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## Apparatus and Method for Photocatalytic Conditioning of Flue Gas Fly-Ash Particles

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# United States Patent [19]

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Tabatabaie-Raissi et al.

[45] Date of Patent: **Aug. 10, 1999**

[54] **APPARATUS AND METHOD FOR PHOTOCATALYTIC CONDITIONING OF FLUE GAS FLY-ASH PARTICLES**

5,350,441 9/1994 Wright ..... 95/58

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[73] Assignee: **University of Central Florida**, Orlando, Fla.

[21] Appl. No.: **09/128,443**

[22] Filed: **Aug. 3, 1998**

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[62] Division of application No. 08/613,856, Mar. 11, 1996, Pat. No. 5,842,110.

[51] **Int. Cl.<sup>6</sup>** ..... **B01J 8/00; B01J 19/12**

[52] **U.S. Cl.** ..... **423/215.5; 423/242.1; 423/532; 95/57; 96/16; 204/157.3; 204/157.49**

[58] **Field of Search** ..... **423/215.5, 242.1, 423/532; 95/57; 204/157.15, 157.3, 157.49; 96/16, 27**

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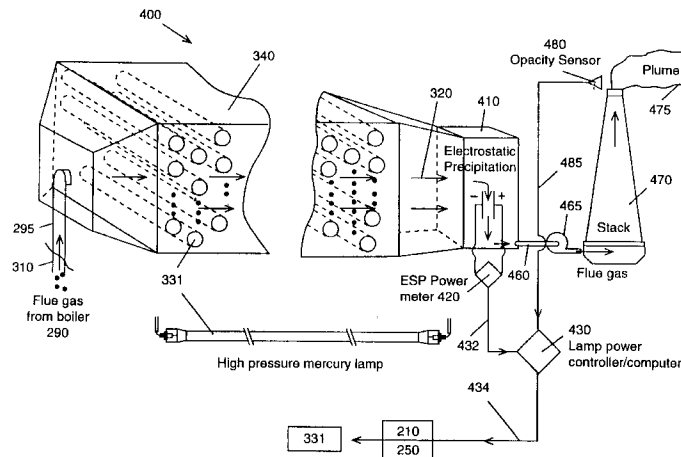
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*Assistant Examiner*—Timothy C Vanoy  
*Attorney, Agent, or Firm*—Brian S. Steinberger; Law Office of Brian S. Steinberger

### [57] ABSTRACT

A process is provided for conditioning fly-ash present in flue gas which also contains sulfur dioxide and steam by subjecting the fly-ash containing flue gas to ultraviolet radiation so as to convert steam present in the flue gas into hydroxyl radicals which oxidizes about 5 to 10 percent of the sulfur dioxide in the flue gas into sulfur trioxide. This photo-produced sulfur trioxide conditions the fly-ash and renders it more easily separated in the electrostatic precipitator.

**3 Claims, 9 Drawing Sheets**



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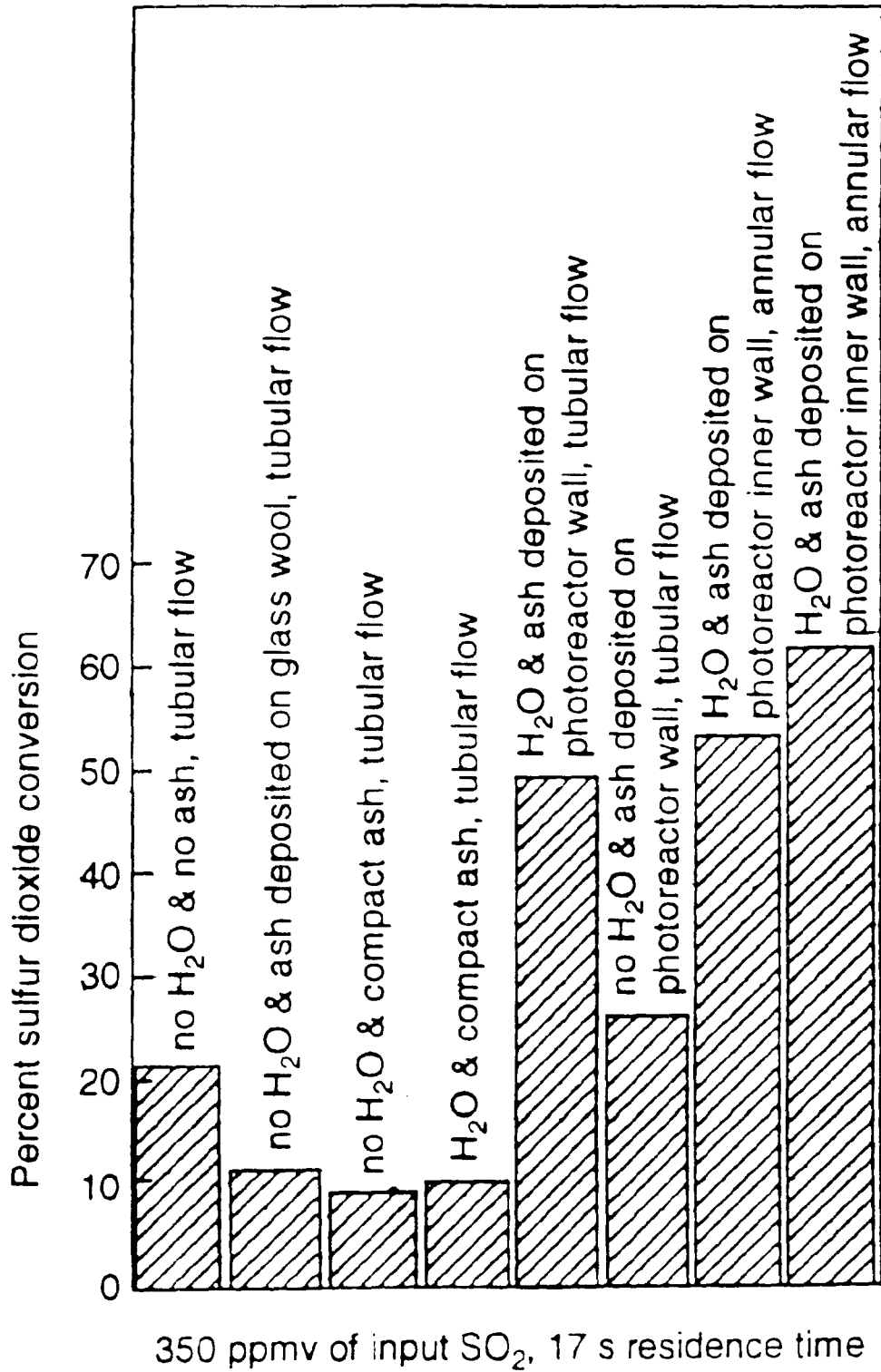


