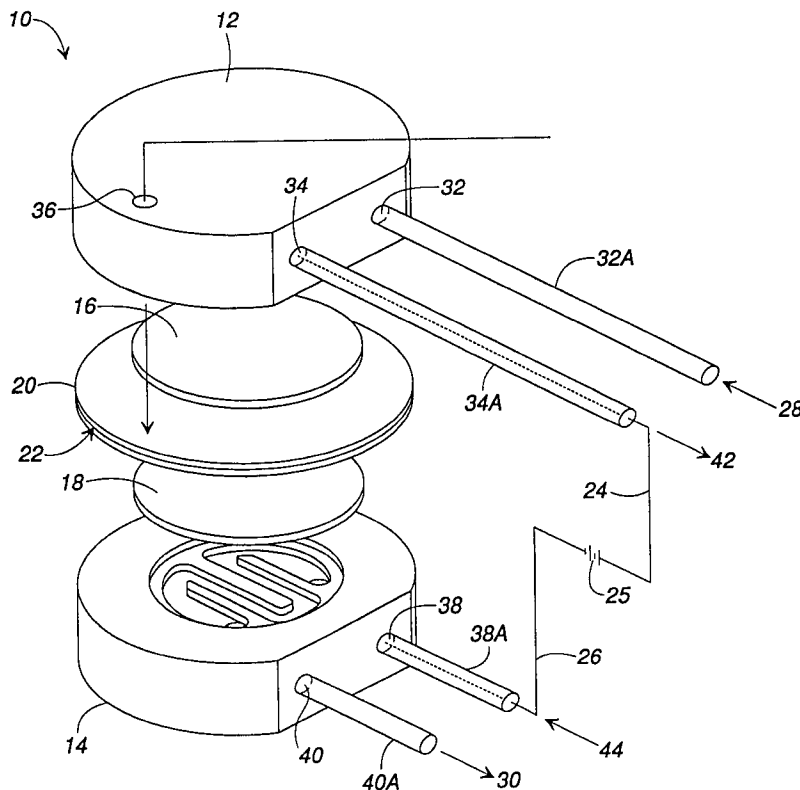
The Recovery of Chlorine From By-Product Hydrogen
Chloride, Part 2: Molten Metal Cathode Method S.
Yoshizawa, A. Takehara, Y. Ito and K. Oka, Journal of
Applied Electrochemistry 1 (1971) 253-259.

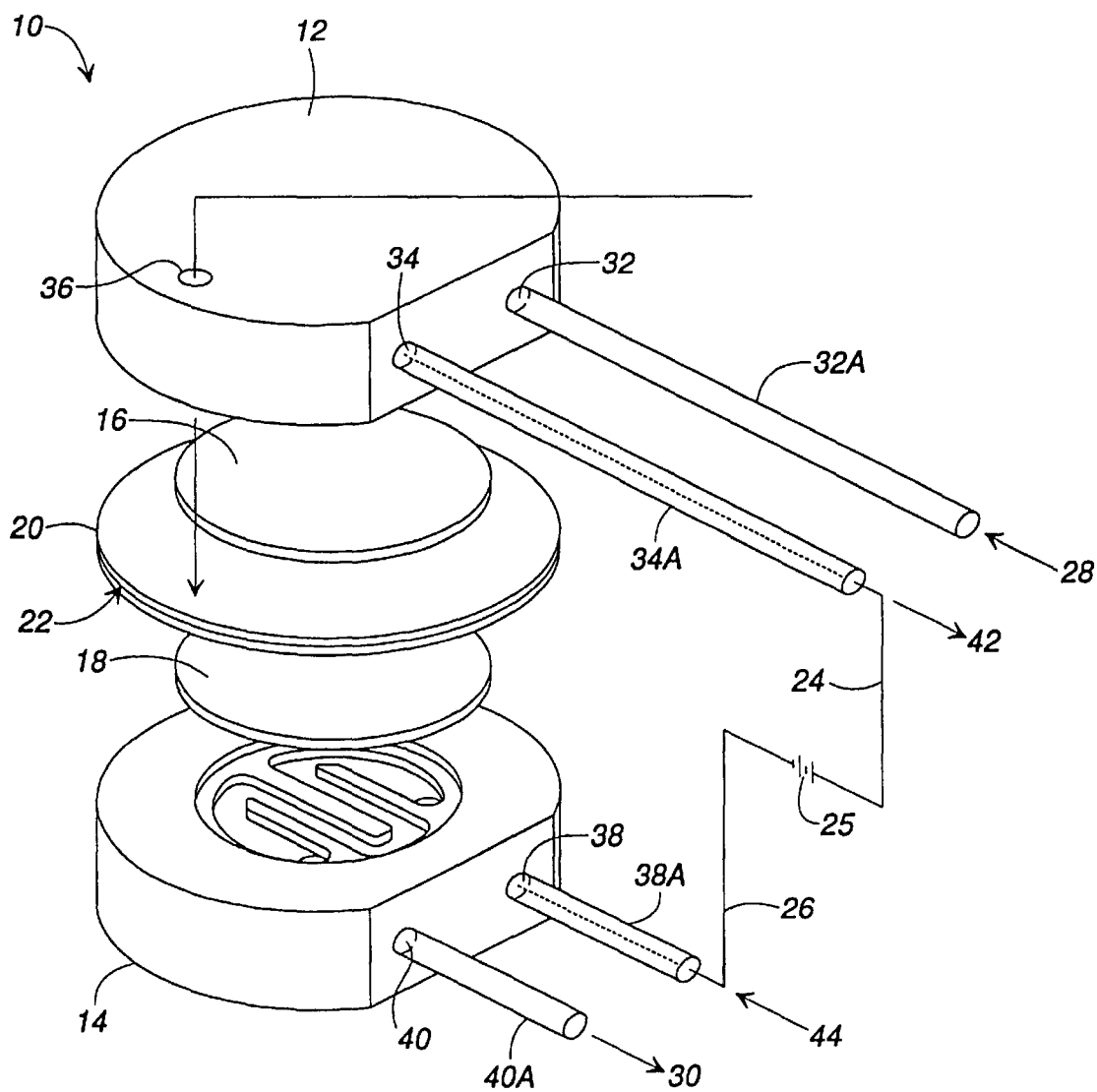
Primary Examiner—Arun S. Phasge
Attorney, Agent, or Firm—Deveau, Colton & Marquis

