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**Ozone injection method and system**

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(71) Applicant(s)  
**Nutech 03, Inc.**

(72) Inventor(s)  
**Jennings, Michael D.;Robinson, Jack H.;Mueller, Richard A.;Van Leeuwen, Johannes**

(74) Agent / Attorney  
**Phillips Ormonde Fitzpatrick, 367 Collins Street, Melbourne, VIC, 3000**

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## ABSTRACT OF THE DISCLOSURE

A method and system of ozone treatment diverts a portion of water from a flow of water in a conduit; injects an ozone-containing gas into the portion to provide an ozonated portion; recombines the ozonated portion with the flow of water in the conduit; and preferably controls and/or regulates the diverted portion to provide a minimum diverted portion flow rate according to flow in the conduit and proportion of ozone in the injected gas. Another method and system identifies a species-destructive reaction product of ozone with a water constituent, determines a life of the reaction product, and contacts ozone with a water containing the species for a period determined according to the determined life of the reaction product. Another method and system treat ballast-water with ozone without release of detrimental off-gas into the atmosphere.

## OZONE INJECTION METHOD AND SYSTEM

## BACKGROUND OF THE INVENTION

- 5 A reference herein to a patent document or other matter which is given as prior art is not to be taken as an admission that that document or matter was, in Australia, known or that the information it contains was part of the common general knowledge as at the priority date of any of the claims.
- 10 [001] The invention relates to a ballast water ozone injection method and system. More particularly, the invention relates to a system for injecting ozone to treat ballast water during loading or discharging ballast water to or from the ballast tanks of a sea faring vessel or ship.
- 15 [002] Ballast water weight is used by sea vessels to compensate for a lack of cargo weight to maintain stability when the cargo hold of the vessel is empty or partially empty. For example in a typical transport operation, a sea vessel docks at a first port where it is loaded with a cargo that the vessel transports to a second port where the cargo is unloaded. The vessel then returns to the first port where it is loaded with  
20 another cargo. Typically, the vessel travels empty from the second port back to the first port to pick up another cargo. The vessel is equipped with ballast tanks that can be filled with water to maintain the balance of the vessel on an even keel when it travels empty and that is discharged as cargo is loaded.
- 25 [003] Ballast water contains species that are indigenous to the ballast tank filling location. These species are loaded into the ballast tanks along with the water. The vessel then transports ballast water to a cargo loading port where the species are discharged into the water environment along with the ballast water. The discharged species may be nonindigenous and deleterious to the discharge water environment. The nonindigenous  
30 species may cause damage to the water environment and replace benthic organisms and clear plankton communities that provide food and larvae for desirable resident native species in overlying waters.

[004] In 1996, the U.S. Congress passed the National Aquatic Invasive Species Act (P. L. 104-332) (“NAIS”) to stem the spread of nonindigenous organisms through ballast water discharge. The act reauthorized the Great Lakes ballast management program and expanded applicability to vessels with ballast tanks. The Act requires the Secretary of  
5 Transportation to develop national guidelines to prevent the spread of organisms and their introduction into U.S. waters via ballast water of commercial vessels. NAIS, the Ballast Water Management Act and pending or to be introduced

legislation regulate the treatment of salt or fresh ballast water prior to its discharge and would require that all ballast water discharged within the territorial waters of the United States (i.e., within 200 miles of the Coast or in the Great Lakes) be treated so as to kill or remove all aquatic nuisance species (i.e., bacteria, viruses, larvae, phytoplankton and zooplankton).

[005] The water loaded into ballast tanks to stabilize sea faring vessels is a complex composition of physical, chemical and biological entities. Further, the composition of the water varies considerably from port to port, particularly in terms of biological constituents. The complexity and variation of the sea water makes disinfectant treatment unpredictable. Various known methods and systems for treating water may not work for treating ballast water because of a resistant life form or unexpected chemical constituency, or a proposed treatment itself may degrade a local ecosystem upon discharge.

[006] Ozonation has been found to be a safe and effective disinfectant method and system to treat ballast water for discharge into destination water environments. U.S. Pat. No. 6,125,778 (Rodden) first suggested an ozone ballast water treatment that included sparging into ballast water tanks.

[007] However direct tank sparging may make ozonation disinfection expensive and ineffective as not all spaces in ballast tanks may be reached. U.S. Pat. No. 6,869,540 (Robinson) has suggested an in-line treatment of loading and/or unloading ballast water. The Robinson method can comprise injecting ozone into a line of water loading into a sea faring vessel prior to charging the water into a ballast tank; charging the ozone injected water into the ballast tank; and adjusting a rate of injection of the ozone into the water and adjusting the rate of water loading into the vessel to provide a target biokill of species within the water.

[008] Robinson ozonation achieves disinfection by a sequential and combined two mechanism effect – ozonation and bromination. Ozone directly kills species by oxidation. Additionally, a reaction between ozone and naturally occurring seawater bromides results in a disinfecting bromination through the formation of hypobromous ion and hypobromous acid. The effect of the ozonation and bromination disinfecting processes has been found to be synergistic in that the combined effect is an improvement over the effects of the separate disinfectant processes.

[009] While in-line ozonation of seawater during pumping intake or discharge is more effective and more economical than in-tank treatment, in some instances there are serous cost restrictions on direct ozonation. For example, ballast water

intake/discharge lines on vessels in the 100,000 to 150,000 DWT range are 18" in diameter. The cost of equipment for direct injection into this size line is prohibitive.

5 Thus, there is a need for an uncomplicated and cost effective system and method for direct ozonation of intake/discharge ballast water.

Throughout the description and claims of this specification the word "comprise" and variations of that word, such as "comprises" and "comprising", are not  
10 intended to exclude other additives or components or integers.

#### SUMMARY OF THE INVENTION

Accordingly, a first aspect of the invention is a method of ozone treatment, comprising: determining a target biokill of species for water charging into a ballast  
15 tank of a sea faring vessel; regulating a diverted portion of the water prior to charging the water into the ballast tank; adjusting the regulating of the diverted portion of water and a rate of injection of ozone into the portion to attain the target biokill; and injecting ozone at the determined rate into the regulated  
20 diverted portion to attain the target biokill when the portion is recombined into the water for charging to the ballast tank.

A second optional aspect of the invention is a method treatment, comprising: diverting a portion of water charging into a ballast tank of a sea faring vessel; determining an ozone generating capacity  $Q$  sufficient to inject ozone into the  
25 portion to attain a target ozone concentration when the portion is recombined into the water for charging into the ballast tank; injecting ozone into the portion by a generator having the determined ozone generating capacity; and recombining the portion with the water for charging into the ballast tank.

30 A third aspect of the invention is a method of ozone treatment, comprising: determining a target biokill of species for water charging into a ballast tank of a sea faring vessel; diverting a portion of the water prior to charging into the ballast

5 tank; determining an ozone generating capacity sufficient to inject ozone into the portion to attain a target ozone concentration when the portion is recombined into the water for charging into the ballast tank; regulating the diverted portion and adjusting a rate of injection of ozone into the portion with a generator having the determine ozone generating capacity to attain the target biokill when the portion is recombined into the water for charging to the ballast tank; and recombining the portion with the water for charging into the ballast tank.

10 A fourth aspect of the invention is a ballast-water treatment system comprising: a sea faring vessel including at least one ballast tank and at least one conduit conveying water to or from an intake/outlet to the ballast tank; a regulator to divert a portion of the water from the conduit; an injector to provide an ozone injection rate into the portion of water; and a controller operatively connected to the

regulator and the injector to adjust the diverted portion of water and injection rate of the ozone into the portion to attain the target biokill when the portion is recombined with the water.

[0015] A fifth aspect of the invention is a method of ozone treatment, comprising: determining a target biokill of species for ballast water unloading from a sea faring vessel to the sea; regulating a diverted portion of the ballast water prior to unloading; adjusting the regulating of the diverted portion of water and a rate of injection of ozone into the portion to attain the target biokill; and injecting ozone at the determined rate into the regulated diverted portion to attain the target biokill when the portion is recombined into the water for unloading the ozone injected water to the sea.

[0016] A sixth aspect of the invention is a ballast-water treatment system comprising: a sea faring vessel including at least one ballast tank; an ozone generator that generates ozone, a ballast water conduit that discharges water from the ballast tank and conducts the water to an unloading port of the sea faring vessel; a regulator to divert a portion of the water from the conduit; an injector to provide an ozone injection rate into the portion of water; and a controller operatively connected to the regulator and the injector to adjust the diverted portion of water and injection rate of the ozone into the portion to attain the target biokill when the portion is recombined with the water in the conduit.

[0017] A seventh aspect of the invention is a method of ozone treatment, comprising: uploading sea water to a ballast tank of a sea faring vessel; regulating a diverted portion of the uploading water prior to charging the water into the ballast tank; adjusting the regulating of the diverted portion of water and a rate of injection of ozone into the portion to attain a target biokill; and injecting ozone at the determined rate into the regulated diverted portion to attain the target biokill when the portion is recombined into the uploading water for charging to the ballast tank.

[0018] An eighth aspect of the invention is a method of ozone treatment, comprising: diverting a portion of water from a flow of water in a conduit; injecting an ozone-containing gas into the portion to provide an ozonated portion; recombining the ozonated portion with the flow of water in the conduit; and regulating the diverted portion to provide a minimum diverted portion flow rate according to flow in the conduit and proportion of ozone in the injected gas.

[0019] A ninth aspect of the invention is a water treatment system comprising: a water conduit that transports water from a first intake location to a discharge location; a bypass line from a first point of the water conduit to a second, return point wherein

the bypass line diverts a portion of the water from the conduit for circulation in the bypass line and back to the water conduit at a return point; an injector included in the bypass line to inject ozone into the diverted portion of water; an ozone generator that generates ozone for injection by the injector; and a regulator that  
5 regulates the diverted portion to provide a minimum diverted portion flow rate according to flow in the conduit and proportion of ozone in the injected gas.

A tenth aspect of the invention is a method of ozone treatment, comprising: uploading seawater to a ballast tank of a sea faring vessel; regulating a diverted  
10 portion of the uploading water prior to charging the water into the ballast tank; and adjusting the regulating of the diverted portion of water and a rate of injection of ozone into the portion to provide a minimum diverted portion flow rate according to flow in the conduit and proportion of ozone in the injected gas.

15 An eleventh optional aspect of the invention is a method of ozone treatment, comprising: identifying a species-destructive reaction product of ozone with a water constituent; determining a life of the reaction product; and contacting ozone with a water containing the species for a period determined according to the determined life of the reaction product.

20 A twelfth aspect of the invention is a method of ozone treatment, comprising: diverting a portion of water charging into a ballast tank of a vessel; injecting ozone into the portion to provide an ozonated portion; recombining the ozonated portion with the water charging into the ballast tank; wherein a retention period  
25 between injection the ozone into the portion and recombining the injection ozone portion with the water charging into the tank is controlled below a specified time limit.

A thirteenth optional aspect of the invention is a ballast-water treatment system  
30 comprising: a vessel including at least one ballast tank; an ozone generator that generates ozone; a ballast water conduit that transports water from a first intake location to a discharge location of a vessel; a bypass line from a first point of the

5 water conduit to a second, return point to divert a portion of the water from the conduit for circulation in the bypass line and back to the water conduit at the return point; and an injector to inject ozone into the diverted portion of water and interposed in the bypass line at a location to provide a determined retention time period between a point of ozone injection and a point of recombining the injected portion with the water charging to the ballast tank.

10 A fourteenth aspect of the invention is a ballast-water treatment system comprising: a vessel including at least one ballast tank and at least one conduit conveying water to or from an intake/outlet to the ballast tank; a regulator to divert a portion of the water from the conduit; an injector to provide an ozone injection rate into the portion of water; and a controller operatively connected to the regulator and the injector to regulate the diverted portion to provide a minimum diverted portion flow rate according to flow in the conduit and proportion  
15 of ozone in the injected gas.

20 A fifteenth aspect of the invention is a method of ozone treatment, comprising: determining a target biokill of species for water charging into a ballast tank of a vessel; diverting a portion of water from a flow of the water charging into the ballast tank; injecting ozone into the diverted portion at a rate determined to attain the target biokill when the portion is recombined into the water for charging to the ballast tank; and regulating the diverted portion of the water to a minimum diverted portion flow rate according to flow in the conduit and proportion of ozone  
25 in the injected gas.

30 A sixteenth aspect of the invention is a ballast-water treatment system comprising: a sea faring vessel including at least one ballast tank; an ozone generator that generates ozone; a ballast water conduit that discharges water from the ballast tank and conducts the water to an unloading port of the sea faring vessel; a regulator to divert a portion of the water from the conduit; an injector to provide an ozone injection rate into the portion of water; wherein the regulator regulates the diverted portion to provide a minimum diverted portion

flow rate according to flow in the conduit and proportion of ozone in the injected gas.

5 A seventeenth aspect of the invention is a ballast-water treatment system without an off-gas destruction device; comprising: a salt water or fresh water sea faring vessel including at least one ballast tank and at least one conduit conveying water to or from an intake/outlet to the ballast tank; a regulator to divert a portion of the water from the conduit; an injector to provide an ozone injection rate into the portion of water; and a controller operatively connected to the regulator and  
10 the injector to adjust the diverted portion of water and an injection rate of the ozone into the portion to attain the target biokill while avoiding a release of detrimental gas into the atmosphere without an off-gas destruction device.

15 A eighteenth aspect of the invention is a method of ozone treatment, comprising: determining a target biokill of species for water charging into a ballast tank of a sea faring vessel; determining an injection of ozone into the water to attain the target biokill without releasing an environmentally toxic off-gas into the atmosphere; regulating a diverted portion of the water prior to charging the water into

the ballast tank; adjusting the regulating of the diverted portion of water and a rate of injection of ozone into the portion to attain the target biokill without release of an environmentally toxic off-gas; and injecting ozone at the determined rate into the regulated diverted portion to attain the target biokill when the portion is recombined into the water for charging to the ballast tank without releasing an environmentally toxic off-gas into the atmosphere.