Fig. 1A

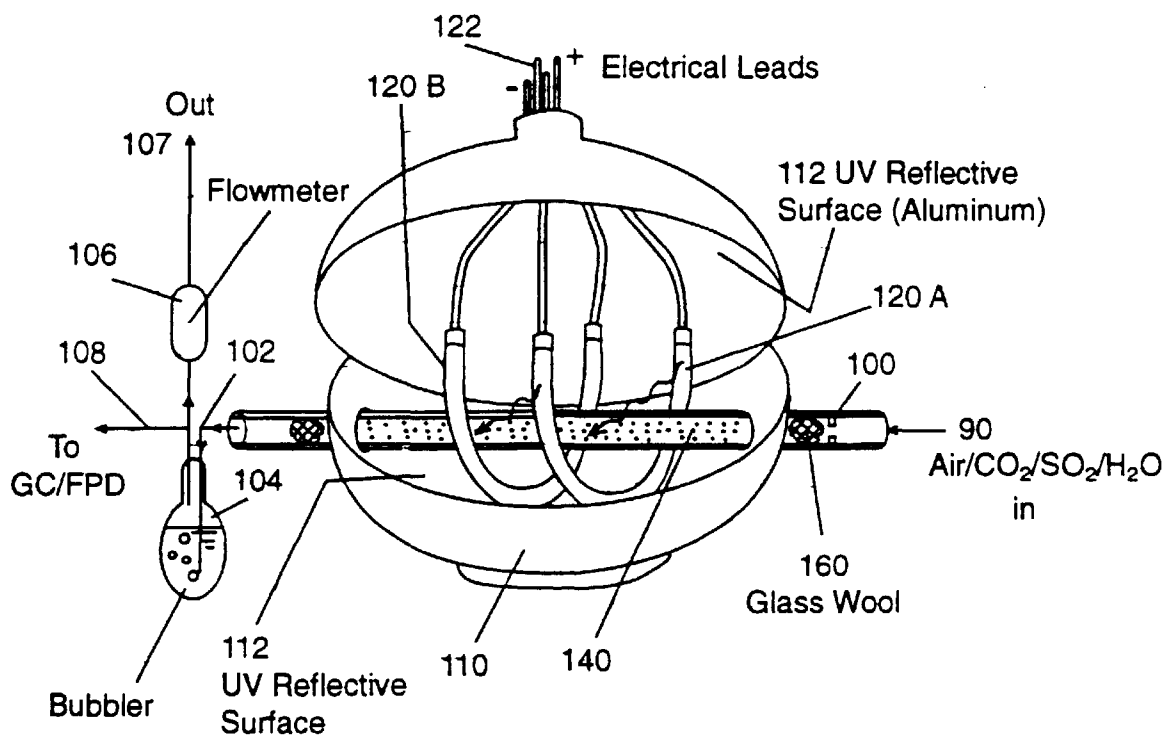


Fig. 1B

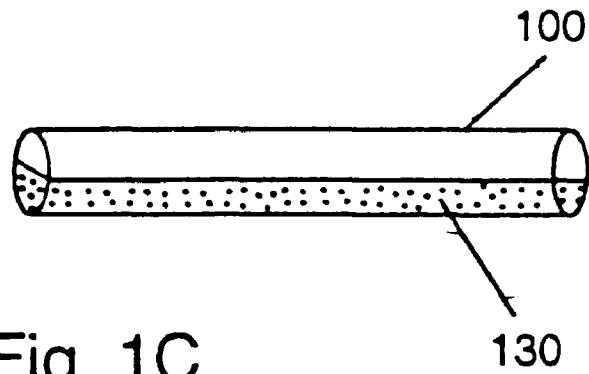


Fig. 1C