[57] **ABSTRACT**

A low temperature method and apparatus for removing
halides from relatively low temperature gas mixtures (below
about 150° C.) using an electrochemical cell provided with
inert electrodes and an electrolyte which will provide anions
compatible with the halide anions formed at the anode. The
electrolyte is elected to provide inert stable cations at the
temperatures encountered. The gas mixture is passed by the
cathode where the halides are converted to X⁻. The anions
migrate to the anode where they are converted to a stable
gaseous form at much greater concentration levels. Current
flow may be effected by utilizing an external source of
electrical energy or by passing a reducing gas such as
hydrogen past the anode.

25 Claims, 3 Drawing Sheets



**FIG. 1**

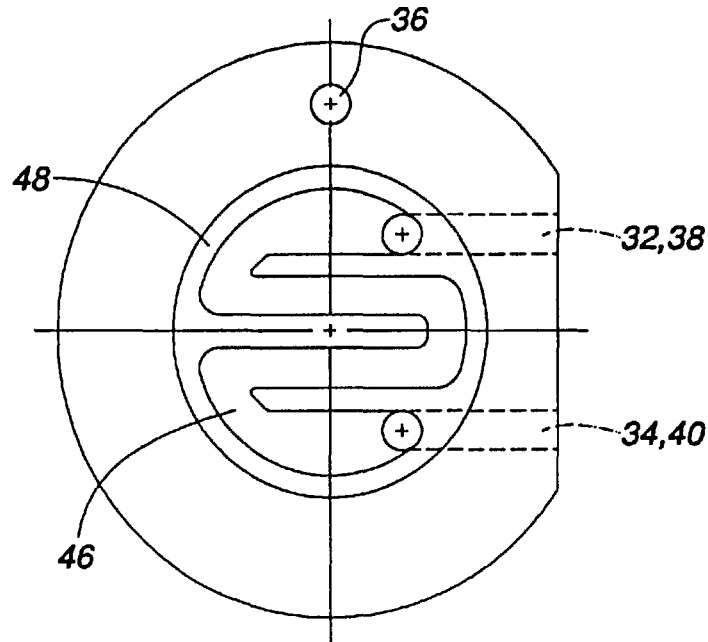


FIG. 2

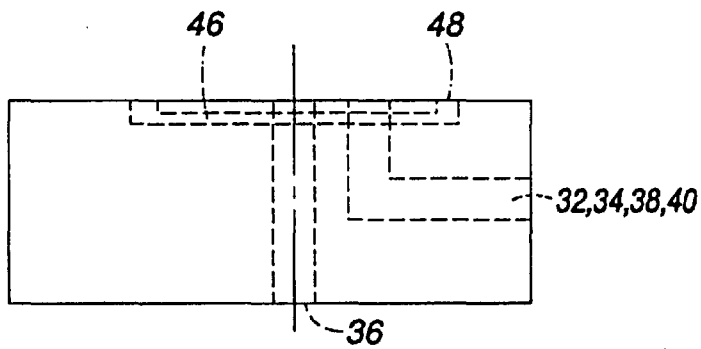


FIG. 3

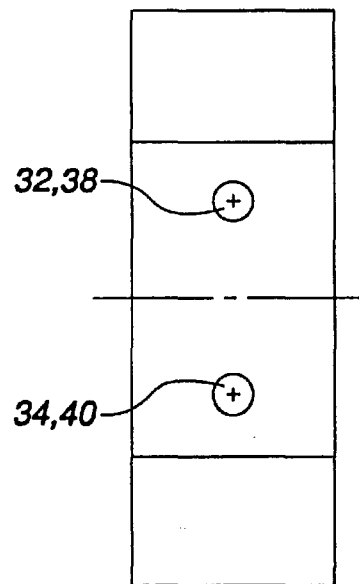
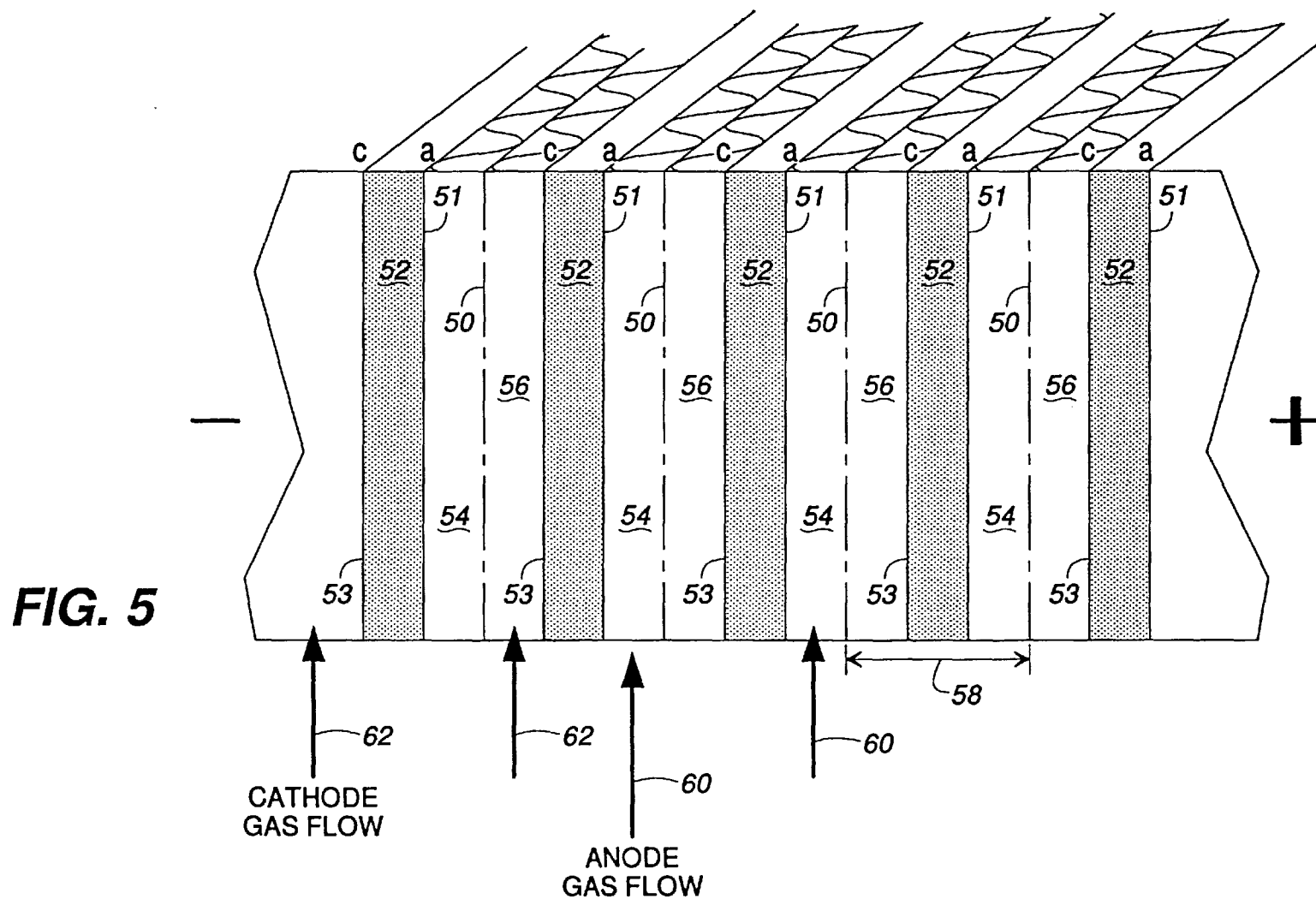


FIG. 4



BIPOLAR ARRAY FOR INDUSTRIAL APPLICATION

LOW TEMPERATURE REMOVAL AND RECOVERY OF HYDROGEN HALIDES USING AN ELECTROCHEMICAL MEMBRANE

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates generally to the low temperature removal and recovery of hydrogen halides from gases using an electrochemical membrane and, more particularly, to a low temperature method and apparatus comprising an electrochemical halide recovery cell which allows the recycling of waste hydrogen halide streams into refreshed hydrogen halide or elemental halide.