[0029] The invention preferably provides a correct dose of ozone in ballast water so as to assure complete disinfecting treatment of ballast water without deleterious off gas.

#### BRIEF DESCRIPTION OF THE DRAWING

[0030] FIG. 1 is a schematic perspective view of a double hulled vessel and treatment system;

[0031] FIG. 2 is a schematic top view of the vessel and treatment system;

[0032] FIG 3 is a schematic side view of the vessel and treatment system;

[0033] FIGS. 4A and 4B are schematic representations of an embodiment of a ballast water ozone injection method and system;

[0034] FIGS. 5A, 5B and 5C are flow diagrams of alternative embodiments of a method and system for ballast water ozone injection;

[0035] FIG. 6 is a schematic side view of a bypass conduit system;

[0036] FIG. 7 comprises: Table 1 showing effects of short-term ozone exposure on survival; Table 2 showing time value testing results; and Table 3 showing LC50 values for *Americamysis bahia*;

[0037] FIG. 8 shows LT50 (median-lethal times) values derived for three species;

[0038] FIG. 9 is a graph of mortality at ozone loading rates; and

[0039] FIG. 10 is a graph showing toxicity of residual oxidants over time.

#### DETAILED DESCRIPTION OF THE INVENTION

[0040] Ozone is generated at a pressure of about 10-12 psi above atmospheric. Deviations from this pressure may adversely affect ozone output. Ballast water is pumped aboard at variable pressure, which may be high as tanks are filled. Relatively low-pressure ozone/oxygen or ozone/air mixtures can be compressed to a higher pressure by very special and expensive equipment (due to the corrosivity of ozone and more importantly, the fact that ozone will decompose under the heat of compression).

[0041] In an embodiment, the invention relates to ozone ballast water treatment. Proposed NAIS amendments define "ballast water" as "any water (with its suspended matter) used to maintain the trim and stability of a vessel." In another definition,

“ballast water” is A) water taken on board a vessel to control trim, list, draught, stability or stresses of a vessel including matter suspended in such water; and B) any water placed in a ballast tank during cleaning, maintenance or other operations. These definitions are incorporated into this specification as embodiments of treatable water.

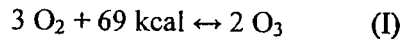
[0042] In an embodiment of the invention, an inline gas injector such as a venturi is interposed to temporarily lower pressure of flowing ballast water by increasing the velocity of the water flow in a conduit. An interposed inline injector can create a lower pressure by increasing liquid velocity. A venturi is a preferred injector in an inline injection ballast water treatment.

[0043] In an embodiment, the invention relates to a ballast water treatment system for a vessel. The system can comprise an injector interposed in a water conduit with an inlet port adapted to receive the water, an injector port adapted to receive a treating gas and an outlet port adapted to expel the water. However, ballast water conduits that charge water to or discharge water from a ballast tank are large, typically on the order of about 18 inches in diameter. The cost of an injector such as a venturi for a conduit of this size is substantial. Further, installing such an injector into a main conduit will impact operational parameters of the vessel. An interposed injector will increase flow backpressure and require an increased ballast water pump capacity. Applicants' calculations indicate that an interposed venturi will increase a pumping time required to fill ballast tanks of some vessels by one or two hours (about 10%). Further, ballast water conduits may serve both to load ballast water and to discharge ballast water. An interposed injector may interfere with a reversed water flow, for example to discharge ballast water. These disadvantages can be overcome by a preferred embodiment of the invention wherein ozone is injected into a portion of ballast water in a line that bypasses a part of the main water conduit.

[0044] A further preferred embodiment of bypass line ozone injection is based on consideration of the physical and chemical nature of ozone in ballast water including the solubility of ozone in seawater and the relationship of the chemical reactions of the ozone to solubility.

[0045] Ozone ( $O_3$ ) is an allotropic form of oxygen. It is an unstable blue gas with a pungent odor, a molecular weight of 48 g/mol and a density as a gas of 2.154 g/liter at 0° and 1 atm. It is approximately 13 times more soluble in water than is oxygen. Ozone is highly unstable and is a powerful oxidizing agent. It is non-persistent and has a very short half-life.

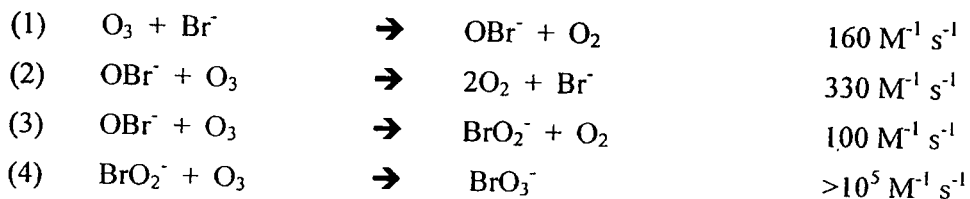
[0046] Typically, ozone is produced by passing oxygen, in some concentration, through a highly charged corona field, a technique known as "corona discharge". The corona may be produced by applying a very high electric potential (up to 20 kV) between two conductors that are separated by an insulating dielectric layer and a small air gap. Under these conditions, molecular oxygen (O<sub>2</sub>) passing through the gap between the conductors experiences sufficient dissociation energy to partially dissociate. A certain fraction of the free oxygen radicals will associate with oxygen molecules to form O<sub>3</sub>, according to the equilibrium reaction equation:



[0047] The generation of ozone as represented by equation (I), is an equilibrium reaction. The reaction is endothermic to produce O<sub>3</sub>, requiring energy, and is exothermic to produce O<sub>2</sub>, giving up energy. Because of its equilibrium nature, actual conversion to ozone is relatively low, in the range of 2-14%, depending on the oxygen content of feed gas, the temperature of the reaction and properties of the ozone generator.

[0048] Other considerations in providing an effective ozone treatment method and system relate to the mechanism of gas treatment of ballast water. U.S. Pat. No. 6,840,983 (McNulty) discloses a ballast water treatment system that comprises an injector interposed in a main water conduit with an inlet port adapted to receive the water, an injector port adapted to receive an oxygen stripping gas and an outlet port adapted to expel the water. McNulty injects an oxygen stripping gas that scavenges oxygen from the ballast water purported to cause suffocation of oxygen-dependent species. On the other hand, ozone is an oxidizing gas that has different and at least double disinfecting mechanisms. These mechanisms include rapid conversion of naturally occurring ballast water chemical constituents into products that are toxic to organisms as well as direct ozone destructive oxidation of organisms.

[0049] The following four equations (Von Gunten & Hoigné, 1994) describe the utilization of ozone in seawater assuming the only ozone demand is between ozone and dissolved bromide.



[0050] Hypobromous ion (OBr<sup>-</sup>) is created in reaction (1). Most of the reaction (1) ion is then converted to hypobromous acid (HOBr) by addition of a hydrogen ion

from water. The hypobromous ion and hypobromous acid formed are known as total residual oxidant (TRO). Only reaction (1) leads to the formation of TRO. The further reactions (2) to (4) undesirably remove both ozone and bromine products from the disinfectant process. A first goal of seawater ozonation is to convert as much ozone as possible to HOBr or OBr<sup>-</sup>. Therefore, maximizing reaction (1) and minimizing reactions (2) – (4) will maximize OBr<sup>-</sup>.

[0051] The reactions shown are of second order. The given reaction rate constants indicate the speed at which the reaction occurs as a function of the ozone concentration. To determine a relative rate between reactions (1) and (2), the rate constant of (2) is divided by that of (1). The rate of reaction (2) is approximately 2 times faster than reaction (1) - that is for equal concentrations of the reactants.

[0052] The above reaction rates are such that if the molar concentration ratio of Br<sup>-</sup> to OBr<sup>-</sup> drops below about 2.7, further ozone dosages do not produce more OBr<sup>-</sup> as the ozone consumption in reactions (2) and (3) will exceed reaction (1). The hypobromous ion forming reaction dominates when ozone is introduced into an excess of bromide. Typically about 70 mg/L of bromide is available in seawater. This provides enough bromide excess to minimize ozone losses at typical ozonation levels (1 to 5 mg/L of ozone) into a conduit of loading or unloading ballast water. However, a bypass line will present a lesser amount of water and a corresponding lesser amount of bromide available to be used up before dominance of the ozone and OBr<sup>-</sup> dissipation reactions (2) to (4).

[0053] The available amount of bromide in bypass seawater needs to be taken into consideration when determining a flow rate or retention time for bypass ozonation. Retention time is a period for transport of ozone and water from a point of injection of the ozone to reinjection of bypass water and ozone into a main conduit. In an embodiment, a method and system are provided whereby dissipating ozone and OBr<sup>-</sup> reactions are minimized while the synergistic disinfection by ozonation and bromination is maintained. According to an embodiment of the invention, a method and system are provided to minimize retention time. In this specification, retention time is a period of time from injection of ozone into water in a bypass to reinjection time of the bypass line seawater into the seawater of a main conduit or tank. An embodiment of the invention provides for reinjecting an ozone treated bypass water portion back into "bromide rich" main conduit seawater to avoid substantial ozone and OBr<sup>-</sup> consumption in BrO<sub>2</sub><sup>-</sup> and BrO<sub>3</sub><sup>-</sup> formation and oxygen reversion per reactions (2) to (4). "Retention time" is minimized.

[0054] In an embodiment, a 0.21 second retention time results in an acceptable 4.3% ozone loss. According to an embodiment of the invention, a method and system are provided wherein retention time is controlled at less than 5 seconds, desirably less than 0.25 seconds and preferably less than 0.21 seconds to minimize reactions (2) to (4).

[0055] Features of the invention will become apparent from the drawings and following detailed discussion, which by way of example without limitation, describe preferred embodiments of the invention.

[0056] FIGS. 1 to 3 schematically show vessel 10 including stern 12, bow 14 and a double hull formed from outer hull 16 and inner hull 18. Vessel 10 is representative of the types of vessels encompassed within the invention and is a conventionally proportioned double hulled oil tanker having cargo compartments within inner hull 18. However, the present invention can be applied to any sea faring ship or vessel that has ballast tanks or bilge water. The vessel 10 is typical of vessels that transport partly or fully refined or residual petroleum or other bulk liquid products such as seed oil.

[0057] Ozone generator 30 is illustrated located on vessel 10 aft deck 102 with main ozone feed line 130 shown as part of the ozone injection system of the invention. Generator 30 can be structured and can generate ozone according to known ozone generators, such as described by Rodden U.S. Pats.; and, Tabata U.S. DN 20040223893; Eidem U.S. DN 20030015481; Lee et al. U.S. Pat. 6,730,277; Borgstrom 6,726,885; Golota et al. U. S. Pat. 6,544,486; Conrad U.S. Pat. 6,491,879; Cannon U.S. Pat 6,516,738; Smith 6,468,400; and Pean et al. U.S. 6,231,769. The disclosures of these patent documents are incorporated herein by reference in their entirety. PCI-WEDECO (PCI-WEDECO Environmental Technologies, 1 Fairfield Crescent, West Caldwell, NJ 07006) type SMO/SMA series generators and WEDECO Effizon® technology high concentration ozone production generators are further examples of suitable ozone generators.

[0058] Ozone gas is pumped through generator 30 and subsequently through line 130 for injection into water in respective ballast water intake/discharge conduits 116, 118 and 120 via respective connector lines 110, 112 and 114 in accordance with the FIGS. 1 through 3 and 4A and 4B embodiment of the invention. Intake/discharge conduit 116 conveys water from stern intake/outlet sea chest 132 to forward battery 124 of ballast tanks. Intake/discharge conduit 118 conveys water from starboard intake/outlet sea chest 134 to a starboard battery 126 of ballast tanks. Intake/discharge

conduit 120 conveys water from port intake/outlet sea chest 136 to a port battery 128 of ballast tanks.

[0059] Ballast water is loaded into the vessel 10 via the sea chests 132, 134, 136 and is then pumped to load respective ballast tank batteries 124, 126, 128 through the system of conduits 116, 118 and 120 shown. At a destination location, the process is reversed and water is pumped from tank batteries 124, 126, 128 through the respective conduits 116, 118, 120 for discharge through respective sea chests 132, 134, 136 to the sea. Or, discharge can be effected through another, separate conduit and sea chest system (not shown) from tank batteries 124, 126, 128. After injection with ozone, the water is conveyed by one of the main conduits 116, 118, 120 to respective tank batteries 124, 126, 128. As each main conduit 116, 118, 120 passes through each ballast tank 124, 126 or 128, a smaller footer pipe (not shown) can be taken off to provide a suction/discharge conduit. Valving for the footer pipe can be contained in a tunnel or cofferdam area, or actually placed in the tank itself, if space is an issue.

[0060] In FIG. 4A, conduit 118 delivers ozone treated water to each ballast tank of a starboard battery of tanks 126 and conduit 120 delivers ozone treated water to each ballast tank of a port battery of tanks 128. Water enters through respective sea chests 134 and 136 and is treated and charged into a tank of either the starboard battery 126 or the port battery 128 until each respective tank is sufficiently filled and balanced to compensate for off-loaded cargo. Similarly, as shown in FIGS. 4A and 4B, water enters through stern sea chest 132, is treated with ozone delivered via line 110 and charged into a tank of forward battery 124 until each tank is filled to balance the vessel 10.

