

WASTEWATER TREATMENT APPARATUS AND METHOD

Technical Field of the Invention

5 This invention relates to the treatment of wastewater, and in particular to an apparatus and method for treatment of contaminated water in an electrolytic cell.

Background of the Invention

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Water may be contaminated by organic and inorganic matter from various sources including domestic, municipal, industrial and agricultural sources. Contaminants may be in solution, colloidal or in suspension. Colloids, and in particular negatively-charged colloids, are often
15 the predominant form in which water contaminants exist.

Electrocoagulation is an electrochemical method of treating water contaminated with various species in an electrocoagulation reactor having a cathode and a sacrificial anode. Supplying current to the
20 electrodes causes the release of metal cations (usually iron or aluminum) from the sacrificial anode, and the formation of hydrogen gas at the cathode. Other chemical species may form which participate in a variety of processes that facilitate removal of contaminants from water.

25 The use of rotating electrodes has been proposed as one way to improve the remediation efficacy of systems using electrocoagulation. See, for example, Syversen et al., US 6,099,703. Rotating the cathode helps to ensure even consumption of the sacrificial anode and inhibit fouling of the active surface of the cathode. However, despite develop-
30 ments in the art of electrocoagulation, most known electrocoagulation-based wastewater treatment systems are not capable of sufficient remediation of contaminated waters for subsequent release into the environment at an affordable cost or at the volumes necessary

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for full commercialization of large-scale treatment projects. The present invention provides improved apparatus and method for the bulk treatment of contaminated water.

5 Summary of the Invention

The invention provides an electrocoagulation reactor having a reaction vessel with an inlet for inflow of water, an outlet for outflow of water, a sacrificial anode, a rotatable cathode and a non-sacrificial
10 anode. A first gap between the sacrificial anode and the cathode comprises a first treatment zone that is downstream of the inlet. The sacrificial anode and the cathode are adapted to apply a first voltage across the first gap. A second gap between the non-sacrificial anode and the cathode provides a second treatment zone downstream of the
15 first treatment zone. The non-sacrificial anode and the cathode are adapted to apply a second voltage across the second gap. The second voltage may be less than the first voltage. The flow path of water through the reaction vessel is from the inlet to the first treatment zone, then to the second treatment zone and then to the outlet.

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The invention further provides a rotatable cathode for an electrocoagulation reactor. The cathode has an active face generally perpendicular to the axis of rotation of the cathode. The active face has a center and a periphery and surface features which define a plurality of
25 water flow paths from the center to the periphery. The surface features may comprise channels or studs. The rotatable cathode may be employed in electrocoagulation reactors having a single treatment zone, and accordingly the invention provides an electrocoagulation reactor having a sacrificial anode, a rotatable cathode and a gap between the
30 sacrificial anode and the cathode comprising a first treatment zone, the

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cathode having surface features which define a plurality of water flow paths through the gap.

5 The invention further provides a clarifier for receiving effluent from an electrocoagulation reactor. The clarifier has a cylindrical side wall, an upper wall, a conical bottom wall, a first outlet port in the upper wall connected to a first outlet conduit and a second outlet port in the bottom wall connected to a second outlet conduit. The clarifier has an inlet conduit extending into the clarifier having an opening within the clarifier that is larger in cross-sectional area than the inner cross-sectional area of the inlet conduit.

15 The invention further provides a method for treating contaminated water using an electrocoagulation reactor. A reactor is provided having a water inlet, a water outlet, a gap between a sacrificial anode and a rotating cathode comprising a first treatment zone, and a gap between the rotating cathode and a non-sacrificial anode comprising a second treatment zone. A first electrolyzing voltage is applied across the first treatment zone and a second electrolyzing voltage is applied across the second treatment zone. The water is caused to flow into the reactor from the inlet, through the first treatment zone, then through the second treatment zone, and then through the outlet.

25 These and other features of the invention will be apparent from the following description and drawings of the preferred embodiments.

Brief Description of the Drawings

30 Figure 1 is a schematic view of a treatment system according to the invention.

Figure 2A is an elevation view, partly in section, of one embodiment of the treatment reactor of the system.

5 Figure 2B is a sectional view on the line 2B-2B of Figure 2A.

Figure 3 is an elevation view, partly in section, of a second embodiment of the treatment reactor.

10 Figure 4 is an elevation view, partly in section, of a third embodiment of the treatment reactor.

Figure 5 is an elevation view, partly in section, of a fourth embodiment of the treatment reactor.

15 Figure 6 is an elevation view, partly in section, of the clarifier of the treatment system.

20 Figures 7A, 7B, 7C and 7D are plan views of the active surface of the reactor cathode, showing examples of features on the bottom face of the cathode.

Description of the Preferred Embodiments

25 Exemplary embodiments of the invention are described hereunder and are illustrated in the referenced figures of the drawings. These embodiments are to be considered as illustrative rather than restrictive. In the following description and drawings, corresponding and like parts are referred by the same reference characters.