2. Prior Art

Electrochemical techniques previously have been employed in fuel cells for the separation of carbon dioxide from closed environments. The known processes of the prior art are, however, inoperable at extremely high temperatures, such as in the 150° C. to 1000° C. range. At high temperatures, for example as commonly encountered in industrial stack gases, the known techniques for removing water soluble gases, such as halides, is through water scrubbers. Water scrubbers are expensive to install and maintain, normally requiring chemical additives to improve absorption, and often resulting in liquid-sludge disposal problems. Water scrubbers also have high energy requirements in that the stack gas must be reheated before release to the environment. Additionally, recovery of elemental halides is difficult and expensive using known methods.

The use of molten salt electrolytes, specifically a lithium chloride-potassium chloride mixture, to recover a halide, specifically chlorine, from a gas, specifically, hydrogen chloride, has been reported in Yoshizawa, S. et al., I J. Appl. Electrochem. 245-251 (1971). The Yoshizawa method recovers hydrogen and chlorine by passing hydrogen chloride gas through a carbon pipe to a gas diffusion-type porous carbon cathode, which is immersed in a molten salt of lithium chloride-potassium chloride. A graphite anode is immersed in the same electrolyte. The hydrogen chloride is electrolyzed and hydrogen is obtained from the cathode and chlorine is obtained from the anode. The cell is operated at 400° C.

A method and apparatus for the electrochemical separation and concentration of sulfur containing gases from gas mixtures is disclosed and claimed in this inventor's U.S. Pat. No. 4,246,081. The '081 patent discloses an electrochemical cell similar to the cell disclosed in this specification. However the '081 patent cell is configured to remove sulfur and it was not apparent to configure the cell for the removal and recovery of halides, nor to even use the cell for the removal and recovery of halides.

A method and apparatus for the removal and recovery of hydrogen halides using an electrochemical membrane from high temperature (150°-1000° C.) gas mixtures has been patented by the present inventor in U.S. Pat. No. 5,618,405 to Winnick. The '405 patent discloses and claims an electrolytic cell which operates at temperatures at or above 150° C. using an electrolyte which is molten at or above 150° C. Although the invention disclosed and claimed in the '405 patent is suitable for its intended purpose, it contemplates use of relatively high melting electrolytes and operating temperatures. The present invention utilizes electrolytes which have lower melting temperatures allowing relatively low operating temperatures. This is a significant step forward in the art.

Although the basic idea of using an electrochemical cell for the concentration of certain specific gases is known, electrochemical cells have not been known or considered for use in concentrating, removing or recovering halides from high temperature gases. In contrast to existing methods and apparatuses for dealing with waste hydrogen halides, such as neutralization and disposal or recycling by catalytic means, the present cell utilizes an electrochemical membrane for recycling. The method for operating the electrochemical cell involves only one step and is much more economical and environmentally sound than the existing methods and apparatuses. Further, the present cell can operate at temperatures below 150° C., increasing the range at which such removal and recovery can occur.

SUMMARY OF THE INVENTION

Briefly described, in a first preferred form the present invention comprises a method of removing halides from a gas mixture at a temperature below about 150° C. using an electrolyte comprising hydrogen halide and alkali metal halides. The method comprises the steps of:

- a. providing an electrochemical cell having an inert cathode and an inert anode;
- b. providing the cell with an electrolyte which is molten at temperatures below about 150° C. selected from the group comprising hydrogen halide combined with one or more alkali metal halides, such as hydrogen fluoride combined with potassium, sodium, lithium or cesium fluoride, or mixtures thereof;
- c. maintaining the temperature of the cell below about 150° C. whereby the electrolyte is in its molten state;
- d. effecting current flow between the cathode and the anode;
- e. directing the gas mixture past the cathode where oxidation of the halide occurs and halide anions are formed which migrate toward the anode and are converted to gaseous species,

whereby halide gases are evolved at the anode.

In another preferred form, the present invention comprises an electrochemical cell for removing halides from a gas mixture at a temperature of below about 150° C. The electrochemical cell comprises a first cell housing and a second cell housing. The cell further includes a cathode associated with the first cell housing and an anode associated with the second cell housing. The cell also includes a porous ceramic membrane between the first cell housing and the second cell housing, separating the first cell housing from the second cell housing. The cell also includes an electrolyte within the porous ceramic membrane which is molten at temperatures below about 150° C.