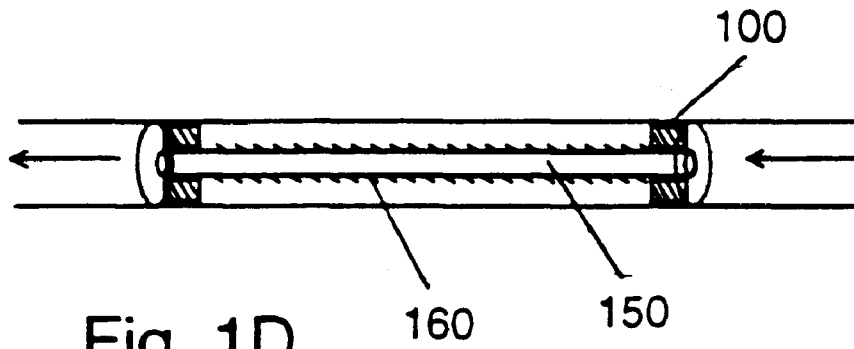


Fig. 1D

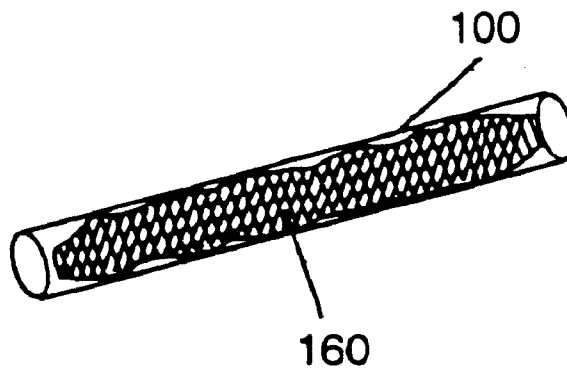


Fig. 1E