30 The treatment system 20 is illustrated schematically in Figure 1. Contaminated water flows from a source 22 through a conduit 24 into an electrocoagulation reactor 26, the reactor having an electrolytic cell

as described below. The effluent of the reactor flows through an outlet conduit 28 into a clarifier 30. An electrolyte, for example sodium chloride from a tank 36, and hydrogen peroxide from a tank 38, are added to the contaminated water in the conduit 24. Flocculant from a tank 40 is added to the reactor effluent in the conduit 28. In the clarifier 30, the effluent from the reactor 26 is separated into sludge, which exits the clarifier through an outlet conduit 32, and cleaned water, which exits the clarifier through another outlet conduit 34. Pumps 42, 44, 46 are provided in the conduits 24, 32 and 34 respectively.

The contaminated water that comprises the feedstock of the treatment system 20 is contaminated with organic contaminants, inorganic contaminants or both. The wastewaters may include municipal sewage, storm water, farm leachate, mine leachate, industrial, institutional and commercial wastewater. The contaminated water will typically have undergone some upstream processing such as screening to remove large particle contaminants. For example, in the case of municipal wastewater, the contaminated water will have undergone primary treatment such as screening, sedimentation and removal of sand and grit, prior to introducing it into the treatment system 20.

The reactor 26, shown in Figures 2A and 2B, has a housing 48 which is generally cylindrical, with a circumferential side wall 50 and a flat bottom wall 52, and with a conical upper wall 54. The housing 48 is supported on a base 56. The housing is made of an electrically non-conductive material, for example fiberglass. The bottom wall 52 of the reactor has an inlet port 58 for the inflow of contaminated water from the inlet conduit 24. The upper wall 54 has an outlet port 60 for the outflow of the effluent of the reactor 26. The outlet conduit 28 extends

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into the housing **48** through the outlet port **60**, and has an opening **62** at its inner end.

The reactor **26** has a sacrificial anode **64**, a non-sacrificial anode **66** and a rotatable cathode **68**. The sacrificial anode **64** and the rotatable cathode are separated by a gap **70**. The sacrificial anode **64** is attached to the bottom wall **52** of the reactor and does not rotate. It has a vertical bore **72** at its center, aligned with the inlet opening **58**. The sacrificial anode **64** comprises a high valency metal such as iron or aluminum.

The non-sacrificial anode **66** is cylindrical in form and is attached to the inside of the side wall **50** of the housing **48**. It is fixed in position and does not rotate. It comprises a suitable low valency metal, for example stainless steel or titanium, or ceramic, and may be coated with a coating which increases its active surface area, for example TiO_2 . TiO_2 has high chemical durability and oxidizing strength and is particularly suitable. The non-sacrificial anode **66** is spaced from the cathode **68** by a gap **74**. It is also spaced from the sacrificial anode **64**; this space facilitates the periodic removal and replacement of the sacrificial anode and also permits the two anodes to be at different electrical potentials.

The cathode **68** is a sealed cylindrical structure having a circumferential side wall **76**, a bottom wall **78** and a top wall **80**. The cathode is made of a suitable low valency metal, for example stainless steel or titanium, or ceramic. The active surface of the cathode, namely the outer surface **79** of the bottom wall **78** and the outer surface of the side wall **76**, may be coated with TiO_2 . This coating promotes the

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formation of hydrogen peroxide from the hydrogen and oxygen generated during electrolysis in the reactor.

The outer surface **79** of the bottom wall **78** of the cathode may be provided with grooves **82** which act as channels to increase the flow rate of water moving radially outward in the gap **70**. The grooves also direct radially outward the gas bubbles formed in the electrolysis reaction, along with the contaminants adsorbed by the bubbles. As shown in Figure 7A, B and C, the grooves may take various forms, including straight channels, tapered channels and spirals.

Figure 7A shows channels **82** which extend from the center **83** to the periphery **85** of the outer surface of the bottom wall **78** of the cathode **68** in a spiral form. The channels are separated by lands **87**. Alternatively, the channels **82** may extend straight from the middle of the cathode to its periphery without curving, and may be tapered, as illustrated in Figure 7B, or untapered as illustrated in Figure 7C. Different numbers of channels may be provided, for example from three channels to seven channels. They may be about one-half inch (13 mm) in depth. The depth, shape and number of channels may be selected so as to optimize the flow rate and inter-electrode spacing for a particular application.

Surface features other than channels may be provided on the face of the cathode to produce particular flow characteristics. Figure 7D shows a cathode face having a plurality of raised studs **89**. The studs create irregular flow paths **91** between them for the water moving in the gap from the center to the periphery of the electrode face. The studs may be, for example, about one-inch (25 mm) in diameter and 3/16 inch (4.8 mm) in height, and made of stainless steel.

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It will be understood that the feature of channels or studs on the face of a rotatable cathode has utility in electrocoagulation reactors other than the reactors described herein, including in prior art electrocoagulation reactors of the type having a rotatable cathode spaced
5 from a sacrificial anode.