In yet another preferred form, the present invention comprises a bipolar array of electrochemical cells for removing halides from a gas mixture at a temperature of below about 150° C. The array includes a plurality of electrochemical cells arranged in series (electrically). Each of the cells comprises an electrolyte-filled membrane having first and second sides, a cathode held in electrical contact with the first side of the membrane, and an anode held in electrical contact with the second side of the membrane. Each cell also includes a cathode gas flow channel connected to the cathode opposite the membrane, and an anode gas flow channel connected to the anode opposite the membrane. At least two such cells are connected to one another by an electrically conductive cell interconnect to form an array of cells.

It is therefore an object of the present invention to provide an electrochemical process and device for the recovery and

removal of halides from lower temperature gas mixtures using electrochemical membrane technology.

It is another object of the present invention to provide an electrochemical process and device for the recovery and removal of halides from lower temperature gas mixtures which allows the recycle of waste hydrogen halide streams into refreshed hydrogen halide.

It is another object of the present invention to provide an electrochemical process and device for the recovery and removal of halides from lower temperature gas mixtures which allows the recycle of waste hydrogen halide streams into elemental halide.

Another object of the invention is to provide an electrochemical process for the recovery and removal of halides from lower temperature gas mixtures which is more economical to operate than conventional methods.

Yet another object of the invention is to provide an electrochemical process and device for the recovery and removal of halides from lower temperature gas mixtures which is more effective in recovering the removed gases in forms more easily stored and sold, thereby making recovery of the removed gas more feasible.

These and other objects, features and advantages of the invention will become more apparent to one skilled in the art from the following description and claims when read in light of the accompanying drawings.

BRIEF DESCRIPTION OF THE FIGURES

FIG. 1 is an exploded view of an electrochemical cell according to a preferred form of the present invention.

FIG. 2 is a top view of one of the half cell housings of the electrochemical cell shown in FIG. 1.

FIG. 3 is a side view of one of the half cell housings of the electrochemical cell shown in FIG. 2.

FIG. 4 is a front view of one of the half cell housings of the electrochemical cell shown in FIG. 2.

FIG. 5 shows another embodiment of the present invention having cells stacked in a bipolar series array with parallel flow.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring now to FIG. 1, the present electrochemical cell apparatus 10 comprises two half cell housings, a waste stream housing 12 and a sweep stream housing 14, each fitted with a highly porous electrode 16, 18 and separated by a porous ceramic membrane 20 saturated in a eutectic mixture of molten salt 22. Waste stream housing 12 is fitted with the cathode electrode 16 and sweep stream housing 14 is fitted with the anode electrode 18. A conductive non-reactive material such as reticulated vitreous carbon is used as the material for electrodes 16, 18. The electrodes 16, 18 are preferably fitted with gold electrical leads (unshown) using a graphite cement. The ceramic membrane 20 acts to separate the waste hydrogen halide (the waste stream 28) from the elemental halide (the sweep stream 30). The molten salt 22 acts to both form a wet seal at each half cell housing 12, 14 and for ion transport from the cathode 16 to the anode 18.

Waste stream housing 12 comprises a plurality of ports 32, 34, 36 communicating with the exterior of the cell 10. Conduits 32A, 34A are in communication with the respective ports 32, 34. The waste stream 28 containing the halide to be recovered is introduced to the cell 10 through conduit 32A and port 32. After the halide has been removed from the

waste stream 28, the polished waste stream 42 exits the cell 10 through port 34 and conduit 34A. Additional molten salt electrolyte 22 can be added to the cell 10 through port 36.

Sweep stream housing 14 comprises a plurality of ports 38, 40 communicating with the exterior of the cell 10. Conduits 38A, 40A are in communication with the respective ports 38, 40. The pure sweep stream 44 (prior to recovering the halide) is introduced to the cell 10 through conduit 38A and port 38. After the halide has been removed from the waste stream 28 by the pure sweep stream 44, the halide-enriched sweep stream 30 exits the cell 10 through port 40 and conduit 40A.

Disposed centrally of the cell 10 is an electrolyte tile 22 which holds the electrolyte matrix and the electrolyte material. Tile 22 preferably is formed from a ceramic or other highly porous inert material which is stable at the temperatures required for operation of the present cell 10. Although materials which can withstand temperatures up to 150° C. are required, materials which can withstand temperatures over 150° C. are preferred so that the cell 10 can be used both in the currently disclosed low temperature setting and in high temperature settings. Located adjacent to and in close contact with tile 22 is the porous cathode of the cell which is designated by the numeral 16. Cathode 16 can be held in place by a porous grid (unshown), or by shelf 48, as is more fully described below. The anode of the cell is designated by the numeral 18 and is also in intimate contact with electrolyte tile 22. The anode can be held in place by a second porous grid (unshown), or by the shelf and flow path arrangement described below.