[0061] While the figures describe treating ballast water from sea chests 134 and 136, the invention applies to water either charging to a ballast tank or treatment of water being discharged from a ballast tank and to a fresh or salt water body such as a sea. An amount of ozone (in terms of a dosed proportion to the loading or discharging ballast water) is important to the proper operation of the ballast water treatment system. Typically, ozone is generated at a concentration of about 10-12% ozone/oxygen. This means that about 9 lbs. of oxygen are dosed for every pound of ozone. If 3.5 mg ozone is dosed per liter of water then about 32 mg/L of accompanying oxygen is dosed. It has been found that if properly controlled according to the invention, then both the ozone and the oxygen will be fully soluble in the full ballast water intake or discharge stream without release to the atmosphere.

[0062] While the following is not binding, avoidance of deleterious atmospheric release may be explained as follows: Henry's law constant for oxygen indicates that the solubility of pure oxygen will be 49 mg/L at 1 atmosphere pressure in pure water at 15° C. The solubility of oxygen in seawater is about 40 mg/L. The solubility of pure ozone is 8 times as high as that of oxygen.

[0063] Pressure in ballast tanks typically varies between 1 and 3 atmospheres as a tank is filled. Gas solubilities are three times higher at 3 atmospheres as at 1 atmosphere. Typically seawater is saturated with oxygen at about 15° C. Hence prior to injection, the seawater already contains about 8 mg/L of oxygen. Controlling injection according to the invention can provide an additional 32 mg/L of oxygen and all the ozone will be dissolved at 1 atmosphere. At three atmospheres, the invention provides an excess capacity for dissolving both oxygen and ozone.

[0064] Further, dissolving all the oxygen along with the ozone averts an equilibrium situation. Consuming ozone by chemical reactions in the seawater averts the release of ozone from solution when subsequently exposed to the atmosphere. Hence, averting equilibrium permits a nearly total transfer of ozone to water or seawater.

[0065] FIGS. 5A, 5B and 5C are flow diagrams of embodiments of a method and system for ballast water ozone injection that can be used in conjunction with the system of vessel 10 shown in FIGS. 1 to 3 and 4A and 4B. In FIGS. 5A, 5B and 5C, ozone generation system 502 includes air compressor 514, refrigerated air dryer 516, coalescing filter 518, air receiver 520, O<sub>2</sub> enricher 522, O<sub>2</sub> receiver 524, dew point monitor 526, filter 528, ozone generator 530, power supply 532, ozone monitor 534, ozone destruct unit 536 and chiller 538 with circulation pump 540. In operation, air is drawn into the system 502 via air intake 512. The air is compressed 514, dried and refrigerated 516, filtered 518 and temporarily stored in 520. Then according to generator demand, air is withdrawn to enricher 524, where oxygen content of the gas is differentially increased by adsorption of nitrogen. Oxygen enriched gas is delivered to receiver 524, monitored 526 and filtered 528 until injected into ozone generator 530 operated via power supply 532. Off-gas from generator 530 is monitored 534, and destroyed 536 to prevent environment discharge. Generated ozone is stored at chiller 538 until demanded by bypass injection systems 550, 552, 554 as hereinafter described.

[0066] Each of FIGS. 5A, 5B and 5C shows three separate bypass injection systems 550, 552, 554, which can correspond respectively to injection into aft intake conduit

116 via 110, injection into starboard intake conduit 118 via 112 and injection into port intake conduit 120 via 114 as shown in FIGS. 2, 3 and 4A.

[0067] In FIG. 5A, injection system 550 includes ozone injector pump 560, flow regulator 562, ozone injector 564, predisperser (or static mixer) 566 and mainline contactor 568. Similarly, injection system 552 includes ozone injector pump 570, flow regulator 572, ozone injector 574, predisperser 576 and mainline contactor 578, and injection system 554 includes ozone injector pump 580, flow regulator 582, ozone injector 584, predisperser 586 and mainline contactor 588.

[0068] In FIGS. 5B and 5C, injection system 550 includes ozone regulator 560, which can be a pump to regulate flow in the bypass 594. Further, the injection system 550 includes ozone injector 564, static mixer 566 and reinjector 568. Similarly, injection system 552 includes regulator 570, ozone injector 574, static mixer 576 and reinjector 578, and injection system 554 includes regulator 580, ozone injector 584, static mixer 586 and reinjector 588.

[0069] As shown in FIGS. 5A and 5B, injection systems 550, 552 and 554 are controlled respectively by controllers 610, 612 and 614. Controllers 610, 612 and 614 can be processors, computers, microprocessors or the like for controlling injected ozone as hereinafter described.

[0070] FIG. 6 schematically shows detail of bypass injection of ozone into a diverted portion of water loading to or unloading from a ballast tank. The bypass injection allows for ozone injection, provides proper mixing and solubilization of the ozone gas into the ballast water and proper remixing of the ozonated diverted portion with the main water flow. Shown in FIG. 6 is exemplary aft load/discharge bypass injection system 550. The system 550 includes a bypass conduit 594 that diverges from main conduit 116 at an upstream point 622 and reconverges with the main conduit 116 at a downstream point 624. Bypass conduit 620 includes pump 560, venturi 564, mixer 566 and main conduit reinjector 568.

[0071] Taking system 550 of FIG. 5A as an exemplary system, operation is described as follows: Seawater from sea chest 132 (FIGS. 2-3) is fed in conduit 116 via main ballast water pump 592 to injection system 550. A portion of the seawater is diverted by circulation pump 560 from conduit 116 into by-pass line 594. Flow of the diverted water portion is controlled by flow regulator 562. Injector 564 injects ozone from generator 530 into the diverted seawater portion. The ozone injector 564 can be a venturi injector or the like. The injected ozone is dispersed further into the seawater

portion by predisperser (or static mixer) 566 and combined back with the main seawater in conduit 116 at mainline contactor 568.

[0072] In each of the aft conduit injector system 550, starboard conduit injector system 552 and port conduit injector system 554 of FIG. 5A, each of flow regulators 562, 572, 582 and each valve 616, 618, 620 to each respective ozone injector 564, 574, 584 are controlled by respective controller 610, 612, 614. The controller 610, 612 and 614 can be a computer or microprocessor or the like.

[0073] A target biokill of species for ballast water discharged from a sea faring vessel can be established, in a typical case by reference to a discharge jurisdiction requirement, for example by reference to the NAIS or like legislation. An ozone concentration in the water to attain the target biokill is then determined empirically and according to physical and chemical factors relating to the ozone. The controller can include a set of instructions to adjust the regulating of the diverted portion of water and rate of injection of the ozone into the portion to attain the target biokill. The diverted portion can be regulated and the rate of ozone injection can be adjusted according to a set of instructions resident in the computer memory to provide the target biokill at a lowest threshold ozone concentration in the recombined water.

[0074] In operation for example, controller 610 controls flow regulator 562 to regulate water flow in coordination with ozone injection by injector 562 to effectively achieve biokill prior to water loading into ballast tanks 124 to effectively achieve biokill prior to discharging ballast water from ballast tanks 124 to the sea. For example, the system can be controlled to attain a target 95% biokill of species that are proscribed by the National Invasive Species Act. Thus the controller 610 can coordinate flow regulator 562 with injector 564 to provide a concentration of 2.5 mg/l of ozone in the sea water to effectively provide a target biokill.

[0075] The injector 564 can be any gas into fluid injector such as a jet injector, but preferably is a venturi to address the requirements of mixing gas into a high volume of liquid to achieve a high degree of solubility. Further, a venturi is desirable because of its very low power consumption, few moving parts, and minimal system backpressure. A venturi works by forcing a fluid through a conic constriction that initiates a pressure differential in the venturi tube between an inlet and an outlet port. The pressure differential inside the venturi tube imitates suction of another fluid (ozone containing gas in the present case) through a port of an intersecting side line. A venturi injector can include a venturi tube that comprises a short straight pipe section or throat between two tapered sections. The tapered sections form the

constriction that causes a drop in pressure as fluid flows through the pipe. The pressure drop draws ozone into the flow from the intersecting side line.

[0076] The ozone gas/water mixture can be processed through predisperser 566 after exiting the venturi injector. Predisperser 566 is preferably a static mixer that provides additional solubilization of ozone into the water and ensures that entrained ozone gas bubbles are uniformly dispersed in the bypass conduit water. Predisperser 566 can be any suitable mixer but a static mixer is preferred. Typically, a static mixer comprises a series of fins, obstructions, or channels mounted or fixed into a piping arrangement. The fins, obstructions or channels are designed to promote further mixing of the ozone gas and ballast water liquid. A static mixer may use some method of first dividing the flow, then rotating, channeling, or diverting it. The static mixer intensifies the physical and chemical processes of ozone solubilization. The intensified mixing lengthens the distance covered by gas bubbles and breaks the bubbles into still smaller bubbles thereby increasing the ability to transfer ozone from the gas mixture to the water. The mixer of the system can provide an additional 5-10% solubilization.

[0077] The static mixer 566 is selected by considering the material to be processed and the rate at which it must be processed. A static mixer with at least 12 elements or equivalent composite mixer can be used to fit a pipe of the same diameter as that exiting from the injector. In addition, allowable pressure drop must be assessed, in order to make certain that the bypass circulating pump has both flow capacity and pressure capability to provide proper mixing in the static mixer. Also, the water flow rate should be high enough to ensure a low enough contact time to minimize ozone losses to wasteful by reactions in seawater.

[0078] According to an aspect of the invention, a minimum bypass flow rate is required to provide sufficient ozonation of ballast water when the bypass is reinjected back into a main conduit. In an embodiment, a minimum bypass flow rate must be maintained of at least 0.25% of the main conduit flow for every mg/L of ozone injected into the bypass. Desirably the bypass flow rate is maintained at more than 0.30% of the main conduit flow and preferably, the flow rate is maintained at 0.35% of the main conduit flow. For example as described hereinafter for 0.33%, a flow ratio between a bypass flow and that in the main conduit flow is about 66 gal/min to 10,000 gal/min. In operation for example, controller 610 controls pump 560 to regulate water flow in coordination with ozone injection by injector 562 to effectively provide a minimum diverted portion flow rate according to flow in the conduit and

proportion of ozone generated in the injected gas. Thus the controller 610 can coordinate flow by pump 560 with injector 564 to provide diverted portion flow of at least 0.25% of a main conduit flow for every mg/L of ozone injected into the bypass.

[0079] The following examples serve as illustrations and are not intended as limitations of the present invention as defined in the claims.

[0080] EXAMPLE 1

[0081] The ozone generator 530 of FIGS. 5A-5C can be selected according to the following. First, a target species biokill is established. In this example, a 99% biokill is targeted; meaning that the treatment target of the process is to kill 99 % of the species contained in the sea water intake loaded into the ballast tanks. Expressed in another manner, a target biokill may result in sea water having 1 microbe per cubic meter of treated water or less. Empirical TRO testing of subject sea water loading establishes that an ozone concentration of between 1.0 mg/liter and 3.0 mg/liter of seawater is required to obtain the 99% target biokill.  $Q_T$  is a summation of the capacities of the vessel 10 ballast water intake pumps at all sea chests ( $\tau$ ) according to formula (I):

$$(I) \quad Q_T = Q_1 + Q_2 + \dots + Q_n$$

[0082] where  $Q_T$  is a capacity total of the respective pump capacities of n number of intake pumps. In this EXAMPLE, n is three in respect of stern intake pump at stern sea chest 132; starboard intake pump at starboard sea chest 134 and port intake pump at port sea chest 136. In this EXAMPLE, the respective pump out capacities are 17,000 gallons per minute (gpm), 500 gpm and 2,000 gpm and  $Q_T$  equals 19,600 gpm.

[0083] An ozone production rate capacity  $Q_r$  to attain an upper target ozone treatment rate of 3.0 mg/liter ( $T_R$ ) for a required 99% biokill is:

$$(II) \quad Q_r = Q_T T_R C_1 C_2 C_3$$

[0084] where  $C_1$  is a pounds to kilogram conversion constant;  $C_2$  is a gallons to liters conversion constant and  $C_3$  is a minutes to daily conversion constant.

[0085] The conversion constants convert the ozone production rate capacity to an Imperial unit of measure for comparison to standard rating capacities of pump manufacturers and suppliers. In formula (II) above,  $Q_r$  is  $Q_T T_R$  (2.206 lbs/kg/10<sup>6</sup> mg/Kg) (3.79 liters/gallon) (60 x 24) and  $Q_r$  equals 707.60 ozone pounds per day. Available ozone generators are compared to the  $Q_r$  707.60 ozone pounds per day requirement to select a generator 530 to attain the required biokill.

[0086] A corresponding injector 564 can be selected according to the following: The capacity of the selected generator is converted to a standard cubic feet per minute

(SCFM) gas injection. This value is  $Q_a$  is the generator capacity of 707.60 pounds per day converted to SCFM considering that the selected generator generates a 12% ozone-containing gas. In this EXAMPLE, the SCFM is 56.

[0087] Then each injector is sized according to the following representative required output proportionation:

$$(III) Q_{a1} = (Q_1 / Q_r) Q_a$$

[0088] For example for a first injector, the required capacity  $Q_{a1}$  is  $(17,000/19,6000) \times 56$  equal to 48.7 SCFM. Available injectors are compared to the respective  $Q_{a1}$ ,  $Q_{a2}$  and  $Q_{a3}$  requirements to select respective injectors to attain the required biokill.

[0089] The procedure of this EXAMPLE provides a precise generator sizing and gas flow for each injector to attain a target biokill.

[0090] EXAMPLE 2

[0091] In this EXAMPLE, ballast water is fed from an intake/discharge conduit between a sea chest and a battery of ballast tanks of a 100,000 to 150,000 DWT tanker. The water is fed at a 10,000 gpm flow rate. The seawater contains 70 mg/L of bromide.