The cathode 68 is mounted for rotation on a shaft 84, which is connected to a motor or other suitable drive means (not shown). Rotation of the cathode reduces passivation of the active cathode surface. A bushing and seal assembly 95 surrounds the shaft 84 where the
10 shaft passes through the upper wall 54 of the housing 48. The shaft 84 is further coupled to a suitable drive means (not shown) for vertical adjustment of the position of the cathode. This adjustability of the position of the cathode permits adjustment of the distance across the gap
15 70 during operation of the reactor in order to optimize the conditions for electrolysis of the feedstock. For example, changes in the turbidity of the feedstock may require adjustment of the gap distance. Vertical adjustment may be controlled manually or by sensors, for example sensors which monitor the electrical current across the gap 70.

20 In an industrial-scale electrocoagulation reactor, the cathode 68 may have a diameter of about 4 to 6 feet (1.2 to 1.8 m), a bottom wall thickness of 3/4 inch (19 mm) and a side wall thickness of 1/4 inch (6.4 mm). The distance across the gap 70 may be in the range of 1/8 to 1/2
25 inch (3.2 to 13 mm) and across the gap 74 in the range of 1/8 to 3/8 inch (3.2 to 9.5 mm). The rotation speed of the cathode may be in the range of 20 to 170 rpm and the flow rate of wastewater through the reactor in the range of 25 to 200 imperial gallons (114 to 909 L) per minute. Much larger electrocoagulation reactors, having a greater
30 throughput, can also be made in accordance with the invention.

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The electrical power supplied to the cathode **68**, the sacrificial anode **64** and the non-sacrificial anode **66** can be DC, pulsed DC or high frequency AC. Power sources (not shown) are connected to the base of the sacrificial anode **64** at a terminal **65**, to the non-sacrificial
5 anode **66** at a terminal **69** and to the shaft **84** of the cathode at a terminal **67**, the shaft being electrically conductive. The non-sacrificial anode **66** is typically maintained at a lower potential than the sacrificial anode **64** and has its own power supply, though for some feedstocks it may be maintained at the same potential or a higher potential. The
10 selection of the type of electrical power used depends on the feedstock and the nature of the contaminants. For example, if the feedstock has a high level of organic contaminants, the preferred selection may be DC current to the sacrificial anode and high frequency AC to the non-sacrificial anode; or if the feedstock is one requiring a lower level of
15 iron ions in solution, the selection may be pulsed DC for the sacrificial anode and high frequency AC for the non-sacrificial anode. Typical voltages/currents are about 6.5 V at 900 A and 7.5 V at 3,000 A.

Prior to treatment in the reactor **26**, an electrolyte, such as
20 sodium chloride, may be added to the contaminated water to increase its conductivity. Also, hydrogen peroxide may optionally be added to the feedstock. Generally, hydrogen peroxide is useful where the contaminants are organic, and a higher level of hydrogen peroxide may be used for higher levels of organic contaminants. The pH of the contaminated
25 water may also be adjusted prior to the reactor if required, a pH range of about 3.5 to 7 being preferred.

In the reactor **26**, the contaminated water flows in through inlet port **58**, through the bore **72** in the sacrificial anode **64** and radially
30 outward in the gap **70** between the active surface **86** of the anode **64** and

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the bottom surface of the rotating cathode **68**. In this space, which is the first reaction zone of the reactor **26**, iron cations go into solution as the active surface of the sacrificial anode is consumed, chemical reactions occur and contaminants are electrocoagulated. From the first
5 reaction zone, the contaminated water flows into the gap **74** between the non-sacrificial anode **66** and the side wall **76** of the cathode. In this space, which is the second reaction zone of the reactor **26**, it is believed that further oxidation of contaminants occurs by means of various reactions including Fenton reactions, ferrous ions (Fe^{2+}) and hydrogen
10 peroxide both being present, resulting in the formation of hydroxyl radical oxidants.

The contaminated water flows from the second reaction zone into the space **88** between the top wall **80** of the cathode and the upper wall
15 **54** of the housing. It then flows into the opening **62** of the discharge conduit **28**, exiting the reactor.

Following treatment of the contaminated water in the reactor, effecting coagulation of solids and oxidation of contaminants, including
20 bacterial contaminants, the effluent is treated to separate the coagulated solids from the water. Various types of downstream processes can be used to achieve this separation, for example a dissolved air flotation system or a separating tank with a skimmer to remove solids. In the preferred embodiment of the invention, the effluent from the reactor **26**
25 is fed to a clarifier **30**, shown in Figure 6.

A flocculant from a tank **40** is fed into the effluent in conduit **28** prior to the effluent being fed into the clarifier. The type and concentration of flocculant employed depends on the particular wastewater
30 feedstock.

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Inside the clarifier **30**, the conduit **28** has an outlet opening **90** that is oriented upwards and has a diameter larger than the diameter of the inside of the conduit **28**. This slows the flow rate of effluent into the clarifier per unit area of the opening **90** to reduce turbulence.