In one embodiment, lead lines (unshown), extending through cell housings 12, 14 are in electrical contact with the anode 18 and cathode 16 and are coupled with an external source of electrical energy or control.

Referring now to FIGS. 2, 3, and 4, each half cell housing 12, 14 has a generally similar configuration. Cell housings 12, 14 are generally solid components comprising flow path 46 through which either the waste stream 28 or the sweep stream 30 flow, respectively. Flow path 46 is formed in the surface of the one cell housing 12, 14 which, when the cell 10 is in its operational mode, is closest to the other cell housing 14, 12, with the ceramic membrane 20 therebetween. Flow path 46 typically is serpentine so as to allow the most transfer of halide from the waste stream 28 to the sweep stream 30.

Shelf 48 is located immediately above flow path 46 and is used to support the respective electrode 16, 18. Cathode 16 is supported by shelf 48 formed on waste cell housing 12 and anode 18 is supported by shelf 48 formed on sweep cell housing 14. Shelf 48 should have approximately the same height as the thickness of electrodes 16, 18 so that electrodes 16, 18 will fit snugly within housings 12, 14 respectively.

Ports 32, 34, 38, 40 allow communication between flow path 46 and the exterior of the cell 10. Port 32 allows communication with one end of flow path 46 from the exterior of the waste cell housing 12 and port 34 allows communication with the other end of flow path 46 from the exterior of the waste cell housing 12. Likewise, port 38 allows communication with one end of flow path 46 from the exterior of the sweep cell housing 14 and port 40 allows communication with the other end of flow path 46 from the exterior of the sweep cell housing 14. Port 36 allows communication between the ceramic membrane 20 and the exterior of cell 10, and can be provided in either cell housing 12, 14.

FIG. 5 shows, in partial sectional view, an embodiment of the present invention having multiple cells, each cell sub-

stantially as described above, stacked in a bipolar series (electrically) array with parallel flow of the anode gas and the cathode gas. Individual cells **58** are connected by cell interconnects **50**. Cell interconnects **50** are electrically conductive and impermeable to the anode and cathode gasses, and are preferably fabricated from graphite. Each cell comprises an electrolyte-filled membrane **52**, centrally disposed, in close registration, between an anode **51** and a cathode **53**.

Each cell **58** further comprises an anode gas flow channel **54** and a cathode gas flow channel **56**. Gas flow channels **54**, **56** are preferably formed from corrugated graphite, vitreous carbon or carbon. Anode gas flow channel **54** is held in close registration and is in electrical contact with anode **51** on one side, and with a cell interconnect **50** on the other. Cathode gas flow channel **56** is held in close registration and in electrical contact with cathode **53** on one side, and with another cell interconnect **50** on the other.

Because the cell interconnects **50** are in electrical contact on one side with the anode gas flow channel **54** of one cell, and on the other side with cathode gas flow channel **56** of a neighboring cell, the stacked cells act as a series array (electrically, the cells are in series).

Anode gas flow **60** is introduced, preferably through an anode gas manifold (unshown), to the anode gas flow channel **54**, and flows therethrough. Anode gas flow **60** is equivalent to sweep stream **44** described above in relation to the individual cell. Cathode gas flow **62** is, likewise, introduced to the cathode gas flow channel **56** through an unshown cathode gas manifold, and is equivalent to the above-described waste stream **28**. Anode gas flow **60** and cathode gas flow **62** can flow in the same direction, as shown in FIG. **5**, or can operate in cross flow.

For improved removal and recovery of halides, two or more of the above-described arrays may be operated in series, with the effluent gas flows from one array being introduced as the influent feed to the second array. As is known in the art, the different concentrations of halides in the two arrays will require that the electrical operating parameters of each array be adjusted accordingly.

The present invention is useful for the recovery of halides from hydrogen halide gases. In particular, the present cell is useful for the recovery of fluorine from hydrogen fluoride gas.

The preferred molten salt electrolyte is a hydrogen halide combined with an alkali metal halide. In particular, using hydrogen fluoride in combination with lithium, potassium, sodium, cesium and mixtures thereof as the electrolyte will produce the most economical results. The electrolyte can be made prior to forming the cell by selecting one or a mixture of suitable electrolyte materials, mixing them if necessary to form the electrolyte, and placing the electrolyte in the cell. Alternatively, the electrolyte can be made in situ in the cell itself by placing the electrolyte materials in the cell prior to operation.