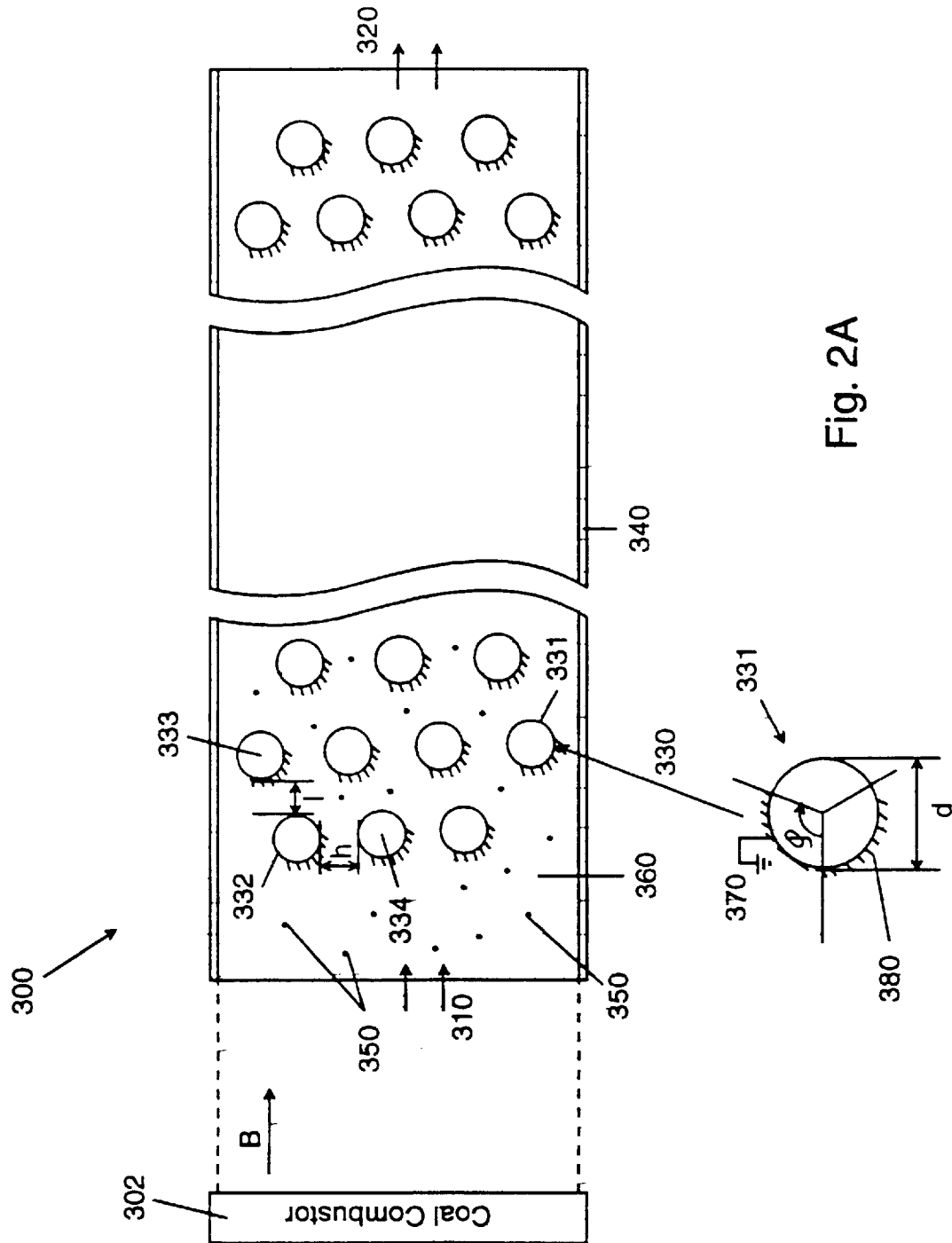


Fig. 2A

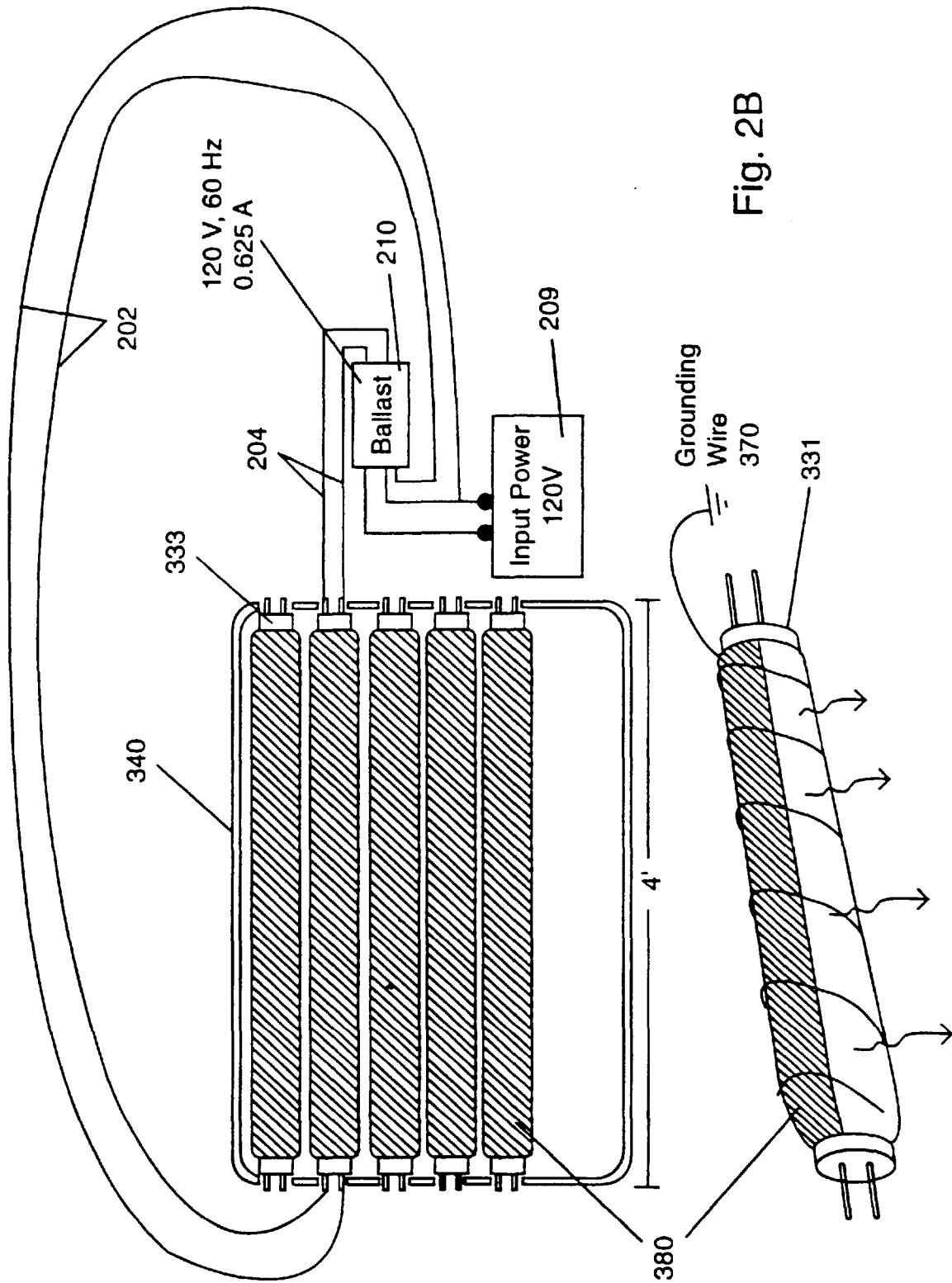
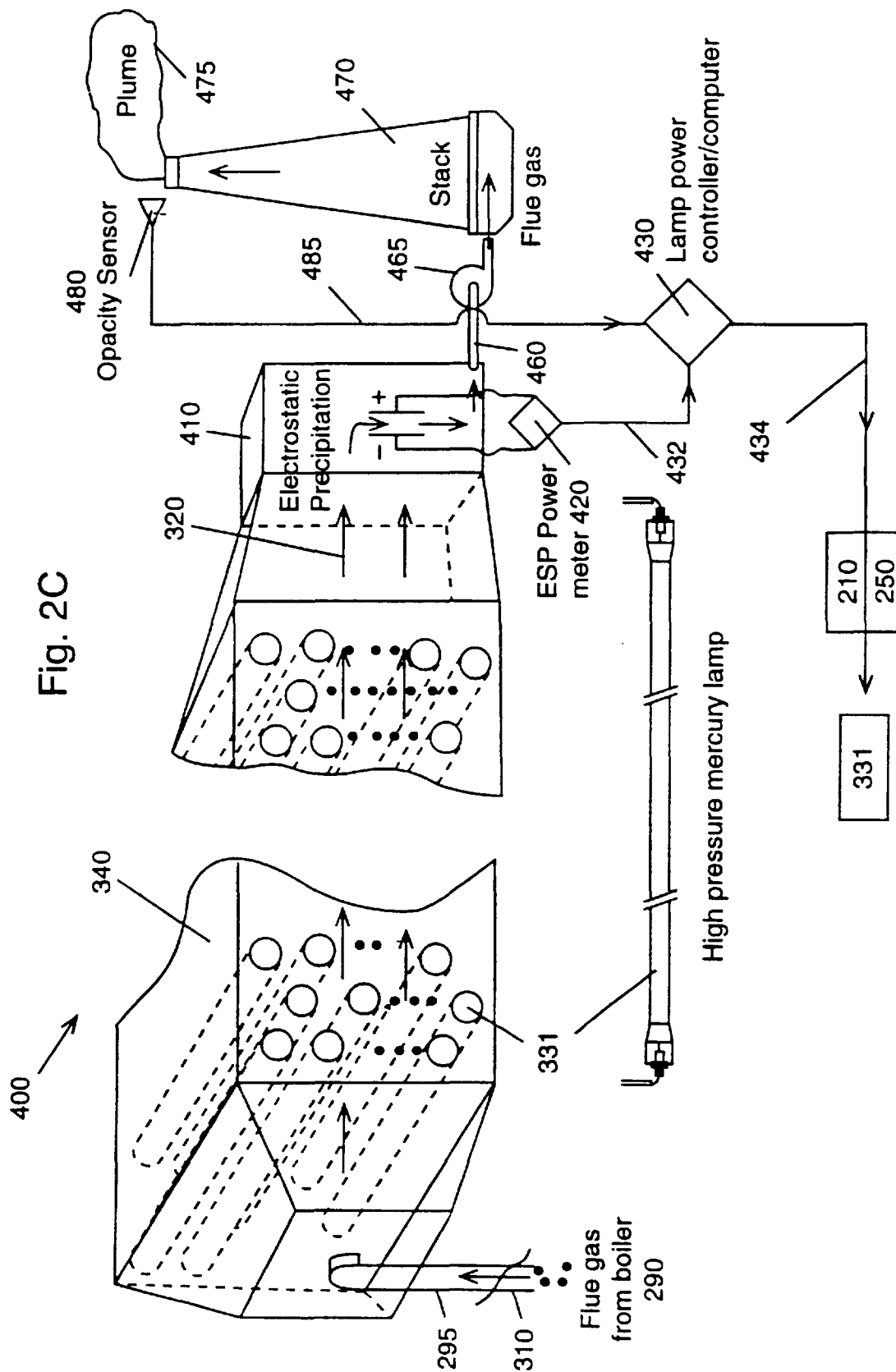