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The clarifier **30** has a generally cylindrical tank body with a conical top wall **92** and a conical bottom wall **93**. The volume of the clarifier is sufficient, relative to the inflow rate of reactor effluent, that the retention time in the clarifier is adequate to achieve separation of the solids from the water. For example, the retention time may be about 5 to 8 minutes. The top wall **92** forms an angle at its point of juncture with the cylindrical side wall **94** that is about 60° (relative to the horizontal). The clarifier is supported on legs **96**. There is an outlet port **98** at the bottom end of the clarifier, connected to the effluent outlet conduit **34**. The conduit is provided with an effluent pump **46**. There is an outlet port **100** at the upper end of the clarifier, connected to the sludge outlet conduit **32**. The conduit **32** is provided with a sludge pump **44**. A pair of vertically-spaced level sensors **102** are provided in the upper wall **92** of the clarifier, to detect the level of water and sludge. The effluent pump **46** regulates the water level through input from these sensors.

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The pumps **44**, **46** operate so as to create a partial vacuum within the clarifier, for example a pressure in the range of 5 to 25 kPa. By means of the conduit **28** connecting the reactor **26** to the clarifier **30**, this partial vacuum is also applied to the full reactor system. It is believed that the treatment process in the reactor system is enhanced by such partial vacuum.

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The partial vacuum within the clarifier enhances the separation of the flocculated solids, which rise to the top of the clarifier, and the water, which descends to the bottom of the clarifier. The solids comprise a sludge which exits the top of the tank through the outlet **100** and is pumped by the sludge pump **44** through the outlet conduit **32**. The cleaned water, separated from the sludge, exits the bottom of the tank through the outlet **98** and is pumped by the effluent pump **46** through the outlet conduit **34**. The cleaned water may be released to the environment or subjected to further treatment, for example pH adjustment, prior to release. A portion of the cleaned water exiting through the outlet conduit **34** may be recirculated via a recirculation conduit (not shown) into the reactor inlet conduit **24** for further treatment in the system **20**.

In an alternative mode of operation of the clarifier **30**, a coagulant, rather than a flocculant, is fed into the reactor effluent in the conduit **28** prior to the effluent being fed into the clarifier. The coagulant causes separated solids to sink to the bottom of the clarifier rather than float to the top (as occurs with a flocculant). This mode of operation may be used when treating feedstocks having contaminants with naturally negative buoyancy, for example heavy metals. The upper outlet conduit **32** accordingly removes the cleaned water from the clarifier and the lower outlet conduit **34** removes the sludge. The pumps **44** and **46** are switched so that the upper outlet conduit **32** has an effluent pump and the lower outlet conduit **34** has a sludge pump; and the level sensors **102** are moved to the bottom wall **93**. The opening **90** of the conduit **28** may be directed downwards.

It will be understood that the clarifier **30** (arranged to operate in either of the two modes of operation) may be connected to receive the

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effluent of other types of electrocoagulation reactor, for example prior art reactors.

The treatment system may be operated by means of a
5 programable logic computer (PLC), with appropriate devices to measure and control fluid flows throughout the apparatus, electrical current across the inter-electrode gaps, conductivity and pH of the feedstock, pump speeds, fluid levels in the clarifier, and so on. The process is to be run so as to produce cleaned effluent water meeting the requirements
10 for a particular application.

In another embodiment **126** of the reactor, illustrated in Figure 3, the non-sacrificial anode is positioned horizontally above the cathode and is moveable vertically with it as the cathode is moved to adjust the gap
15 between it and the sacrificial anode. The reactor **126** is otherwise substantially the same as the reactor **26**. More particularly, the reactor **126** has a rotatable cathode **168** that comprises a flat plate, and a non-sacrificial anode **164** that comprises a flat plate, spaced from the upper surface **180** of the cathode **168** by a gap **174**. The non-sacrificial anode
20 **164** does not rotate and is supported by support members **104** affixed to a collar and bearing assembly **106**. The collar and bearing assembly **106** permits rotation of the cathode shaft relative to the non-sacrificial anode **164**, which maintains a fixed vertical position on the shaft **84**, so that the non-sacrificial anode **164** (and the collar and bearing assembly
25 **106**) moves vertically with the cathode. The collar and bearing assembly **106** is electrically insulated from the cathode shaft **84**. A seal **108** extends the periphery of the non-sacrificial anode and the side wall **50** of the reactor housing, preventing the flow of water therebetween. The active surface **86** of the sacrificial anode **64** is spaced from the lower
30 side of the cathode by a gap **70**, this gap comprising the first treatment

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zone of the reactor **126**, the gap **174** comprising the second treatment zone. The treatment zones function in the manner described above for the two treatment zones of the reactor **26** of the first embodiment. As indicated by the directional arrows in Figure 3, wastewater enters the reactor through the inlet port **58**, flows through the bore **72** in the sacrificial anode **64** and into the first gap **70**. It then flows radially outward in the gap **70**, around the circumferential edge **176** of the cathode and into the second gap **174**. It then flows through the central opening **114** in the non-sacrificial anode **164**, into the space between the upper wall **54** of the housing **48** and the non-sacrificial anode **164**, and then out through the effluent conduit **28**.