Any inert porous material may be used as the porous ceramic membrane. In particular, using silica (SiO₂), magnesia (MgO), boron nitride (BN), silicon nitride (SiN), silicon carbide (SiC) or similar inert ceramics or mixtures thereof as the porous ceramic membrane has produced the most economical results. Typically, the porous ceramic membrane is formed by tape casting, cold pressing or other known forming procedures. The membrane may be formed with or without electrolyte present in the interstices.

Any conductive non-reactive material can be used for the electrodes. For example, graphite or other forms of carbon, as well as conductive ceramics and metals, are suitable.

Porous vitreous carbon electrodes have been selected as the preferred electrodes because of their ability to withstand the temperatures achieved in the cell while still being able to maintain structural integrity, as well as their unexpected ability to withstand temperatures above 150° C. should one desire to use the cell **10** in a high temperature setting. Other porous, conductive, non-reactive ceramic materials do not have this ability. In fact, it is surprising and unexpected that porous vitreous carbon does have this ability.

The cell housings can be made of any nonporous inert ceramic material, or graphite. The preferred materials for the cell housings are alumina (Al₂O₃), boron nitride (BN), zirconia (ZrO₃), or similar inert completely densified ceramic materials.

The process of the present invention encompasses a method of removing halides from gases utilizing electrochemical cell **10**, or a stacked bipolar array of such cells. To this end, an electrolyte is selected which will provide anions compatible with those formed by the halides at the cathode of the cell. Thus in the case of fluorine, an alkali metal salt is selected for the electrolyte. The electrolyte is selected with consideration for providing unreactive stable cations at temperatures up to about 150° C. The alkali metals are particularly applicable because, when combined with hydrogen fluoride, they meet the foregoing criteria and they also are readily available. Suitable matrices for the electrolyte include MgO and SiO₂. Other matrix materials may be utilized if suitably inert and stable at the high temperature encountered. The combination of hydrogen fluoride and the salt mixture has a melting point of less than 150° C., making it suitable for operation in the temperature range appropriate for this cell **10**.

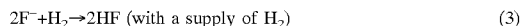
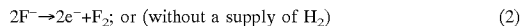
In one form of the invention the current flow between cathode **24** and anode **26** is effected by an external power source (not shown) connected across leads **24**, **26**. The halide containing waste gas **28** is directed into the cell **10** through conduit **32A** and exits through conduit **34A**. As the waste gas **28** comes into intimate contact with cathode **16** the following reactions will take place.

The electrochemical cell follows these half cell reactions, where HF is the example hydrogen halide.

At the cathode:



At the anode:



Combination of the two half cell reactions yields the following full cell reaction:



The end product of the electrolysis process evolves through conduits **40A** for disposal or further processing. The concentrated halide gas liberated at the anode **18** can be utilized to manufacture other useful products, or used as is. The concentrated gas has been found to be many times the concentration of halide waste stream **28**. Since the system is operated without the large amounts of water required in scrubbers, operating efficiency is greatly increased over conventional processes and there is no sludge disposal problem.

In an alternative operation of the invention process, cell 10 may be changed from a driven to a spontaneous cell. To this end, the lead lines are simply connected together, bypassing the external current source referred to above or they may be connected through a current controller. Current flow is effected by passing H₂ or other reducing gas in through one of conduits 32A, 34A and out through the other 34A, 32A. The reactions at the cathode remain as previously described. Partial dissolution of some electrode materials may provide an internal current path with precludes the use of an external current path or control.

The above description sets forth the best mode of the invention as known to the inventor at this time, and the above Examples are for illustrative purposes only, as it is obvious to one skilled in the art to make modifications to this process without departing from the spirit and scope of the invention and its equivalents as set forth in the appended claims.

What is claimed is:

1. A method of removing halides from a gas mixture at a temperature of below about 150° C., said method comprising the steps of:

- a. providing an electrochemical cell having an inert cathode and an inert anode;
- b. providing said cell with a porous ceramic membrane filled with an electrolyte which is molten at temperatures below about 150° C. selected from the group comprising hydrogen halide mixed with one or more alkali metal halide;
- c. maintaining the temperature of said cell to below about 150° C. whereby said electrolyte is in its molten state;
- d. effecting current flow between said cathode and said anode;
- e. directing the gas mixture past said cathode where oxidation of the halide occurs and halide anions are formed which migrate toward said anode and are converted to gaseous species,

whereby halide gases are evolved at said anode.

2. A method as claimed in claim 1, wherein said step of directing said gas mixture past said cathode results in the formation of X⁻ ions at the cathode.

3. A method as claimed in claim 2, wherein said step of providing an electrolyte comprises providing hydrogen halide and at least one alkali metal salt.