[0092] A bypass stream of water is diverted from the intake/discharge conduit at a constant flow into a bypass conduit system illustrated in FIG. 6. Ozone gas is fed under slight pressure (12-15 psi) from its generating source through 316L stainless steel piping to a venturi injector. The ozone is injected as a 10-12% ozone in oxygen admixture. A bypass flow rate is set to permit effective injection by the venturi. In this EXAMPLE, a bypass flow rate is set at 66 gpm and pressure of approximately 90 psi. This flow rate is 0.3% of the main flow for every mg/L of ozone to be dosed (2.0 mg/L in this EXAMPLE). Flow and pressure are maintained by a positive displacement pump.

[0093] The selected flow rate and pressure are confirmed as follows: The flow ratio between the main flow and that in the bypass is about 10,000 gal/min to 66 gal/min. The specific ozone dosage in the bypass to achieve 2 mg/L in the main stream would be 303 mg/L so that with only 70 mg/L of bromide in the seawater,  $OBr^-$  would exceed  $Br^-$  by far, favoring the undesirable reactions. The beneficial reactions producing  $OBr^-$  will only dominate once the bypass stream is remixed with the main stream. Hence, bypass retention time is minimized to avoid as much ozone loss as possible and to meet the main dosage requirement of 2.0 mg/L.

[0094] The bypass injection venturi minimizes back-pressure and provides 90-95% solubilization of ozone gas in seawater.

**[0095] EXAMPLE 3**

**[0096]** In this EXAMPLE, bypass piping length for the bypass 594 is limited and a higher than typical pumping rate is maintained to reduce retention time down to almost 0.2 seconds as follows:

**[0097]** A bypass flow rate of 66 gpm typically requires a 2" pipe size. In this EXAMPLE, a smaller pipe size is selected to improve the flow velocity. Since back pressure on the venturi is also a limitation, the selected pipe size is decreased by only one size increment, i.e. to 1½". The cross-sectional area of a 1½" Schedule 80 pipe is 0.01227 square feet. The flow rate is  $(66/(7.48 \times 60)) = 0.1471 \text{ ft}^3/\text{sec}$ , so that the velocity in the pipe is increased to  $0.1471/0.01227 = 12 \text{ ft/sec}$ .

**[0098]** The bypass system is designed to provide a minimum length (retention length) from venturi to main conduit reinjection point as follows. The retention length is limited to a first 15 nominal diameters length to accommodate a static mixer and an additional 30 inches to accommodate an angled reinjector. The retention length for these requirements is 2.5 feet. The resulting retention time in traveling 2.5 ft at  $12 \text{ ft/sec} = 0.21 \text{ s}$ .

**[0099] EXAMPLE 4**

**[00100]** This EXAMPLE determined concentrations of ozone to eliminate an acceptable percentage of organisms from ballast water tanks and to avoid off-gas. The toxicity of ozone gas was determined to five species of marine organisms by ozone sparging into artificial seawater (ASW) in short-term (i.e., < 5 h) batch exposures.

**[00101]** Adult mysid shrimp, larval topsmelt, juvenile sheepshead minnows, and adult amphipods were tested. Adult *Americamysis bahia*, larval *Atherinops affinis*, juvenile *C. variegatus*, and adult *L. plumulosus* were obtained from Aquatic Biosystems (ABS, Fort Collins, CO, USA), while adult *R. abronius* were collected in the field near Anacortes, WA, and shipped overnight to the testing laboratory. Juvenile *Americamysis bahia* (10 d) were also received from ABS for tests concerning post ozonation exposure and the persistence of ozone byproducts. All organisms were in good condition before beginning testing.

**[00102]** All toxicity tests were conducted in glass aquaria (either 10 or 20 L) containing artificial seawater (ASW; Forty Fathoms Crystal Sea and deionized water) at 28-30 ppt. Prior to testing, aquaria were filled with ASW, placed in a water bath, and equilibrated overnight to test temperature. Small pieces of nylon mesh were

placed as substrate in aquaria used to conduct toxicity tests with *L. plumulosus* and *R. abronius*.

[00103] Ozone was dispensed using a Model SC-10 ozone generator (Nutech O3 Inc., McLean, VA). Total flow through the system was 2500 mL/min. Flow to each chamber was controlled with an N012-10 flow meter with a glass float (Gilmont Instruments, Barrington, IL). Ozone gas was distributed to the chambers using Kynar tubing and ozone tolerant diffusers (Aquatic Ecosystems).

[00104] TRO measurements were obtained using an *N,N*-diethyl-1,4 phenylenediammonium/potassium iodide (DPD/KI) indicator and a Pocket Colorimeter (Hach, Loveland, CO). This procedure was equivalent to USEPA Method 330.5 for wastewater and Standard Method 4500-Cl G for drinking water. TRO concentration (mg/L) measurements were calculated and expressed as equivalent concentrations of bromine ( $\text{Br}_2$ ,  $1 \text{ mol Cl}_2 = 0.44 \text{ mol Br}_2$ ).

[00105] Three 20-L aquaria containing ASW at 28-30 ppt salinity were treated with ozone at a flow rate of 61.6 ml/min over a period of 24 h. A 20-L control aquarium received compressed air at the same flow rate. Similarly to methods used on the *Tonsina* by Cooper et al. (2002). TRO measurements were obtained from all chambers at 0.5 h intervals from 0 to 6 h.

[00106] Ozone toxicity experiments for larval *Atherinops affinis*, juvenile *C. variegatus*, and adult *R. abronius* were conducted in 20-L aquaria, while experiments with adult *Americamysis bahia* and adult *L. plumulosus* were performed in 10-L aquaria. All experiments used a total of five 108 chambers each containing ten organisms, with one chamber tested per treatment. Chambers containing all organisms except *R. abronius* ( $15 \pm 2$  degree C) were maintained at  $23 \pm 2^\circ \text{C}$ .

[00107] Total gas flow rates for 20-L chambers were 97.5, 63.2, 38.6, and 20.0 mL/min. These flow rates corresponded to nominal ozone supply rates of 0.43, 0.28, 0.17, and 0.09 mg O<sub>3</sub>/L/min. Controls received compressed, ambient air at 97.5 mL/min (i.e., maximum flow rate). Total gas flow rates for 10-L chambers were 38.6, 28.3, 20.0, and 13.1 mL/min (0.34, 0.25, 0.17, 114 and 0.11 mg O<sub>3</sub>/L/min; control air flow = 38.6 mL/min). Experiments were run for a maximum of five h. TRO measurements were recorded with biological observations (mortality and motility of survivors) at 0.5-, 1-, 2-, 3-, 4-, and 5-h following test initiation. Experiments were terminated within the 5-h exposure period if all organisms in a treatment died.

[00108] To determine effects of short-term ozone exposure on longer-term survival Juvenile *Americamysis bahia* (10 d) were placed in five 20-L glass aquaria ( $19 \pm 2^\circ \text{C}$ ,

ten organisms per chamber). Total gas flow rates for 20-L chambers were 97.5, 63.2, 38.6, and 20.0 mL/min (0.43, 0.28, 0.17, and 0.09 mg O<sub>3</sub>/L/min; control air flow = 97.5 ml/min). TRO measurements were taken both before initiating ozone treatment and after 75 min of exposure. After 90 min of exposure, surviving organisms from each chamber were removed and placed into beakers of clean seawater maintained in a water bath at 19 ± 2°C, and fed *Artemia franciscana* (0.1 mL per beaker). The shrimp were examined at 24 h after terminating exposure for mortality, and dead organisms were removed. Surviving organisms were again fed *Artemia franciscana*, and examined again for mortality at 48 h after exposure.

[00109] To determine toxicity of residual oxidants over time A 20-L glass aquarium containing ASW at 19° C was treated with ozone at 97.5 ml/min (0.43 mg O<sub>3</sub>/L/min) until targeted TRO values (> 4.0 mg/L) were reached (1.5 h; see results). A portion of the treated water (2.5 L) was obtained for immediate use, while the remainder was transferred from the aquarium to 20-L low-density polyethylene Cubitainers (Hedwin Corporation, Laporte, IN) and stored in darkness without container headspace at 12° C. Toxicity experiments were initiated with the ozone-treated water at 0, 24, and 48 h following this exposure period. A range of TRO concentrations was achieved by mixing the ozonated water with fresh ASW. Concentrations of ozonated water used in toxicity tests were 100 % (ozonated water only), 75 %, 50 %, 25 %, and 0 % (ASW only). Three, 300 ml replicates of each concentration in 500 ml beakers were used for each test and maintained at 19 ± 2° C in a water bath. TRO was measured for each treatment concentration. Ten juvenile *Americamysis bahia* (8 d) were used in each replicate, and were fed 0.2 ml *Artemia franciscana* at test initiation. The shrimp were examined at 24 h for mortality, and dead organisms were removed. Surviving organisms were again fed *A. franciscana*, and examined again for mortality at 48 h after the beginning of the test.

[00110] Toxicity endpoints were expressed either as median-lethal concentrations (LC50) at specific exposure times ranging from 1 – 48 h, or as median-lethal times (LT50) as a function of ozone gas loading rates. In addition, 95%-lethal concentrations (LC95) were calculated to estimate time-specific TRO concentrations associated with nearly complete mortality. All endpoints were calculated using the Trimmed Spearman-Kärber method (e.g. Hamilton et al. 1977), or by linear interpolation if acceptable trim values were exceeded. All endpoint calculations were conducted using the Comprehensive Environmental Toxicity Information System (CETIS V1.0, Tidepool Scientific Software, McKinleyville, CA). LC50 and LC95

values for batch ozone toxicity tests were obtained from measured TRO concentrations and the total number of mortalities observed at each time period following test initiation. LC50 and LC95 values for experiments testing the toxicity of residual oxidants over time were expressed as a function of TRO concentrations measured immediately after test initiation.

[00111] Ozonation of ASW in glass aquaria over 5 h during the acute batch toxicity tests indicated a gradual increase of TRO over time without saturation. An example plot of TRO concentrations at each ozone flow rate as a function of time for the *L. plumulosus* tests is presented in FIG 8. At lower flow rates (0.11 – 0.17 mg O<sub>3</sub>/L/min), TRO concentrations reached 1.9 – 3.6 mg/L, whereas concentrations reached 4.6 – 5.6 mg TRO/L at higher flow rates. Thus, at any given exposure period, increasing ozone gas delivery rates generated increasing instantaneous TRO concentrations in ASW.

[00112] *Effects of short-term ozone exposure on survival:* LC50 values for all organisms ranged from 0.31 to > 5.63 mg/L, with 100 % mortality of each species except *L. plumulosus* occurring in less than 5 h (Table 1 of FIG. 6). The juvenile topmelt (*Atherinops affinis*) was the most sensitive organism tested, with LC50 values of 0.38 and 0.31 mg TRO/L after only 1 and 2 h of ozone exposure, respectively. Juvenile sheepshead minnows (*C. variegatus*) were nearly as sensitive, but it took up to 4 h to reach a similar final LC50 (0.35 mg TRO/L). In contrast, all three invertebrates tested were significantly more tolerant of ozone exposure, with juvenile *Americamysis bahia* reaching a lowest LC50 of 0.62 mg TRO/L at 3 h, and adult *R. abronius* reaching a lowest LC50 of 0.94 mg TRO/L after 4 h. This same trend in relative species sensitivity was also evident at 2 h (i.e., the longest exposure period with less than 100 % mortality for all species) with the two juvenile fish having the lowest LC50s (0.31 and 0.44 mg TRO/L), and the invertebrates *Americamysis bahia* and *R. abronius* exhibiting significantly higher LC50s (1.37 and 1.72 mg TRO/L, respectively; Table 1 of FIG. 6). 95 %-lethal effect concentrations (LC95) were approximately two to three-fold higher than LC50 values for all species and time values testing (Table 2 of FIG. 6). No significant mortality was observed in the amphipod *L. plumulosus* at any TRO concentrations tested up to 5.63 mg TRO/L after 5 h of batch ozonation (Tables 1 and 2 of FIG. 6).

[00113] To indicate the time needed to induce significant mortality via batch ozonation, LT50 values were derived for the three most sensitive species (FIG. 7). Similarly to the LC50 results, juvenile topmelt (*Atherinops affinis*) were the most

sensitive to ozone exposure in ASW with median lethal times ranging from 84 – 38 min at the lowest to highest ozone loading rates, respectively. Both the mysid shrimp (*Americamysis bahia*) and sheepshead minnows (*C. variegatus*) exhibited longer median lethal times ranging from 139 – 184 min at the lowest ozone loading rate to 86 – 60 min at the highest ozone loading rates. LT50 data could not be derived for either of the less sensitive amphipods, *R. abronius* or *L. plumulosus*.

[00114] *Effects of short-term ozone exposure on longer-term survival:* When juvenile mysids (*Americamysis bahia*) were removed from ozonated ASW after 1.5 h, only 30 – 60 % mortality had occurred at the two highest ozone loading rates (FIG. 8). However, mortality continued to occur even after organisms were transferred to clean ASW. Mortality ranged from 20 – 100 % in organisms previously exposed to the highest three ozone loading rates after 24 h, and from 60 – 100 % in organisms previously exposed to all four ozone loading rates after 48 h.

[00115] *Toxicity of residual oxidants over time:* After 1.5 h of ozonation at 0.43 mg O<sub>3</sub>/L/min, TRO reached 2.24 mg/L which, when diluted with clean ASW, created a dilution series ranging down to 0.59 mg TRO/L at 25 % ozonated ASW (FIG. 9). Relatively little TRO loss occurred after ASW storage with a maximum concentration of 2.13 mg TRO/L at 24 h, and 1.66 mg TRO/L at 48 h. As a result, dilution series generated an acceptable range of TRO concentrations for deriving median lethal effects levels in *Americamysis bahia* when measured at the time of test initiation (FIG. 9).