A third embodiment **127** of the reactor, illustrated in Figure 4, is essentially the same as the reactor **126** of Figure 3, except for the positioning of the collar and bearing assembly, which is outside the reactor, and the support members which connect the non-sacrificial anode **164** to the collar and bearing assembly. In reactor **127**, the collar and bearing assembly **106** is on the shaft **84** of the cathode **168** outside and above the reactor housing **48**. The assembly **106** has a pair horizontal support members **128**, and a pair of vertical support members **130** connect the non-sacrificial anode **164** to a respective horizontal support member. The vertical support members **130** pass through ports in the upper wall **54** of the reactor housing, and a water seal **132** is fitted around the support member **130** at each port.

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In a fourth embodiment **226** of the reactor, shown in Figure 5, the wastewater inlet is through the rotatable cathode, rather than through the sacrificial anode. The reactor has a sacrificial anode **264** fastened to the bottom wall **52** of the reactor housing **48**, a rotatable cathode **268** spaced from the upper, active surface **286** of the sacrificial

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anode **264** by a gap **70**, and a cylindrical non-sacrificial anode **66** attached to the inside of the side wall **50** of the reactor housing **48**, the non-sacrificial anode being spaced from the cathode **268** by a gap **74**. The support shaft **84** of the cathode has a bore **110** therein and a bearing
5 and seal unit **112**, connected to a wastewater inlet pipe **24**, permitting the flow of wastewater into the bore **110** and out through the opening **114** in the bottom wall **78** of the cathode and into the gap **70**. The flow of wastewater in this embodiment of the reactor is radially outward through the gap **70**, which comprises the first treatment zone, through
10 the gap **74**, which comprises the second treatment zone, and into the space between the upper wall **54** of the housing **48** and the top wall **80** of the cathode, and then out through the effluent conduit **28**.

A fifth embodiment of the reactor, not separately illustrated in the
15 drawings, is the same in structure as the reactor **26** shown in Figure 2A, except it does not include the non-sacrificial anode or second treatment zone (or electrical terminal **69**). The single treatment zone is defined by the gap **70** between the top surface **86** of the sacrificial anode **64** and the bottom surface **79** of the rotatable cathode **68**. The
20 water flow path in the reactor is in through the bore **72** in the sacrificial anode **64** to the gap **70**, then through the gap **70** and around the periphery of the cathode, into the space **88** above the cathode and then out through the effluent conduit **28**. The bottom face **79** of the cathode **68** of the reactor has surface features as described above and shown in
25 Figure 7, namely grooves **82** or raised studs **89** to produce particular water flow characteristics in the gap **70**.

Examples

Samples of wastewaters were treated in a laboratory-scale apparatus in accordance with the invention. Various measurements were made of contaminants/parameters of the feedstock and the effluent and, in some cases, the sludge. The results are summarized below.

Example 1

A sample of municipal sewage was treated. The carbonaceous BOD of the feedstock was 169 mg/L and of the effluent was 20 mg/L. The total suspended solids of the effluent was 8 mg/L. The fecal coliform content of the effluent was less than the 1 colony per 100 ml detection limit of the test.

Example 2

Another sample of municipal sewage was treated. The test results are set out in Table 1.

Table 1

Test	Feedstock	Effluent	Sludge
Fe (mg/L)	0.15	--	3
Total Solids (mg/L)	180	16	--
Total BOD (mg/L)	270	40	--
Fecal Coliform (colonies/100 ml)	3 million	< 100	2.4 million

The marking -- indicates that the parameter was not measured.

Example 3

Five 5-gallon samples of underground mine water were treated. Measurements were made of the level of various elements in the feedstock and in the treated effluent and, for Samples 4 and 5 in the sludge. The test results are shown in Tables 2 and 3. In a few cases, the metal

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content increased, for example for iron, manganese and sodium. This is due to additions of those elements from the sacrificial anode or by chemical dosing during the treatment process.

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Table 2

	Element	Sample #1		Sample #2		Sample #3	
		Feedstock	Effluent	Feedstock	Effluent	Feedstock	Effluent
10	Aluminum	11	0.6	22	0.7	10	3
	Barium	0.2	0.08	0.34	0.06	0.16	0.07
	Boron	0.5	0.3	0.5	0.2	0.3	0.4
	Calcium	1150	925	1300	928	916	667
	Cobalt	1.5	0.6	2.1	0.5	1.3	0.4
15	Copper	35.1	1.2	80.2	1.2	34.9	7.6
	Iron	114	26.3	279	26.5	91.4	138
	Magnesium	74	57.3	88	56.6	63	40
	Manganese	2.45	3.81	2.96	3.32	2.13	2.97
	Molybdenum	0.4	0.2	0.4	0.2	0.4	0.4
20	Nickel	48.7	22.5	59.1	16.2	43.8	13.1
	Potassium	86	74	95	74	72	46
	Silicon	39	2.9	45	2.2	35	10
	Sodium	475	549	509	402	392	318
	Strontium	17.7	14.6	19.1	14.6	14.4	9.78
25	Titanium	0.6	0.05	1.6	0.05	0.6	0.1
	Zinc	1.8	0.38	2.8	0.25	0.5	0.7

Measurements are in mg/L.