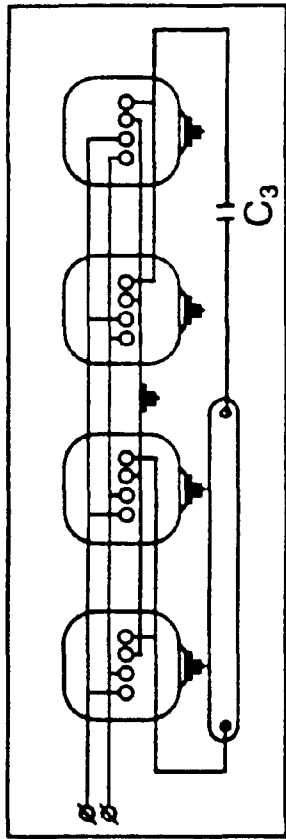
Fig. 2B





210 ↗

Fig. 2D



Wiring diagram  
constant wattage  
ballast

250 ↗

Wiring diagram  
for capacitor

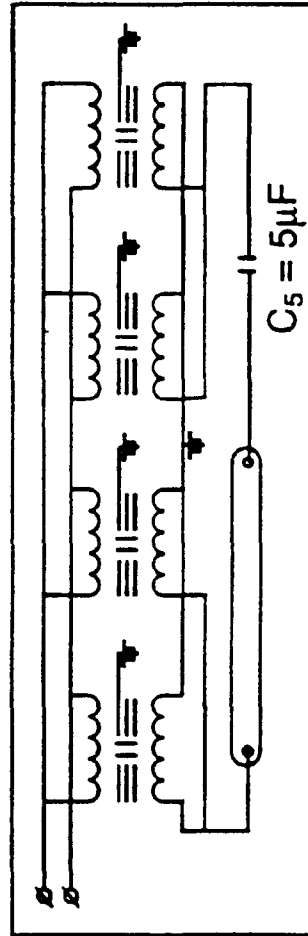


Fig. 2E

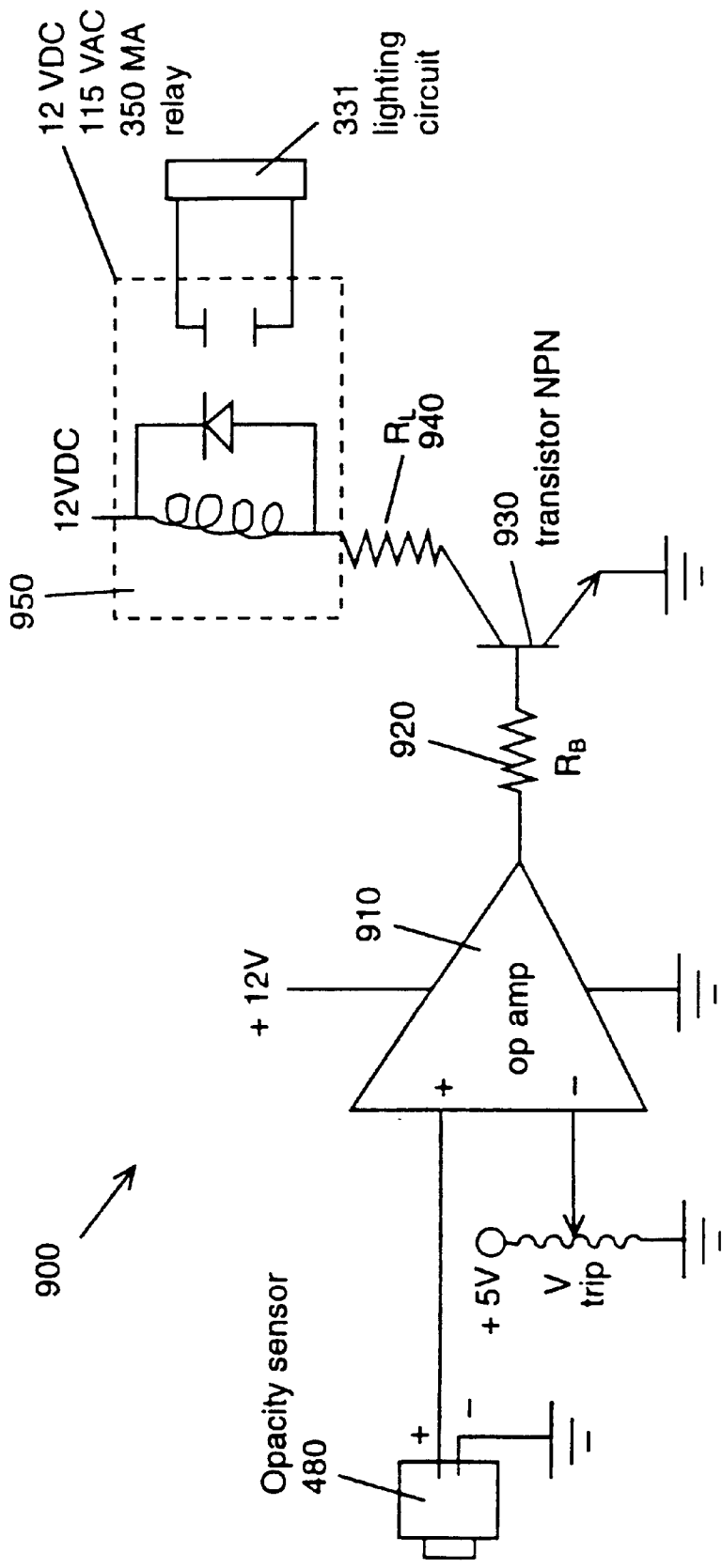


Fig. 2F

Circuit diagram for turning UV lamps on/off using an inexpensive operational amplifier and a relay

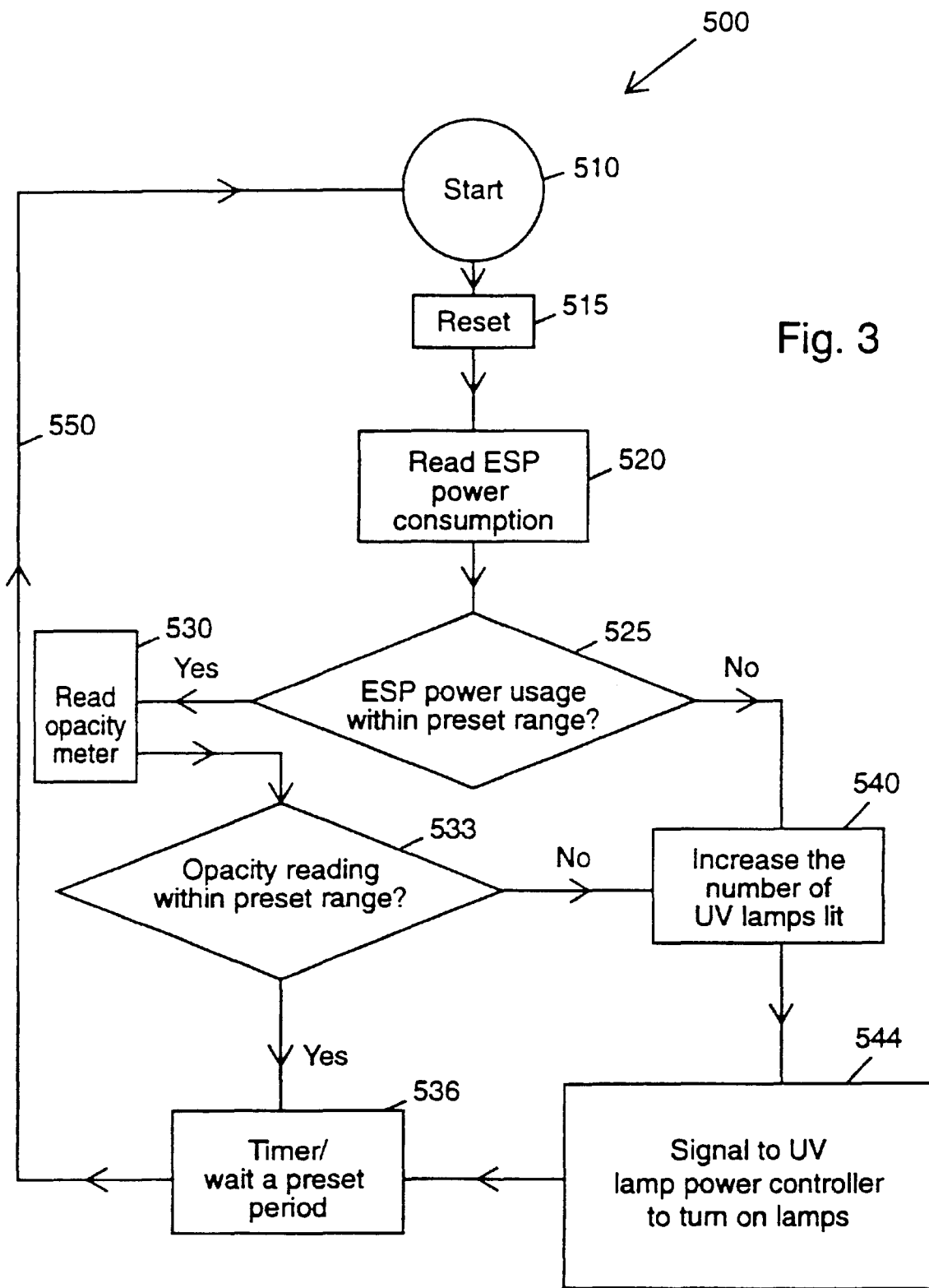


Fig. 3

Operational logic of the photo catalytic ash conditioning system

## APPARATUS AND METHOD FOR PHOTOCATALYTIC CONDITIONING OF FLUE GAS FLY-ASH PARTICLES

This is a Divisional of application Ser. No. 08/613,856  
filed Mar. 11, 1996 and now issued as U.S. Pat. No.  
5,842,110 Nov. 24, 1998.