[00116] LC50 values for *Americamysis bahia* in waters tested immediately following ozone treatment were 0.70 and 0.47 mg TRO/L at 24 h and 48 h, respectively (Table 3 of FIG. 6). For both 24-h and 48-h mortality data, LC50 values tended to decline slightly with increasing storage time, but these differences were not statistically significant (i.e., 95 % confidence limits all overlapped). 95 % effect concentrations exhibited similar trends with 24-h LC95s ranging from 1.06 – 0.75 mg TRO/L, and 48-h LC95s ranging from 1.03 – 0.74 mg TRO/L (Table 3, FIG. 6).

[00117] Juvenile topsmelt and sheepshead minnows (*Atherinops affinis* and *Cyprinodon variegatus*) were the most sensitive to oxidant exposure, with the mysid shrimp *Americamysis bahia* being the most sensitive invertebrate. In contrast, benthic amphipods (*Rhepoxinius abronius*, and *Leptochirus 6 plumulosus*) were the least sensitive of all species tested. Mortality from ozone exposure occurred quickly with median lethal times ranging from 1 – 3 h for the most sensitive species, 8 although additional mortality can occur 1 – 2 d following ozonation. As shown *supra*, ozone

does not persist in seawater under the conditions of treatment according to the invention. Hence, toxicity most likely resulted from oxidation of bromide to bromine species 10 (HOBr, OBr-) which persist and continue to induce mortality even after 1-2 d storage. Therefore, ozonating seawater in short-term batch exposures to generate TRO concentrations ranging from 0.3 – 1.7 mg/L as Br<sub>2</sub> may effectively remove significant portions of marine NIS populations.

[00118] The results indicate that marine invertebrate and fish species can be effectively eliminated following short-term (i.e., less than 5 hours to 100% mortality) ozonation at TRO concentrations less than 1 mg/l as bromine, and that ozone-produced oxidants can accumulate and remain toxic in closed containers for at least two days. Benthic invertebrates, such as blue crabs may be relatively tolerant of ozone-produced oxidants, and so may require other control methods to prevent introductions from ballast water discharge.

[00119] This EXAMPLE shows that ozonating seawater in short-term batch exposures to generate TRO concentrations ranging from 0.3 – 1.7 mg/L as Br<sub>2</sub> effectively removes significant portions of marine NIS populations. Analysis of this range indicates that all oxygen is dissolved with the ozone to avert an equilibrium situation. Consuming ozone by chemical reactions in the seawater averts the release of ozone from solution when subsequently exposed to the. The system can avert equilibrium to permit a nearly total transfer of ozone to water or seawater.

[00120] While preferred embodiments of the invention have been described, the present invention is capable of variation and modification and therefore should not be limited to the precise details of the EXAMPLES. The invention includes changes and alterations that fall within the purview of the following claims.

**The claims defining the invention are as follows:**

1. A method of ozone treatment, comprising:  
determining a target biokill of species for water charging into a ballast tank  
of a sea faring vessel;

5 regulating a diverted portion of the water prior to charging the water into  
the ballast tank;

adjusting the regulating of the diverted portion of water and a rate of  
injection of ozone into the portion to attain the target biokill; and

10 injecting ozone at the determined rate into the regulated diverted portion to  
attain the target biokill when the portion is recombined into the water for charging  
to the ballast tank.

2. A method of ozone treatment, comprising:

determining a target biokill of species for water charging into a ballast tank  
of a sea faring vessel;

15 diverting a portion of the water prior to charging into the ballast tank;

determining an ozone generating capacity sufficient to inject ozone into  
the portion to attain a target ozone concentration when the portion is recombined  
into the water for charging into the ballast tank;

20 regulating the diverted portion and adjusting a rate of injection of ozone  
into the portion with a generator having the determine ozone generating capacity  
to attain the target biokill when the portion is recombined into the water for  
charging to the ballast tank.; and

recombining the portion with the water for charging into the ballast tank.

25 3. The method of claim 2, wherein the diverted portion is regulated  
and the rate of ozone injection is adjusted according to a set of instructions to  
provide the target biokill at a lowest threshold ozone concentration in the  
recombined water.

30 4. The method of claim 2, wherein the diverted portion is regulated  
and the rate of ozone injection is adjusted according to a set of instructions  
resident in a computer memory to provide the target biokill at a lowest threshold  
ozone concentration in the recombined water.

5. A ballast-water treatment system comprising:  
a sea faring vessel including at least one ballast tank and at least one conduit conveying water to or from an intake/outlet to the ballast tank;  
a regulator to divert a portion of the water from the conduit;  
5 an injector to provide an ozone injection rate into the portion of water; and  
a controller operatively connected to the regulator and the injector to adjust the diverted portion of water and injection rate of the ozone into the portion to attain the target biokill when the portion is recombined with the water.

6. The ballast water treatment system of claim 5, further comprising a  
10 disperser to disperse injected ozone through the portion prior to recombining the portion with the water.

7. The ballast water treatment system of claim 5, further comprising an ozone generator to provide ozone to the injector.

8. The ballast water treatment system of claim 5, further comprising  
15 an ozone generator to provide ozone to the injector, wherein the generator is selected according to a capacity  $Q$  determined as sufficient to provide a treatment rate  $T$  of injected ozone into the portion to attain a target ozone concentration when the portion is recombined into the water for charging into the ballast tank.

9. The ballast water treatment system of claim 5, comprising a  
20 plurality of diverter and injector sets to inject ozone into a plurality of portions of water streams prior to charging each stream into a respective ballast tank of a plurality of ballast tanks

10. The ballast water treatment system of claim 5, further comprising  
25 an ozone generator to provide ozone to the injector, wherein the generator is selected according to an ozone generator capacity  $Q_n$  determined according to a summation of a capacity according to a treatment rate  $T$  required to treat ballast water of conduits to the plurality of ballast tanks.

11. A method of ozone treatment, comprising:  
30 determining a target biokill of species for ballast water unloading from a sea faring vessel to the sea;  
regulating a diverted portion of the ballast water prior to unloading;

adjusting the regulating of the diverted portion of water and a rate of injection of ozone into the portion to attain the target biokill; and

injecting ozone at the determined rate into the regulated diverted portion to attain the target biokill when the portion is recombined into the water for unloading the ozone injected water to the sea.

5 12. A ballast-water treatment system comprising:  
a sea faring vessel including at least one ballast tank;  
an ozone generator that generates ozone,  
a ballast water conduit that discharges water from the ballast tank and  
10 conducts the water to an unloading port of the sea faring vessel;  
a regulator to divert a portion of the water from the conduit;  
an injector to provide an ozone injection rate into the portion of water; and  
a controller operatively connected to the regulator and the injector to  
adjust the diverted portion of water and injection rate of the ozone into the portion  
15 to attain the target biokill when the portion is recombined with the water in the conduit.

13. A method of ozone treatment, comprising:  
uploading sea water to a ballast tank of a sea faring vessel;  
regulating a diverted portion of the uploading water prior to charging the  
20 water into the ballast tank;

adjusting the regulating of the diverted portion of water and a rate of injection of ozone into the portion to attain a target biokill; and

injecting ozone at the determined rate into the regulated diverted portion to attain the target biokill when the portion is recombined into the uploading water  
25 for charging to the ballast tank.

14. The method of claim 13, comprising adjusting flow of the diverted portion and injection of ozone to provide a 95% or greater species biokill in the water.

15. A method of ozone treatment, comprising:  
30 diverting a portion of water into a bypass from a flow of water in a conduit;  
injecting an ozone-containing gas into the portion to provide an ozonated portion;

recombining the ozonated portion with the flow of water in the conduit; and regulating the diverted portion to provide a minimum diverted portion flow rate according to flow in the conduit and proportion of ozone in the injected gas.

5 16. The method of claim 15, further comprising limiting a retention period of ozone injected water from a time of ozone injection into the portion to recombining the ozonated portion with the flow of water in the conduit.

17. A water treatment system comprising:

a water conduit that transports water from a first intake location to a discharge location;

10 a bypass from a first point of the water conduit to a return point wherein the bypass diverts a portion of the water from the conduit for circulation in the bypass and back to the water conduit at a return point;

an injector included in the bypass to inject ozone into the diverted portion of water;

15 an ozone generator that generates ozone for injection by the injector; and a regulator that regulates the diverted portion to provide a minimum diverted portion flow rate according to flow in the conduit and proportion of ozone in the injected gas.

20 18. The system of claim 17, further comprising a static mixer located within the bypass downstream to the injector.

19. The system of claim 17, comprising a mixer located within the bypass downstream to the injector; and

a reinjector to reinject the diverted portion with ozone back to the water conduit at the return point.

25 20. The system of claim 17, comprising a plurality of injectors to inject ozone into respective plurality of diverted water portions of streams prior to charging each portion into a respective ballast tank of a plurality of ballast tanks.

21. A method of ozone treatment, comprising:

30 uploading seawater through a conduit to a ballast tank of a sea faring vessel;

regulating a diverted portion of the uploading water to divert the diverted portion through a bypass prior to charging the water into the ballast tank; and

adjusting the regulating of the diverted portion of water and a rate of injection of ozone into the portion to provide a minimum diverted portion flow rate according to flow in the conduit and proportion of ozone in the injected gas.

22. The method of claim 21, further comprising limiting a retention  
5 period of ozone injected water from a time of ozone injection into the portion to recombining the ozonated portion with the flow of water in the conduit.

23. A method of ozone treatment, comprising:  
diverting a portion of water charging into a ballast tank of a vessel;  
injecting ozone into the portion to provide an ozonated portion; and  
10 recombining the ozonated portion with the water charging into the ballast tank;

wherein a retention period between injecting the ozone into the portion and recombining the injected ozone portion with the water charging into the tank is controlled below a specified time limit.

24. The method of claim 23, wherein the water is seawater, containing  
15 bromine that reacts with ozone to provide an  $OBr^-$  reaction product.

25. The method of claim 23, wherein the water is seawater containing  
bromine that reacts with ozone to provide an  $OBr^-$  reaction product and further  
wherein the ozone is contacted with seawater for a period controlled to maintain  
20 a molar ratio of  $Br^-$  to  $OBr^-$  above 2.7.

26. The method of claim 23, wherein the retention period is limited by  
controlling bypass fluid flow velocity.

27. The method of claim 23, wherein the retention period is limited by  
bypass pipe length.

28. The method of claim 23, wherein the retention period is controlled  
25 for a period specified below a limit according to the determined life of the reaction product.

29. The method of claim 23, wherein the retention period is controlled  
for a period specified below a limit according to the determined life of the reaction  
30 product by establishing a length between a point of ozone injection and a point of recombining the injected portion with the water charging to the ballast tank.

30. The method of claim 23, wherein the retention period is controlled for the period by controlling a rate of ozone injection

31. The method of claim 23, wherein the retention period is controlled for the period by controlling a rate of flow of the diverted portion.

5 32. The method of claim 16, 22 or 23, wherein the period is less than 5 seconds.

33. The method of claim 16, 22 or 23, wherein the period is less than 0.25 second.

10 34. The method of claim 16, 22 or 23, wherein the period is less than 0.21 second.

35. A ballast-water treatment system comprising:

a vessel including at least one ballast tank and at least one conduit conveying water to or from an intake/outlet to the ballast tank;

15 a bypass to convey water from a first point of the conduit to a return point of the conduit;

a regulator to divert a portion of the water into the bypass from the conduit;

an injector to provide an ozone injection rate into the portion of water; and

20 a controller operatively connected to the regulator and the injector to regulate the diverted portion to provide a minimum diverted portion flow rate according to flow in the conduit and proportion of ozone in the injected gas.

36. The system of claim 35, further comprising a computer usable medium comprising a set of instructions to operate the controller to adjust the diverted portion of water and injection rate of the ozone into the portion to attain the target biokill when the portion is recombined with the water.

25 37. The system of claim 35, comprising a mixer located within the bypass downstream to the injector; and

a reinjector to reinject the diverted portion with ozone back to the conduit at the return point.

wherein the vessel is a sea faring vessel.

30 38. A method of ozone treatment, comprising:

determining a target biokill of species for water charging into a ballast tank of a vessel;

diverting a portion of water into a bypass from a flow of the water charging into the ballast tank through a conduit;

injecting ozone into the diverted portion at a rate determined to attain the target biokill when the portion is recombined into the water for charging to the ballast tank; and

regulating the diverted portion of the water to a minimum diverted portion flow rate according to flow in the conduit and proportion of ozone in the injected gas.

39. The method of claim 15, 21 or 38, wherein the diverted portion is regulated to at least 0.25% of the main conduit flow for every mg/L of ozone injected into the bypass.

40. The method of claim 15, 21 or 38, wherein the diverted portion is regulated to at least 0.3% of the main conduit flow for every mg/L of ozone injected into the bypass.

41. The method of claim 15, 21 or 38, wherein the diverted portion is regulated to at least 0.35% of the main conduit flow for every mg/L of ozone injected into the bypass.

42. The method of claim 1, 15, 21 or 38, additionally comprising charging the ozone injected water into one ballast tank.

43. The method of claim 1, 15, 21 or 38, additionally comprising charging the ozone injected water into a plurality of ballast tanks.

44. A ballast-water treatment system comprising:  
a sea faring vessel including at least one ballast tank;  
an ozone generator that generates ozone;  
a ballast water conduit that discharges water from the ballast tank and conducts the water to an unloading port of the sea faring vessel;

a regulator to divert a portion of the water from the conduit into a bypass;  
and

an injector to provide an ozone injection rate into the portion of water;  
wherein the regulator regulates the diverted portion to provide a minimum diverted portion flow rate according to flow in the conduit and proportion of ozone in the injected gas.

45. The system of claim 17, 35 or 44, wherein the regulator regulates the diverted portion to provide a diverted portion flow of at least 0.25% of the conduit flow for every mg/L of ozone injected into the bypass.

5 46. The system of claim 17, 35 or 44, wherein the regulator regulates the diverted portion to provide a diverted portion flow of at least 0.3% of the conduit flow for every mg/L of ozone injected into the bypass.