Table 3

	Element	Sample #4			Sample #5		
		Feedstock	Effluent	Sludge	Feedstock	Effluent	Sludge
5	Aluminum	2.6	0.01	3910	0.5	<0.01	358
	Barium	0.16	0.045	18	0.16	0.147	36
	Boron	<0.1	0.028	< 10	0.1	0.114	18
	Calcium	278	229	13000	1020	815	42100
	Chromium	<0.1	<0.001	90	<0.1	<0.001	30
10	Cobalt	0.2	0.083	163	0.2	0.0224	236
	Copper	2.2	0.029	5730	<0.2	0.0318	1030
	Iron	0.4	1070	407000	0.4	10.4	384000
	Lead	<0.3	<0.0002	103	<0.3	0.0005	71
	Magnesium	35.9	21.4	1720	99.9	87.1	4780
15	Manganese	1.14	1.28	2900	1.43	1.11	1360
	Molybdenum	<0.2	0.0008	<20	<0.2	0.0061	<20
	Nickel	8.8	2.95	6090	10.1	0.968	10200
	Potassium	21	18.2	773	<1.5	64.6	2550
	Silicon	7.2	0.7	2260	70	0.9	387
20	Sodium	151	370	13700	484	421	17600
	Strontium	0.96	0.923	65	13.6	12.3	690
	Titanium	<0.5	<0.02	14	<0.05	<0.02	14
	Zinc	0.42	0.021	566	0.3	0.008	510

Measurements are in mg/L.

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List of Reference Numerals in the Drawings

- 20 treatment system
- 22 source of contaminated water
- 30 24 conduit into reactor
- 26 reactor
- 28 conduit into clarifier
- 30 clarifier

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- 32 sludge outlet conduit
- 34 effluent outlet conduit
- 36 salt tank
- 38 hydrogen peroxide tank
- 5 40 flocculant tank
- 42 feedstock pump
- 44 sludge pump
- 46 effluent pump
- 48 reactor housing
- 10 50 side wall of housing
- 52 bottom wall of housing
- 54 upper wall of housing
- 56 reactor base
- 58 reactor inlet
- 15 60 reactor outlet
- 62 opening in conduit 28
- 64 sacrificial anode
- 65 terminal on sacrificial anode
- 66 non-sacrificial anode
- 20 67 terminal on cathode
- 68 cathode
- 69 terminal on non-sacrificial anode
- 70 first gap
- 72 bore in sacrificial anode
- 25 74 second gap
- 76 side wall of cathode
- 78 bottom wall of cathode
- 79 bottom surface of cathode
- 80 top wall of cathode
- 30 82 grooves in cathode

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- 83 center of cathode
- 84 shaft of cathode
- 85 periphery of cathode
- 86 active surface of sacrificial anode
- 5 87 lands of cathode face
- 88 space above cathode
- 89 studs on cathode face
- 90 inlet in clarifier
- 91 water flow paths
- 10 92 upper wall of clarifier
- 93 bottom wall of clarifier
- 94 side wall of clarifier
- 95 bushing and seal assembly
- 96 legs of clarifier
- 15 98 outlet for effluent
- 100 outlet for sludge
- 102 level sensors
- 104 support members
- 106 insulated collar and bearing assembly
- 20 108 seal on anode 164
- 110 bore in cathode shaft
- 112 bearing and seal unit
- 114 central opening in cathode shaft 84
- 126 second embodiment of reactor
- 25 127 third embodiment of reactor
- 128 horizontal support members
- 130 vertical support members
- 132 seal on vertical supports
- 164 non-sacrificial anode
- 30 168 cathode

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- 174 second gap
- 176 periphery of cathode
- 226 fourth embodiment of reactor
- 264 sacrificial anode
- 5 268 cathode
- 286 active surface of sacrificial anode

10 Although the invention has been described in terms of various embodiments, it is not intended that the invention be limited to these embodiments. Various modifications within the scope of the invention will be apparent to those skilled in the art. The scope of the invention is defined by the claims that follow.

WHAT IS CLAIMED IS:

1. An apparatus for treating contaminated water comprising:
 - 5 (a) an electrocoagulation reactor comprising:
 - (i) a reaction vessel having an inlet for inflow of water
and an outlet for outflow of water from the reaction
vessel;
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 - (ii) a sacrificial anode;
 - (iii) a rotatable cathode;
 - 15 (iv) a non-sacrificial anode;
 - (v) a first gap between the sacrificial anode and the cath-
ode, the first gap comprising a first treatment zone
downstream of the inlet, the sacrificial anode and the
20 cathode being adapted to apply a first voltage across
the first gap;
 - (vi) a second gap between the non-sacrificial anode and
the cathode, the second gap comprising a second
25 treatment zone downstream of the first treatment
zone, the non-sacrificial anode and the cathode being
adapted to apply a second voltage across the second
gap, whereby a flow path of water through the reac-
tion vessel is from the inlet to the first treatment

zone, then to the second treatment zone and then to the outlet.