This invention relates to conditioning of flue gas fly-ash,  
and in particular to conditioning flue gas emissions by  
treating the flue gas with SO<sub>3</sub>, where the SO<sub>3</sub> is created in  
the flue gas by photocatalytic conversion of SO<sub>2</sub> using  
selectively spaced and arranged ultra violet light (wave  
lengths of approximately 254 nm or shorter) emitting lamps  
and related automated components.

### BACKGROUND AND PRIOR ART

Coal-fired power plants have long been known to cause  
acid rain and atmospheric pollution. It has been well known  
that to reduce these undesirable forms of pollution, the  
power plants have been forced to reduce ambient sulfur  
dioxide emissions. This reduction of emissions has been  
accomplished by either switching to low-sulfur coal or using  
various flue gas desulfurization(FGD) processes to reduce  
emissions from high-sulfur coals.

Most power plants utilizing high-sulfur coal(i.e. 3% by  
weight sulfur) employ either throw-away or regenerative  
processes. Throw-away processes involve various limestone  
injection or scrubbing techniques(dry or wet). They produce  
gypsum as a by-product which must be disposed of properly.  
Regenerative processes use sodium hydroxide scrubbing  
which is regenerated, resulting in sulfur dioxide which may  
be sold as such or converted to sulfuric acid. These processes  
are all expensive to build and operate. Thus, utilities often  
switch from high to low-sulfur coal(containing less than 1%  
by weight sulfur) in order to reduce sulfur dioxide emis-  
sions. However, using low sulfur coal confronts power plant  
operators with additional problems. When low-sulfur coal is  
burned, the fly-ash produced is too resistive. Thus, electro-  
static precipitators(ESPs) that are designed to operate with  
fly-ash originating from high-sulfur coal burners do not  
work. In the new plants, the use of ESPs designed for the  
low-sulfur coal fly-ash would be very large in size and  
uneconomical.

Other solutions to these problems involve sulfur trioxide  
injection into the flue gas after the boiler and before the  
electrostatic precipitator. Ammonia injection or a combina-  
tion of ammonia and sulfur trioxide have also been used.  
This process has been referred to as fly-ash conditioning or  
flue gas conditioning. Most fly-ash is composed of silica and  
alumina mixed with other metal oxides. Any polar com-  
pound which is sufficiently reactive and able to change the  
surface properties will render the ash less electrically resis-  
tive. While sulfur trioxide injection can condition the flue  
gas and decrease fly-ash resistivity to a level comparable to  
that obtained when high sulfur coal is used, the process is  
expensive. Either liquid sulfur dioxide or elemental sulfur is  
required. A catalytic reactor is needed to convert the sulfur  
dioxide to sulfur trioxide. The catalyst(V<sub>2</sub>O<sub>5</sub>) life is limited,  
so that it must be periodically replenished. Ultra-high purity  
sulfur and filtered air must be used for a trouble-free  
operation. Sulfur must be kept molten, therefore, steam-  
jacketed piping is required. Systems in which sulfur oxides  
and water are present inevitably invite corrosion and require  
constant attention and maintenance. In-line spare pumps and  
air blowers are also necessary. These components result in  
expensive plant installation to generate sulfur trioxide as  
needed.

Several U.S. patents have been concerned with the ultra-  
violet treatment of flue-gases. For example, the photolytic  
oxidation of sulfur dioxide to sulfur trioxide, aided by UV  
radiation is demonstrated in U.S. Pat. No. 3,984,296 to  
Richards; 4,097,349 to Zenty; and 5,138,175 to Kim et al.  
The patents above teach flue gas treatment by a well-known  
photochemical process involving UV radiation to generate  
highly oxidizing species that attack target molecules in the  
flue gas. They may differ on the postulated reaction  
mechanisms, but they all claim to be processes that remove  
or help remove gaseous pollutants from the flue gases.  
However, none of the patents discussed above describe  
methods based on hydroxyl radical reaction engineering and  
photo-system design. None of these prior art references  
describe the importance of using water or water vapor  
solutions in a treatment process and most importantly and  
fundamentally, they do not claim interactions with fly ash.

U.S. Pat. No. 4,097,349 to Zenty describes oxidation of  
NO<sub>x</sub>, SO<sub>2</sub>, and hydrocarbons with UV radiation having a  
wavelength of from 240 nanometers to 340 nanometers.  
Equation 17 of the Zenty U.S. Pat. No. 4,097,349 depicts the  
absorption of 290–340 nanometers UV radiation to generate  
a singlet <sup>1</sup>SO<sub>2</sub>. Equation 18 of the Zenty patent describes the  
absorption of 340–400 nanometer UV radiation by SO<sub>2</sub> to  
produce triplet <sup>3</sup>SO<sub>2</sub>. According to Zenty, through a series of  
steps, the singlet excited <sup>1</sup>SO<sub>2</sub> can be transformed to the  
triplet state, <sup>3</sup>SO<sub>2</sub>. The excited triplet state can be chemically  
quenched with another species present in the gas stream  
such as nitrogen, oxygen, water, carbon dioxide, carbon  
monoxide, ozone, methane, and other hydrocarbons. Zenty's  
patent is essentially based on the aforementioned photo-  
processes and their consequences in photo-oxidation of NO<sub>x</sub>  
and SO<sub>2</sub>. The Zenty patent does not describe any specific  
mechanisms such as: free radical chain reactions, in general,  
and hydroxyl radical formation, in particular. For example,  
Zenty discusses the importance of hydroxyl radical (OH.)  
reactions (column 2, lines 65–68). In the presence of  
moisture, hydroxyl radical reactions dominate SO<sub>2</sub>  
conversion, as shown in equations 13–16 of the Zenty  
patent. Fundamentally, the Zenty process does not deal with  
fly ash conditioning.

U.S. Pat. No. 3,984,296 to Richards describes a process  
for the reduction of sulfur and nitrogen oxide contaminants  
in effluent gas streams. Richards' patent teaches the forma-  
tion of electron donor-acceptor molecular complexes (EDA  
complexes) in the flue-gas by exposure to lewis acids or  
bases generated electrostatically within a corona precipita-  
tor. Also, Richards describes a photochemical technique for  
the production of the EDA complexes using infrared radia-  
tion of 400 to 1,000 nanometers or UV radiation of 120–240  
nanometer wavelengths.