47. The system of claim 17, 35 or 44, wherein the regulator regulates the diverted portion to provide a diverted portion flow of at least 0.35% of the conduit flow for every mg/L of ozone injected into the bypass.

10 48. A ballast-water treatment system without an off-gas destruction device; comprising:

a salt water or fresh water sea faring vessel including at least one ballast tank and at least one conduit conveying water to or from an intake/outlet to the ballast tank;

15 a regulator to divert a portion of the water from the conduit;

an injector to provide an ozone injection rate into the portion of water; and

a controller operatively connected to the regulator and the injector to adjust the diverted portion of water and an injection rate of the ozone into the portion to attain the target biokill while avoiding a release of detrimental gas into the atmosphere without an off-gas destruction device.

20 49. The ballast water treatment system of claim 48, further comprising:

a reinjector to reinject the diverted portion with ozone back to the water conduit at a return point; and

25 a disperser to disperse injected ozone through the portion prior to recombining the portion with the water.

50. The ballast water treatment system of claim 48, further comprising an ozone generator to provide ozone to the injector.

30 51. The ballast water treatment system of claim 48, comprising a plurality of diverter and injector sets to inject ozone into a plurality of portions of water streams prior to charging each stream into a respective ballast tank of a plurality of ballast tanks

52. The ballast water treatment system of claim 5 or 48, wherein the controller is a computer further comprising a computer usable medium comprising a set of instructions to operate the controller to adjust the diverted portion of water and injection rate of the ozone into the portion to attain the target biokill when the portion is recombined with the water.

53. The ballast water treatment system of claim 5 or 48, wherein the controller is a computer further comprising a set of instructions to operate the controllers to coordinate flow of the diverted portion and injection of ozone to provide a target level of biokill in the water.

54. The ballast water treatment system of claim 5, 35 or 48, wherein the controller is a computer further comprising a set of instructions to operate the controller to coordinate flow of the diverted portion and injection of ozone to provide a concentration of ozone of 1.0 to 4.5 mg/l in the water.

55. The ballast water treatment system of claim 5, 35 or 48, wherein the controller is a computer further comprising a set of instructions to operate the controller to coordinate flow of the diverted portion and injection of ozone to provide a concentration of ozone of 1.5 to 4.0 mg/l in the water.

56. The ballast water treatment system of claim 5, 35 or 48, wherein the controller is a computer further comprising a set of instructions to operate the controller to coordinate flow of the diverted portion and injection of ozone to provide a concentration of ozone of 2.0 to 3.0 mg/l in the water.

57. The ballast water treatment system of claim 5, 35 or 48, wherein the controller is a computer further comprising a set of instructions to operate the controllers to coordinate flow of the diverted portion and injection of ozone to provide a 95% or greater species biokill in the water.

58. A method of ozone treatment, comprising:  
determining a target biokill of species for water charging into a ballast tank of a sea faring vessel;  
determining an injection of ozone into the water to attain the target biokill without releasing an environmentally toxic off-gas into the atmosphere.  
regulating a diverted portion of the water prior to charging the water into the ballast tank;

adjusting the regulating of the diverted portion of water and a rate of injection of ozone into the portion to attain the target biokill without release of an environmentally toxic off-gas; and

5 injecting ozone at the determined rate into the regulated diverted portion to attain the target biokill when the portion is recombined into the water for charging to the ballast tank without releasing an environmentally toxic off-gas into the atmosphere.

59. The method of claim 1 or 58, additionally comprising charging ozone injected water into the ballast tank.

10 60. The method of claim 1 or 58, additionally comprising charging ozone injected water into a plurality of ballast tanks.

61. The method of claim 1, 38 or 58, wherein the target biokill is one microbe per cubic meter of water or less.

15 62. The method of claim 1, 38 or 58, comprising adjusting the regulating of the diverted portion of water and a rate of injection of the ozone into the portion of water to provide a concentration of ozone of 1.0 to 4.5 mg/l in the water charging into the ballast tank.

20 63. The method of claim 1, 38 or 58, comprising adjusting the regulating of the diverted portion of water and a rate of injection of the ozone into the portion of water to provide a concentration of ozone of 1.5 to 4.0 mg/l in the water charging into the ballast tank.

25 64. The method of claim 1, 38 or 58, comprising adjusting the regulating of the diverted portion of water and a rate of injection of the ozone into the portion of water to provide a concentration of ozone of 2.0 to 3.0 mg/l in the water charging into the ballast tank.

65. The method of claim 1, 38 or 58, comprising injecting ozone into the diverted portion at a single point prior to charging the water into the ballast tank.

30 66. The method of claim 1, 15, 21, 38 or 58, comprising injecting ozone into a diverted portion of each of a plurality of water streams prior to charging each stream into a respective ballast tank of a plurality of ballast tanks.

67. The method of claim 1, 15, 21, 38 or 58, comprising regulating the diverted portion of water prior to injecting ozone into the portion and dispersing

the injected ozone in the portion prior to recombining the portion into the water for charging into the ballast tank.

68. A method of ozone treatment according to any one of the embodiments substantially as herein described and illustrated.

5 69. A ballast-water treatment system according to any one of the embodiments substantially as herein described and illustrated.