2. An apparatus according to claim 1, wherein the reaction
5 vessel is cylindrical with a circumferential side wall, a bottom wall and a top wall.
3. An apparatus according to claim 2, wherein the top wall is conical.
- 10 4. An apparatus according to claim 2 or 3, wherein the inlet is through the bottom wall of the reaction vessel.
5. An apparatus according to any one of claims 1 to 4,
15 wherein the sacrificial anode has a bore therethrough for the flow of water from the inlet to the first treatment zone.
6. An apparatus according to claim 2, wherein the non-sacrificial anode is cylindrical and adjacent to the circumferential side
20 wall.
7. An apparatus according to any one of claims 1 to 6,
wherein the cathode is rotatable about a substantially vertical axis.
- 25 8. An apparatus according to any one of claims 1 to 7,
wherein the cathode is cylindrical with a bottom wall, a top wall and a circumferential side wall.

9. An apparatus according to any one of claims 1 to 8,
wherein the first gap is between the upper surface of the sacrifi-
cial anode and the bottom surface of the cathode.
- 5 10. An apparatus according to claim 8, wherein the second gap
is between the circumferential side wall of the cathode and the
non-sacrificial anode.
11. An apparatus according to claim 2, wherein the outlet is in
10 the top wall of the reaction vessel.
12. An apparatus according to any one of claims 1 to 7,
wherein the cathode is a circular disk having a bottom surface, a
top surface and a peripheral surface.
- 15 13. An apparatus according to claim 2, wherein the non-sacrifi-
cial anode is a disk having an upper surface and a lower surface,
the non-sacrificial anode extending between the circumferential
side walls of the reaction vessel and having a bore therein for the
20 flow of water.
14. An apparatus according to claim 1, wherein the second
reaction zone is between the upper surface of the cathode and the
lower surface of the non-sacrificial anode.
- 25 15. An apparatus according to any one of claims 1 to 14,
wherein the cathode is movable in a direction parallel to its axis
of rotation.

16. An apparatus according to claim 1 or 13, wherein the non-sacrificial anode is movable in a direction parallel to the axis of rotation of the cathode.
- 5 17. An apparatus according to claim 1, wherein the cathode has a shaft and the shaft is rotatably connected to the non-sacrificial anode.
- 10 18. An apparatus according to claim 17, wherein the cathode shaft is rotatably connected to the non-sacrificial anode by a connector located within the reaction vessel.
- 15 19. An apparatus according to claim 17, wherein the cathode shaft is rotatably connected to the non-sacrificial anode by a connector located outside the reaction vessel.
- 20 20. An apparatus according to any one of claims 1 to 3, wherein the cathode is rotatable on a shaft and the cathode and shaft have a bore therein for the flow of water into the first treatment zone.
21. An apparatus according to any one of claims 1 to 12, wherein the sacrificial anode is non-rotational.
- 25 22. An apparatus according to claim 1 or 21, wherein the non-sacrificial anode is non-rotational.
- 30 23. An apparatus according to any one of claims 1 to 22, further comprising power source means for applying the first voltage and the second voltage.

24. An apparatus according to any one of claims 1 to 23,
further including a separator to receive effluent from the
electrocoagulation reactor outlet to separate solids from clean
water.
- 5
25. An apparatus according to claim 24, wherein the separator
is a clarifier having a cylindrical side wall, an upper wall and a
conical bottom wall.
- 10 26. An apparatus according to claim 25, wherein an inlet
conduit in the clarifier has an opening larger in cross-sectional
area than the inner cross-sectional area of the conduit.
- 15 27. An apparatus according to claim 26, wherein the inlet
conduit opening in the clarifier is directed upwards.
- 20 28. An apparatus according to claim 25, wherein the clarifier
has an upper outlet at its top end connected to an upper outlet
conduit, and a lower outlet at its bottom end connected to a lower
outlet conduit.
- 25 29. An apparatus according to claim 28, wherein the upper
outlet is a solids outlet and the lower outlet is a cleaned water
outlet.
30. An apparatus according to claim 28, wherein the upper
outlet is a cleaned water outlet and the lower outlet is a solids
outlet.