Furthermore, Richards describes a technique for photo-  
induced oxidation of the EDA complexes and reaction of  
SO<sub>2</sub> and NO<sub>x</sub> molecules with EDA constituent of stack gas.  
Richards describes using UV light having a wavelength of  
150–500 nanometers between 300–400 nanometers to pro-  
mote photo-oxidation of EDA complex. Richards suggests  
that free radical reactions may occur due to UV exposure  
(column 8, lines 12–15). A careful examination of the  
Richards patent reveals that (Table of column 9, lines 1–21)  
the underlying reaction mechanisms required for practicing  
his patent are similarly limited to those disclosed by Zenty  
as reactions 17–19 of U.S. Pat. No. 4,097,349. Again,  
Richards does not deal with fly-ash.

U.S. Pat. No. 5,138,175 to Kim, et al. describes irradiation  
of gas mixtures such as combustion gases and flue-gases to  
facilitate removal of sulfur and nitrogen oxide contaminants.

Kim et al. demonstrates SO<sub>2</sub> can be efficiently removed from flue-gases given sufficient exposure to UV light and presence of adequate amounts of oxygen and water. As far as the photo chemistry is concerned, this patent describes a method for the reduction of sulfur and nitrogen oxides in a gas mixture through UV radiation induced generation of ground state (zero charge atomic) oxygen and subsequent attack of such ground state O<sub>2</sub> upon SO<sub>2</sub> and NO<sub>x</sub>. Kim et al., further discloses that a source of radiation having a wavelength of, most desirably, below 220 nanometers installed within a dust-occluding air pressure window device located within the flue-gas stream. What is claimed by Kim, et al., is essentially a sheath design useful for in-situ treatment of flue-gas SO<sub>2</sub> and NO<sub>2</sub>. The device supposedly extends the operating life of the lamp and to protect the surfaces of the lamp from fouling.

The patents above teach flue gas treatment by a known photochemical process involving UV radiation to generate highly oxidizing species that attack target molecules in the flue gas. They may differ on the postulated reaction mechanisms, but they all claim to be processes that remove or help remove gaseous pollutants from the flue gases. More importantly, none of the patents discussed above methods and apparatus based on hydroxyl radical reaction engineering and photo-system design.

Several U.S. patents involve in-situ flue-gas fly-ash conditioning and involve techniques for sulfur trioxide injection. U.S. Pat. Nos.: 3,993,429 to Archer; 4,333,746 to Southam; 5,320,052 to Spokoyne et al.; 5,350,441 and 5,196,038 to Wright; 5,229,077 to Bell et al. and U.S. Pat. Nos. 4,966,610 and 5,122,162 to Krigmont et al. (1992) involve various applications to control the addition of a reagent based on measurements of the feedstream and rely on sulfur trioxide injection components along with using Electrostatic Precipitators (ESP) components. However, none of these patents provides for the in-situ transformation of chemical species present in flue gas to form sulfur trioxide for conditioning fly ash.

### SUMMARY OF THE INVENTION

The first objective of the present invention is to provide a technique for the in-situ transformation of chemical species already present in flue gas to form small amounts of sulfur trioxide (less than approximately 10% conversion) for conditioning fly ash.

The second object of this invention is to provide a technique that forms sulfur trioxide for conditioning fly ash in coal flue gas without artificially injecting sulfur trioxide into the flue gas.

The third object of this invention is to provide a method of altering the surface electrical properties of fly ash particles in order to condition the fly ash without the injection of chemicals.

The fourth object of this invention is to provide selectively spaced and positioned ultraviolet lamps to maximize generation of the vapor-phase free radical oxidizing species and minimizing mass transfer effects and optimum conditioning of fly-ash particles without the injection of chemicals.

The fifth object of this invention is to condition flue gas containing fly-ash in-situ prior to the treating the flue gas in an electrostatic precipitator. A preferred method of in-situ conditioning fly-ash particles produced by a coal burning power plant includes depositing water vapor and other polar compounds on surface of the fly-ash particles in-situ, wherein the deposition alters electrical resistivity of the

particles while photocatalytically converting a small percentage of SO<sub>2</sub> in the flue gas to SO<sub>3</sub> by subjecting the flue gas to mercury vapor UV lamps. The SO<sub>2</sub> conversion is in the range of 2% to 15%, and preferably in the range of 5% to 10%. The UV lamps can be connected in parallel. Each UV lamp can have a diameter of approximately, d, a vertical spacing between adjacent UV lamps of approximately d to 2d, and a horizontal spacing between the adjacent UV lamps of approximately d to 3d, where d can be approximately 1/2 inch to 2 inches. Each UV lamp can further include an angle,  $\phi$ , of approximately 80 degrees. A large scale preferred embodiment allows for conditioning the flue gas prior to feeding the conditioned flue gas into an electrostatic precipitator (ESP), and then to a stack for expelling the ESP treated flue gas. The large scale embodiment further can include a feedback loop for controlling the turning on and turning off of selected UV lamps. The feedback loop includes a power meter for measuring the power output of the ESP, an opacity sensor for measuring the particulate content in the final atmosphere expelled flue gas, and a computer for controlling each of the UV lamps based on these measurements. The computer can further operate a rheostat for controlling the brightness of each of the UV lamps.

The subject invention does not rely on injection of sulfur trioxide. The subject inventors have disclosed an in-situ transformation of chemical species present in the flue gas to form sulfur trioxide and condition the fly-ash particles by altering their surface electrical properties. More specifically, the subject invention is concerned with fly ash conditioning using plural lamps located at specific positions in a specific arrangements and the chemical conversion that would take place.

Further objects and advantages of this invention will be apparent from the following detailed description of a presently preferred embodiment which is illustrated schematically in the accompanying drawings.

### BRIEF DESCRIPTION OF THE FIGURES

FIG. 1A is a graph representing the photolytic conditioning of fly-ash and the effect of moisture using a 16 W UV lamp.

FIG. 1B illustrates the laboratory set-up for demonstrating the effect represented in FIG. 1A of the photolytic conditioning of fly-ash and moisture using a 16 UV lamp.

FIG. 1C depicts a photoreactor containing a layer of compacted ash.

FIG. 1D depicts a thin layer of ash deposited on the outer surface of an inner glass rod with a quartz tube.

FIG. 1E depicts glass wool containing dispersed TiO<sub>2</sub> particles within a quartz reaction tube.

FIG. 2A depicts a cross-sectional view of a preferred light source assembly for in-situ flue-gas fly-ash conditioning.

FIG. 2B depicts a side view of the preferred light source assembly of FIG. 2A along arrow B.

FIG. 2C is a perspective view of the minimal components and circuitry to run high-pressure mercury vapor lamps suitable for large-scale fly-ash conditioning applications with a novel feedback operation.

FIG. 2D shows a conventional wiring diagram for constant wattage ballast used in FIGS. 2A-2C.

FIG. 2E shows a conventional wiring diagram for a capacitor used in FIGS. 2A-2C.

FIG. 2F illustrates a circuit for turning the UV lamps of FIG. 2C on and off.