70. A water treatment system according to any one of the embodiments substantially as herein described and illustrated.

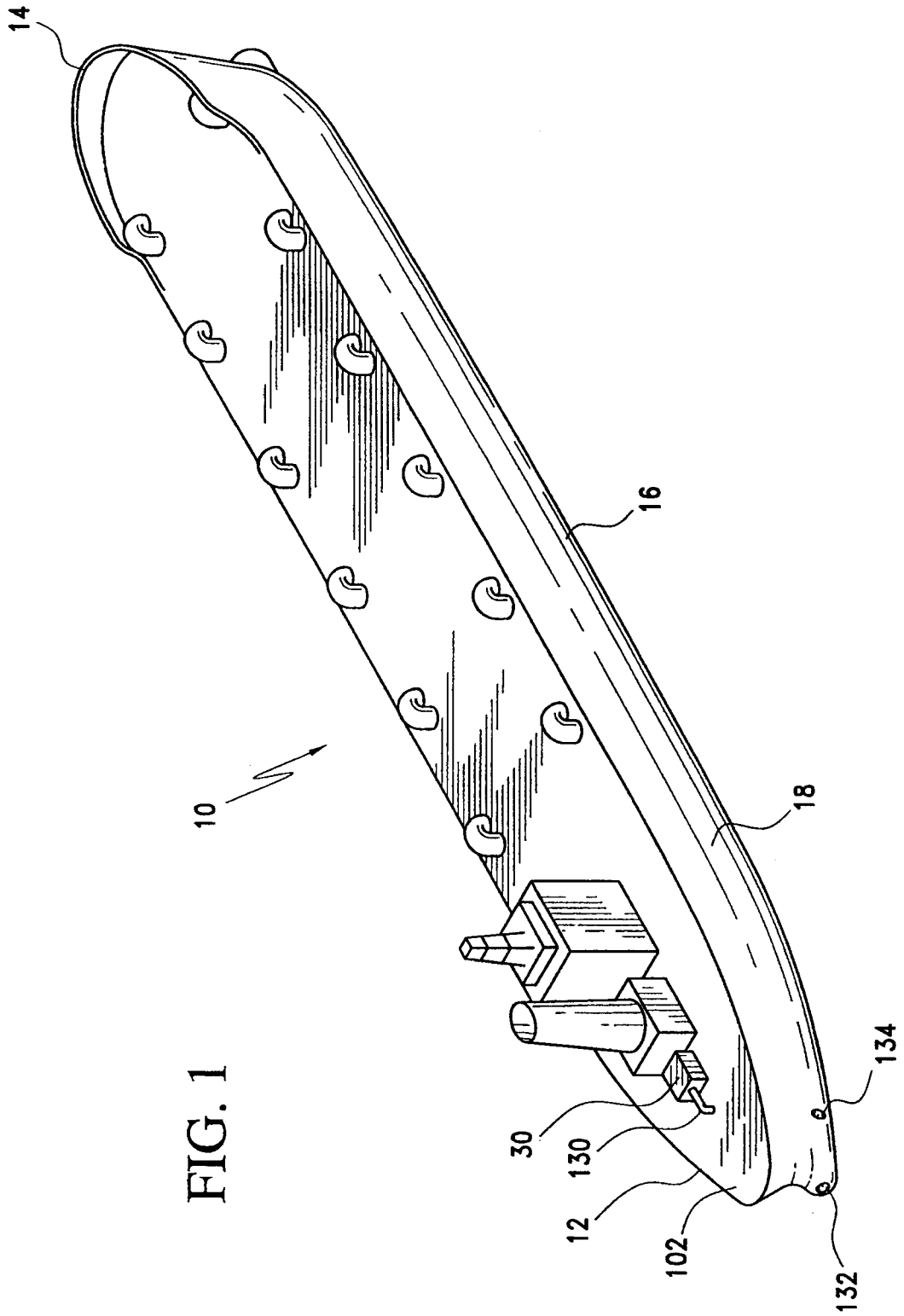


FIG. 1

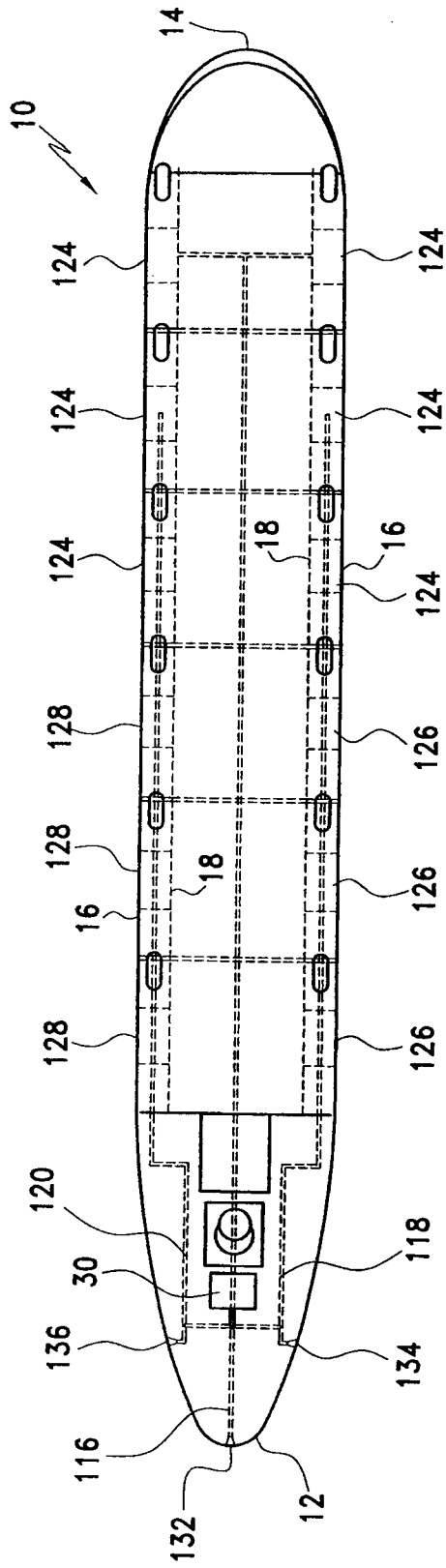


FIG. 2

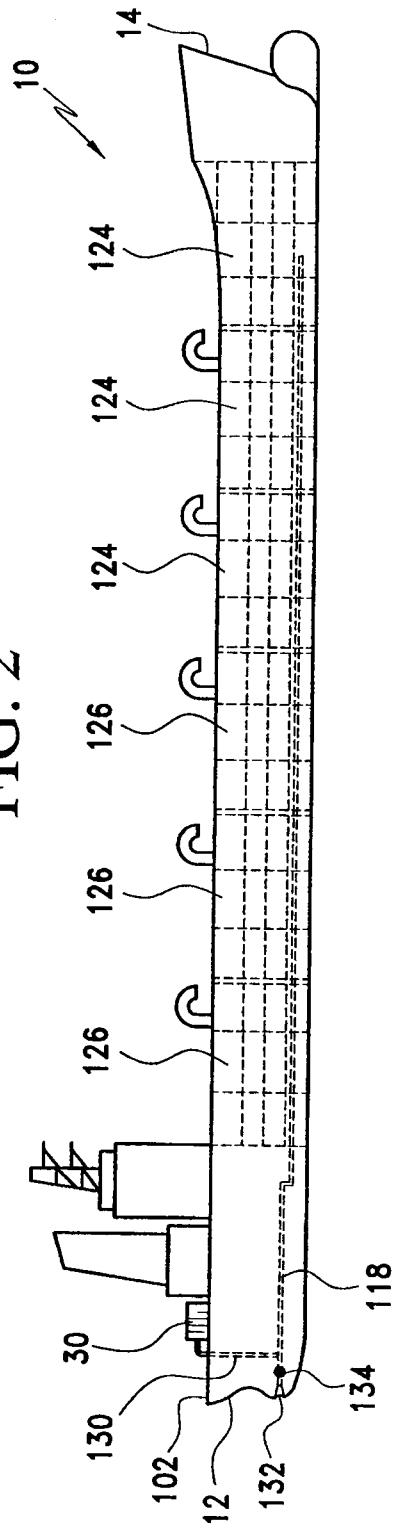


FIG. 3

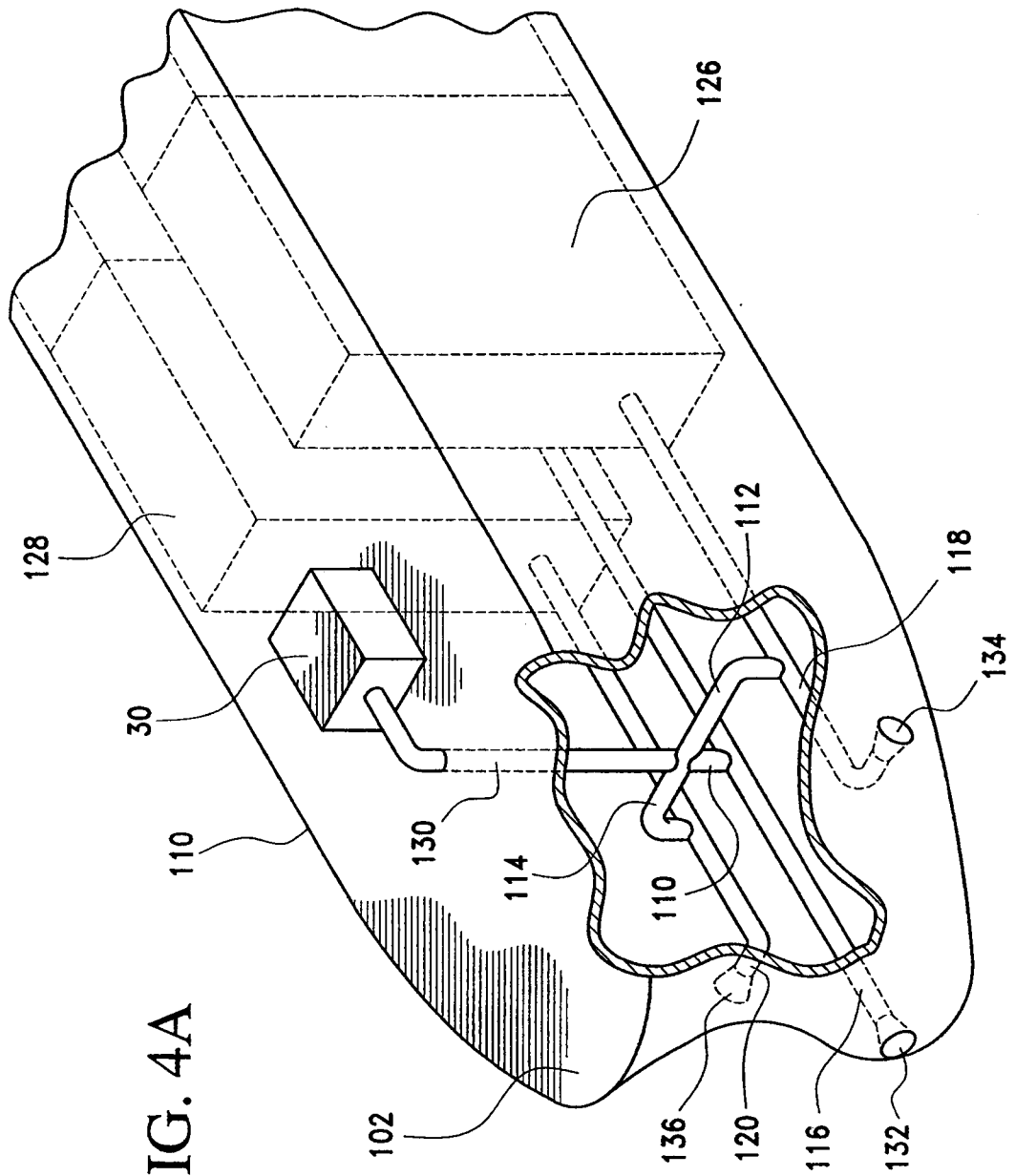


FIG. 4A

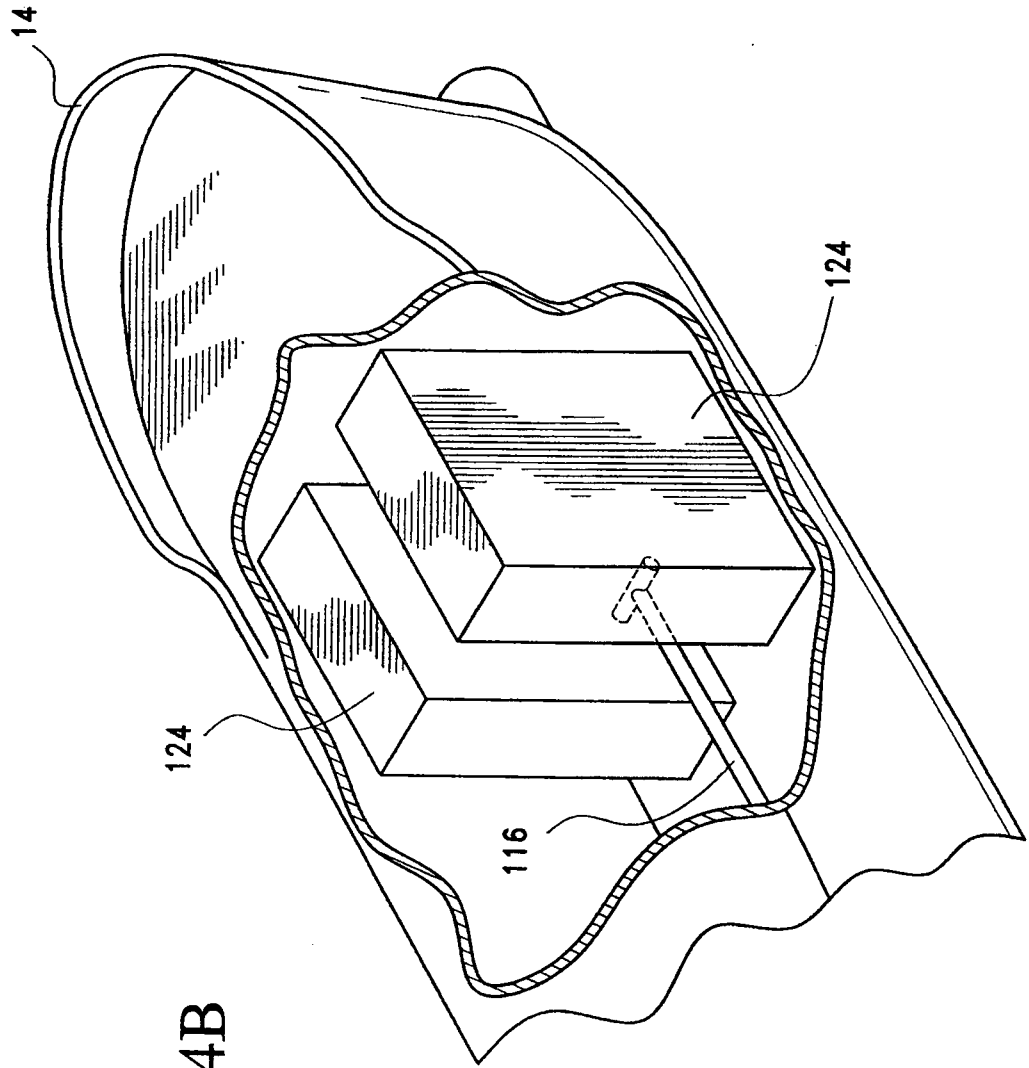


FIG. 4B

FIG. 5A

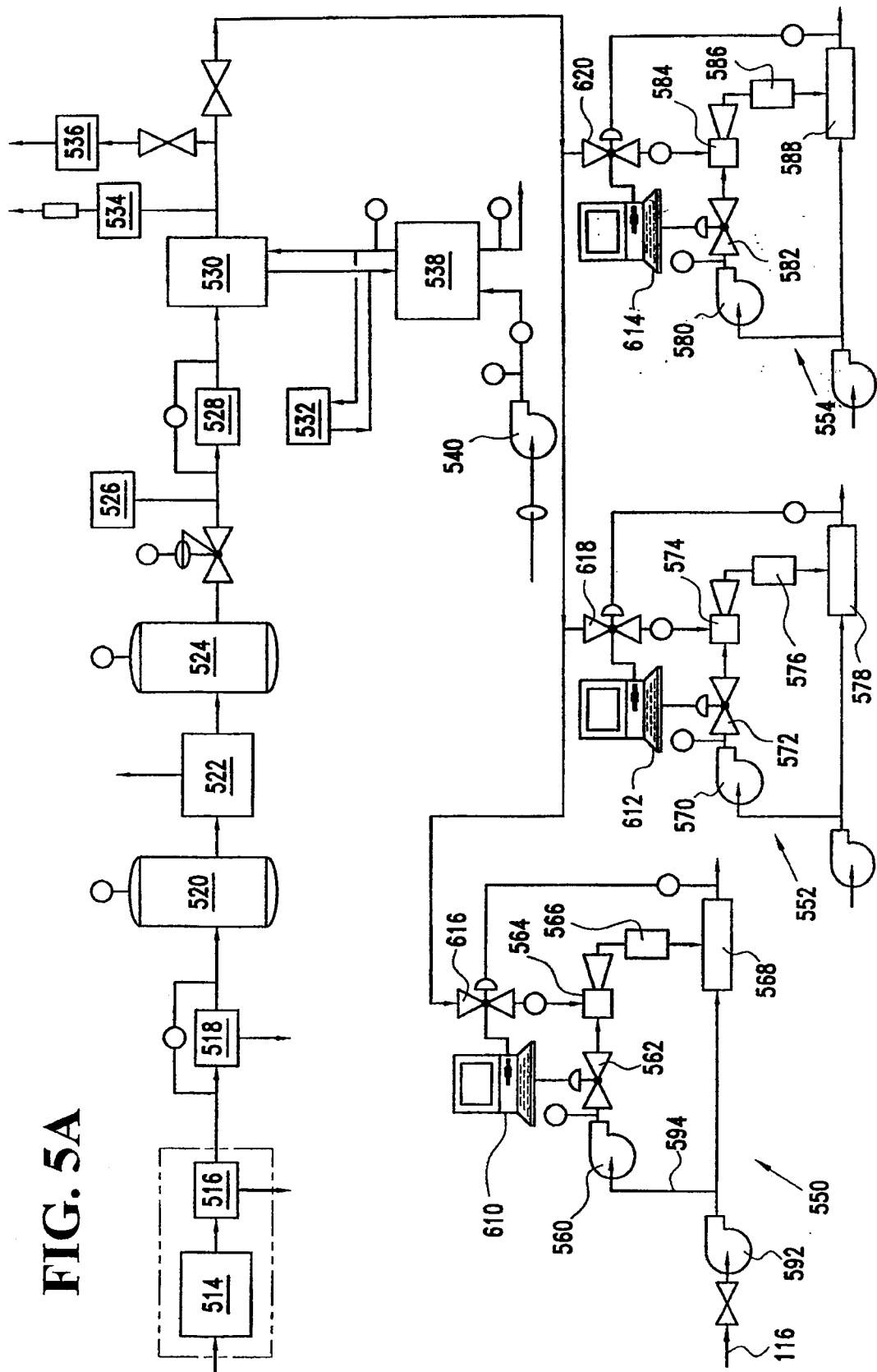
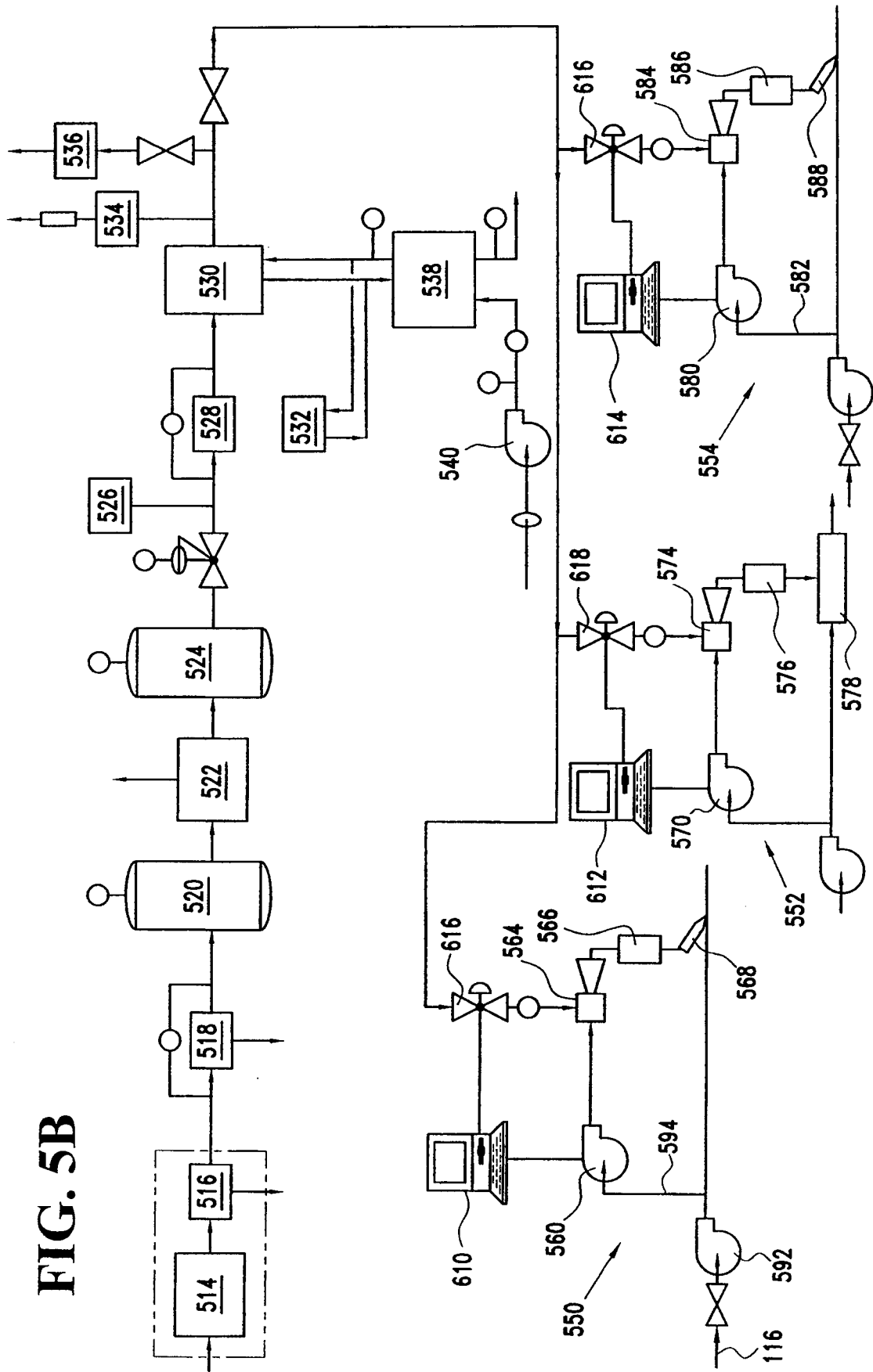