31. An apparatus according to claim 28, further comprising a first pump operationally connected to the upper outlet conduit and a second pump operatively connected to the lower outlet conduit.
- 5 32. An apparatus according to claim 25, further comprising water level sensors on the upper wall of the clarifier operatively connected to the water outlet pump.
- 10 33. An apparatus according to any one of claims 1 to 23, wherein the first voltage is greater than the second voltage.
34. An apparatus according to any one of claims 1 to 23, wherein the first voltage is equal to the second voltage.
- 15 35. An apparatus according to any one of claims 1 to 23, wherein the first voltage is less than the second voltage.
- 20 36. An apparatus according to any one of claims 1 to 35, wherein the rotatable cathode has an active face generally perpendicular to the axis of rotation of the cathode, the active face having a center and a periphery, the active face having surface features which define a plurality of water flow paths from the center to the periphery.
- 25 37. An apparatus according to claim 36, wherein the surface features comprise channels.
- 30 38. An apparatus according to claim 37, wherein the channels are curved or straight.

39. An apparatus according to claim 37, wherein the channels flare outwardly from the center of the face to the periphery thereof.
- 5 40. An apparatus according to claim 36, wherein the surface features comprise studs.
41. An apparatus according to claim 40, wherein the studs are circular in a plane parallel to the face of the cathode.
- 10 42. An apparatus according to any one of claims 1 to 41, further comprising an electrolyte source for adding electrolyte to the water to be treated.
- 15 43. An apparatus according to claim 42, wherein the electrolyte is sodium chloride.
44. An apparatus according to any one of claims 1 to 43, further comprising a hydrogen peroxide source for adding hydrogen peroxide to the water to be treated.
- 20 45. An apparatus according to any one of claims 1 to 44, further comprising a flocculant source for adding flocculant to the water exiting the reaction vessel.
- 25 46. An apparatus according to any one of claims 1 to 44, further comprising a coagulant source for adding coagulant to the water exiting the reaction vessel.

47. An apparatus according to any one of claims 1 to 46, wherein at least a portion of the non-sacrificial anode is coated with TiO_2 .
48. An apparatus according to any one of claims 1 to 47, wherein at least a portion of the cathode is coated with TiO_2 .
49. An apparatus according to any one of claims 1 to 48, wherein the reaction vessel is closed to the atmosphere.
50. An electrocoagulation reactor for treating contaminated water, comprising:
- (a) a reaction vessel having an inlet for inflow of water and an outlet for outflow of water;
 - (b) a sacrificial anode;
 - (c) a rotatable cathode having an active face;
 - (d) a gap between the sacrificial anode and the active face of the cathode, the gap comprising a treatment zone downstream of the inlet, the anode and the cathode being adapted to apply a voltage across the gap;

wherein the active face of the cathode has a center and a periphery and a plurality of walled channels extending across the active face of the cathode from the center to the periphery.

51. An apparatus according to claim 50, wherein the channels are straight.
52. An apparatus according to claim 50, wherein the channels are curved.
53. An apparatus according to claim 50, wherein the channels are tapered.
54. An apparatus according to claim 50, wherein the channels are untapered.
55. An apparatus according to claim 50, wherein the channels are spiral-shaped.
56. An apparatus according to claim 50, wherein the reaction vessel is closed to the atmosphere.
57. An electrocoagulation reactor for treating contaminated water, comprising:
 - (a) a reaction vessel having an inlet for inflow of water and an outlet for outflow of water;
 - (b) a sacrificial anode;
 - (c) a rotatable cathode having an active face;

- (d) a gap between the sacrificial anode and the active face of the cathode, the gap comprising a treatment zone downstream of the inlet, the anode and the cathode being adapted to apply a voltage across the gap;

wherein the cathode is movable in a direction parallel to its axis of rotation for adjustment of the distance across the gap.

- 58. An electrocoagulation reactor according to claim 57, wherein the sacrificial anode has a bore therethrough for the flow of water from the inlet to the treatment zone.
- 59. An apparatus according to claim 57, wherein the reaction vessel is closed to the atmosphere.
- 60. A method of treating contaminated water, comprising the steps of:
 - (a) providing an electrocoagulation reactor having a water inlet, a water outlet, a gap between a sacrificial anode and a rotating cathode comprising a first treatment zone, and a gap between the rotating cathode and a non-sacrificial anode comprising a second treatment zone;
 - (b) applying a first electrolyzing voltage across the first treatment zone and a second electrolyzing voltage across the second treatment zone; and
 - (c) flowing the water from the inlet, through the first treatment zone,

then through the second treatment zone, and then through the outlet.

61. A method according to claim 60, further comprising adding an electrolyte to the water to be treated.
62. A method according to claim 60 or 61, further comprising adding hydrogen peroxide to the water to be treated.
63. A method according to any one of claims 60 to 62, further comprising adding flocculant or coagulant to the water exiting the reactor outlet.
64. A method according to any one of claims 60 to 63, further comprising adjusting the position of the cathode to achieve a desired distance across the first gap.
65. A method according to any one of claims 60 to 64, further comprising passing the effluent from the electrocoagulation reactor through a separator and separating solids from cleaned water.
66. A method according to claim 65, wherein the separator is a clarifier operatively connected to a solids outflow pump and to a water outflow pump.
67. A method according to claim 66, further comprising operating the solids outflow pump and the water outflow pump so as to create a partial vacuum in the clarifier and in the treatment train.