4. A method as claimed in claim 3, wherein said hydrogen halide is hydrogen fluoride.

5. A method as claimed in claim 1, wherein said step of effecting current flow comprises providing an external source of electrical energy across said anode and cathode.

6. A method as claimed in claim 1, wherein said step of effecting current flow comprises passing a reducing gas past said anode.

7. A method as claimed in claim 6, wherein said step of passing a reducing gas comprises passing hydrogen past said anode.

8. A method as claimed in claim 1, wherein said alkali metal halide is selected from the group consisting of lithium, potassium, sodium, and cesium halides, and mixtures thereof.

9. A method as claimed in claim 8, wherein said ceramic membrane is selected from the group consisting of silica, magnesia, boron nitride, silicon nitride, and silicon carbide.

10. A method as claimed in claim 9, wherein said anode and said cathode are porous vitreous carbon.

11. A method of removing halides from a gas mixture at a temperature of below about 150° C., utilizing an electro-

chemical cell characterized by a first and a second cell housing selected from the group consisting of graphite, alumina, boron nitride, and zirconia, an inert anode and an inert cathode and having a porous ceramic membrane filled with an electrolyte which is molten at operating temperatures, said electrolyte comprising at least one alkali metal halide and hydrogen halide, said method comprising the steps of:

- a. maintaining the temperature of said cell below about 150° C. whereby said electrolyte is in its molten state;
- b. effecting current flow between said cathode and said anode;
- c. directing said gas mixture past said cathode where oxidation of the halide occurs and halide containing anions are formed which migrate toward said anode and are converted to gaseous species,

whereby concentrated halide gases are evolved at said anode.

12. A method as set forth in claim 11, further comprising the step of recovering said gas evolving at said anode.

13. A method as set forth in claim 12, wherein said step of effecting current flow comprises providing an external source of electrical energy across said anode and cathode.

14. A method as set forth in claim 12, wherein said step of effecting current flow comprises passing a reducing gas past said anode.

15. A method as claimed in claim 11, wherein said electrolyte is selected from the group consisting of a hydrogen halide and one or more of lithium, potassium, sodium, and cesium halides, and mixtures thereof.

16. A method as claimed in claim 15, wherein said ceramic membrane is selected from the group consisting of silica, magnesia, boron nitride, silicon nitride, and silicon carbide.

17. A method as claimed in claim 16, wherein said anode and said cathode are porous vitreous carbon.

18. An electrochemical cell for removing halides from a gas mixture at a temperature below about 150° C., comprising:

- a. a first cell housing and a second cell housing;
- b. a cathode associated with said first cell housing and an anode associated with said second cell housing;
- c. a porous ceramic membrane between said first cell housing and said second cell housing separating said first cell housing from said second cell housing; and
- d. an electrolyte within said porous ceramic membrane, said electrolyte being molten at temperatures below about 150° C. and said electrolyte comprising a hydrogen halide and one or more alkali metal halides.

19. A cell as claimed in claim 18, further comprising means for introducing the gas mixture to the electrochemical cell through said first cell housing.

20. A cell as claimed in claim 19, further comprising means for removing the recovered halides from the electrochemical cell through said second cell housing.

21. A cell as claimed in claim 18, further comprising means for electrically connecting said anode to said cathode.

22. A cell as claimed in claim 18, wherein said electrolyte is selected from the group consisting of a hydrogen halide and one or more of lithium, potassium, sodium, and cesium halides, and mixtures thereof; said ceramic membrane is selected from the group consisting of silica, magnesia, boron nitride, silicon nitride, and silicon carbide; and said cell housing is selected from the group consisting of alumina, boron nitride, and zirconia.

23. A method as claimed in claim 22, wherein said anode and said cathode are porous vitreous carbon.

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24. A bipolar array of electrochemical cells for removing halides from a gas mixture at a temperature of below about 150° C., comprising at least two electrochemical cells arranged in electrical series, each of said cells comprising:

- a. an electrolyte-filled membrane having first and second sides, said electrolyte being molten at temperatures below about 150° C. and said electrolyte comprising a hydrogen halide and one or more alkali metal halides;
- b. a first cell housing and a second cell housing;
- c. a cathode held in electrical contact with said first side of said membrane;
- d. an anode held in electrical contact with said second side of said membrane;

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- e. a cathode gas flow channel connected to said cathode opposite said membrane; and
- f. an anode gas flow channel connected to said anode opposite said membrane,

said at least two cells being connected to one another by an electrically conductive cell interconnect.

25. A bipolar array as claimed in claim **24**, wherein said membrane is a porous ceramic membrane and said first cell housing and said second cell housing are selected from the group consisting of graphite, alumina, boron nitride, and zirconia.

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