FIG. 5B



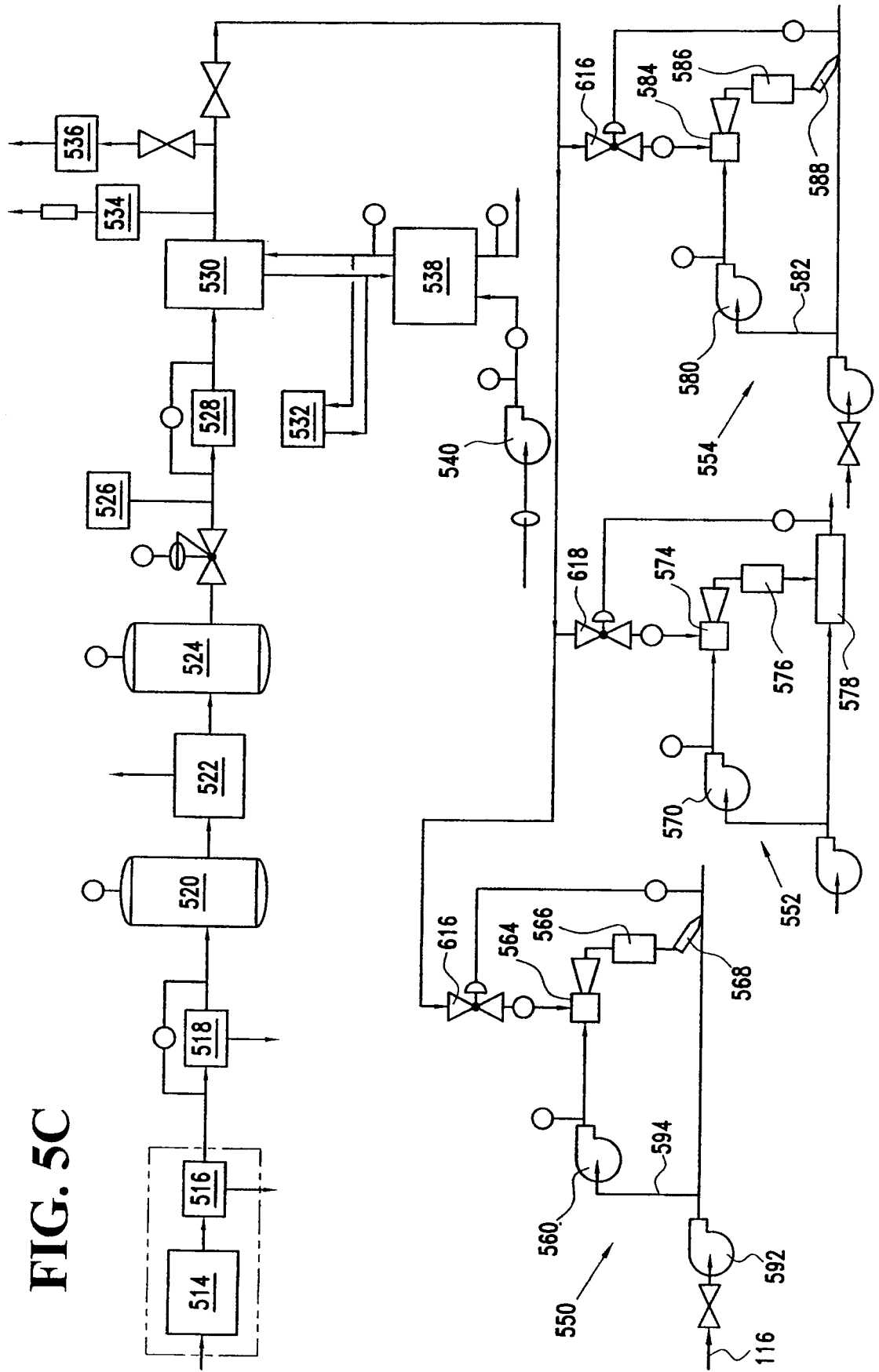


FIG. 5C

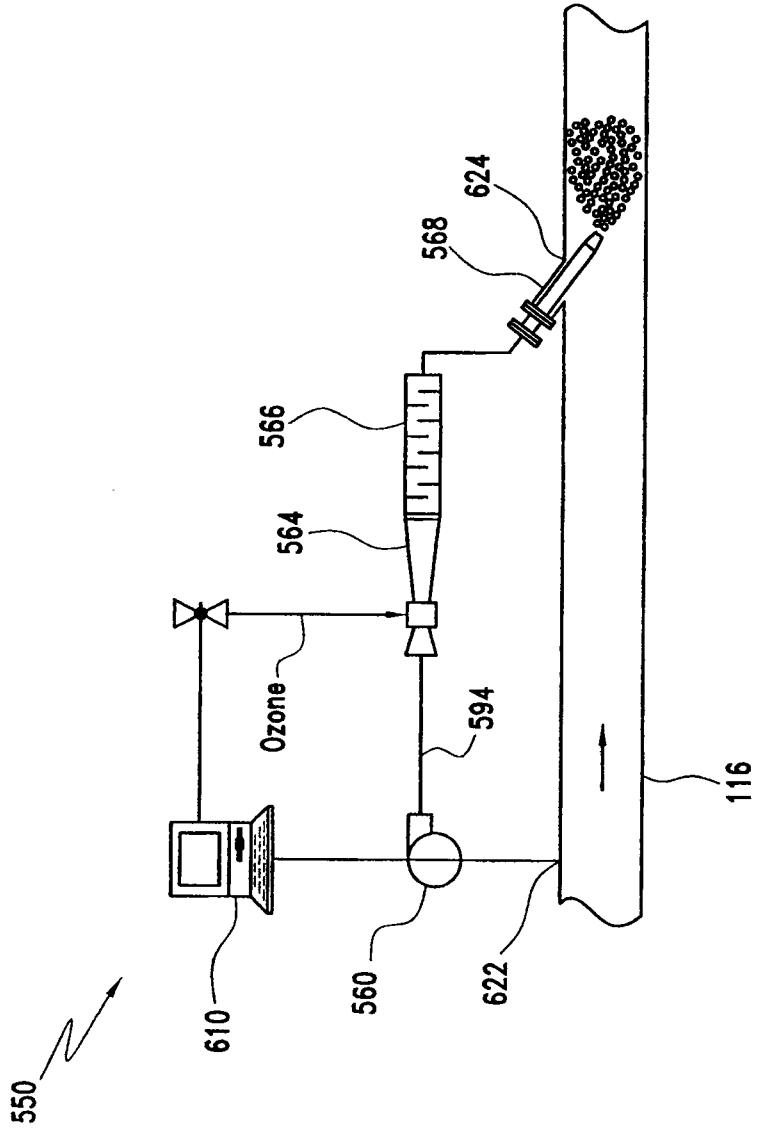


FIG. 6

# FIG. 7

## TABLE 1

Species	LC50(95%C.I.)mg TRO/L as Br <sub>2</sub>					
	0.5h	1h	2h	3h	4h	5h
<i>Americamysis bahia</i>	>0.9	>1.22	1.37 (1.29,1.45)	0.62		
<i>Atherinops affinis</i>	>0.9	0.38 (0.31,0.47)	0.31			
<i>Cyprinodon variegatus</i>	>0.42	1.13 (1.13,1.13)	0.44 (0.39,0.50)	0.44 (0.24,0.85)	0.35	
<i>Rhepoxinius abronius</i>	>0.48	>1.51	1.72 (0.76,3.89)	1.37 (1.27,1.49)	0.94	
<i>Leptocheirus plumulosus</i>	>0.65	>1.24	>2.93	>3.63	>4.21	>5.63

## TABLE 2

Species	LC95(95%C.I.)mg TRO/L as Br <sub>2</sub>					
	0.5h	1h	2h	3h	4h	5h
<i>Americamysis bahia</i>	>0.9	>1.22	1.67	1.14		
<i>Atherinops affinis</i>	>0.9	1.15	0.59			
<i>Cyprinodon variegatus</i>	>0.42	>1.13	0.82	1.46	0.63	
<i>Rhepoxinius abronius</i>	>0.48	>1.51	>2.46	2.66	2.9	
<i>Leptocheirus plumulosus</i>	>0.65	>1.24	>2.93	>3.63	>4.21	>5.63

## TABLE 3

Storage time (h)	24-h LC50	48-h LC50	24-h LC95	48-h LC95
0	0.70 (0.63,0.78)	0.47 (0.27,0.90)	1.06 (1.06,1.06)	1.03 (0.91,1.09)
24	0.50 (0.47,0.54)	0.43 (0.36,0.51)	0.83 (0.83,0.83)	0.82 (0.81,0.82)
48	0.43 (0.38,0.48)	0.32 (0.23,0.43)	0.75 (0.74,0.76)	0.74 (0.70,0.77)

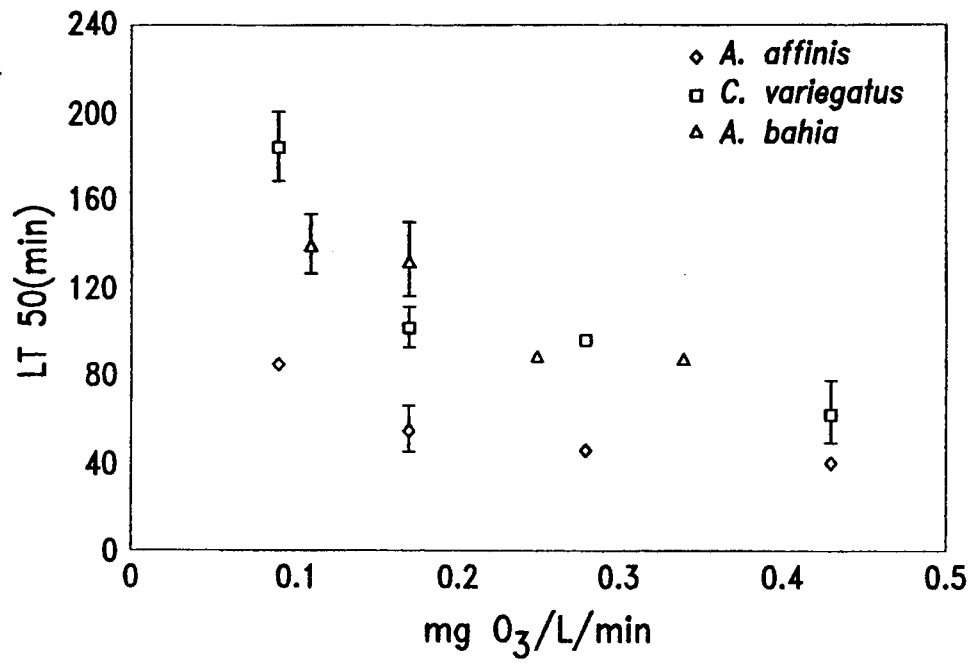


FIG. 8

FIG. 9

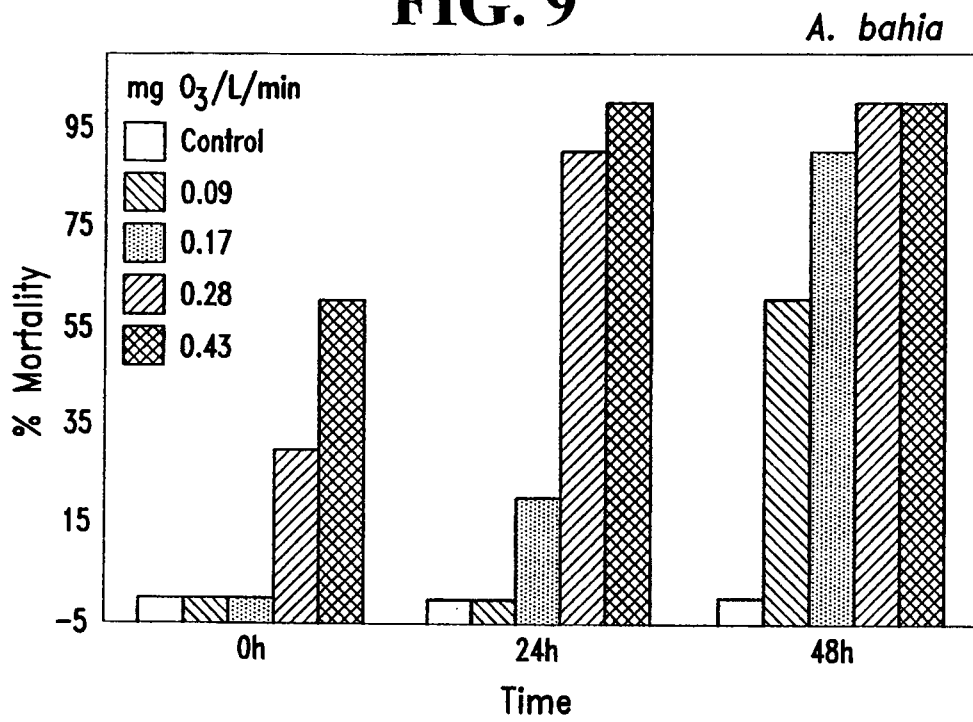


FIG. 10