FIG. 3 is a flow chart depicting the operational logic steps of the preferred embodiment of FIG. 2C.

#### DESCRIPTION OF THE PREFERRED EMBODIMENT

Before explaining the disclosed embodiment of the present invention in detail it is to be understood that the invention is not limited in its application to the details of the particular arrangement shown since the invention is capable of other embodiments. Also, the terminology used herein is for the purpose of description and not of limitation.

The subject invention is directed to condition the fly-ash particles via hydroxyl radical reactions. Fly-ash consists of fine solids entrained in the flue-gas. What is meant by conditioning is changing the surface properties of the fly-ash particles by deposition and nucleation of strongly polar compounds on the surface in sufficient amounts to alter the electrical resistivity of the particle. This invention does not aim at removing and/or scrubbing gaseous pollutants such as NO<sub>2</sub> or SO<sub>2</sub> from flue gases, although a small amount of pollutants will also be removed.

The subject invention takes advantage of the photolytic reaction chemistry and, more importantly, the large effect of moisture (water vapor) present in the flue gas on the hydroxyl radical photo-reactions of importance to ash conditioning. It has been found by the inventors that destruction by photolysis is an order of magnitude slower than by OH radical attack. Table 1 depicts, the relative oxidizing power of hydroxyl radical is highest among all trans-halogen oxidants, surpassed only by fluorine.

TABLE 1

Relative oxidation power of oxidizing species.		
Species	Oxidation potential (volts)	Relative oxidation power (based on Cl = 1)
F	3.06	2.25
OH•	2.80	2.05
atomic oxygen	2.42	1.78
O <sub>3</sub>	2.07	1.52
H <sub>2</sub> O <sub>2</sub>	1.77	1.30
HO <sub>2</sub> •	1.70	1.25
permanganate	1.70	1.25
hypochlorous acid	1.49	1.10
Cl	1.36	1.00

The subject invention focuses on the means to increase hydroxyl radical concentration by improved photo-system design and optimization. The OH radical concentration distribution directly tied to the light intensity profile (irradiance distribution) of the UV lamps. Moreover, the presence of water vapor is thought to be primarily responsible for the observed high SO<sub>2</sub> conversion efficiencies by increasing the OH radical concentration of the flue-gas stream

An important aspect of this invention is that fly-ash present in the flue gas provides catalytic surface. Small amounts of semiconductor metal oxide surfaces present in fly-ash (e.g. ferric oxide) act in a manner similar to titania, enhancing the conversion efficiency of the UV reactions, resulting in a fast and economical process.

At the Florida Solar Energy Center (FSEC), the inventors have verified, through laboratory-scale tests, the fact that the conversion of sulfur dioxide to sulfur trioxide occurs by UV irradiation. Bench-scale tests, conducted at FSEC, used a sample of fly-ash from the Crystal River power plant near St. Petersburg, Fla. FIG. 1A depicts results from the laboratory

experiments conducted at FSEC. FIG. 1A is a graph representing the photolytic conditioning of fly-ash and the effect of moisture using a 16 W UV lamp. A description is given below.

FIG. 1B illustrates the laboratory set-up for demonstrating the effect of moisture using a 16 W UV (ultra violet) lamp. A quartz tube photoreactor **100** having a 12 mm OD (outer diameter), 10 mm ID (inner diameter) and 220 mm length was placed within an enclosed UV light chamber **110** which was connected to a bubbler **104** and flowed to an external ambient location **107** through a flowmeter **106** and to a Gas Chromatograph with flame photometric detector (GC/FPD) **108**. Inner surfaces **112** of chamber **110** had UV reflective surfaces such as but not limited to aluminum and the like. UV illumination was provided by one of two 16 W low-pressure mercury lamps (**120A**, **120B**) located within the light chamber **110** connected by leads **122** to an external electrical power supply **124**. To simulate the condition of fly-ash in the flue gas, several arrangements of the quartz tube photoreactor **100** were employed. Air, carbon dioxide (CO<sub>2</sub>), sulfur dioxide (SO<sub>2</sub>) and water (H<sub>2</sub>O) are introduced into the quartz tube photoreactor at position **90** for these arrangements.

In the first arrangement, a layer of compacted ash **130** shown in FIG. 1C filled lower half of the photoreactor **100** was used, and the results are depicted by the "compact ash" notation in FIG. 1A. The "compact ash" arrangement had approximately a ten percent (10%) sulfur dioxide conversion.

The second arrangement includes the set-up of FIG. 1B where a very thin layer of ash **140** was deposited on the inner wall of the quartz tube **100**, thus the "wall ash" notation of FIG. 1A. In this arrangement, incoming radiation is filtered by the wall ash limiting gas-particle-photon interactions. In an actual case, UV lamps can be placed within exhaust gas ductwork, directly illuminating the gas and entrained particles.

The third configuration of the tube **100** is shown in FIG. 1D. Here, an annular reactor configuration the inner Pyrex glass rod **150** has an OD of 6 mm with rod **150** placed coaxially within outer quartz tube **100**. A thin layer of ash was deposited on the outer surface of the inner glass rod **150**. FIG. 1E shows TiO<sub>2</sub> particles dispersed throughout a piece of glass wool **160** placed within the quartz reaction tube **100**. Using glass wool **160** did not prove very useful as extensive UV filtering by the glass wool did occur.

The results of the laboratory tests in FIG. 1A indicated that sulfur dioxide conversions occurred well above 60% (at a residence time of 17 s). From such rate information, it should be possible to achieve 7–10% SO<sub>2</sub> conversion with residence time of only a second or so.

Presence of fly-ash can also enhance SO<sub>2</sub> conversion and most importantly, the presence of moisture results in much higher conversions. This demonstrates that the reaction mechanism involves hydroxyl radical formation which renders the photocatalytic oxidation much more efficient compared with the externally generated sulfur trioxide as practiced in the present state-of-the-art ash-conditioning systems.

It is clear from the description above and the background information presented that the sulfur trioxide produced is immediately adsorbed by or reacted with the fly-ash and not emitted from the stack.

Although the hydroxyl radical formation and concentration within the photo-system is not affected by the gas stream advection, the flow (velocity) field does affect the

extent of particulate contamination and adhesion on the lamp surface. Further, when chemical reaction rates are in the same order of magnitude as the gas stream advection/residence times, the species concentration are affected by the velocity field and the extent of turbulence and recirculation in the photo-system. For flow passing a cylinder (depicting UV lamp cross section), streamlines separate or break away from the rear forming a pulsating wake behind the cylinder.

The character of this wake is dependent on the numerical value of the dimensionless speed called the Reynolds number  $Re$  of the flow. For large Reynolds numbers, the wake becomes very disorderly. The alternating vortices shed into the wake are called von Karman vortex streets. At higher Reynolds numbers, the vortex pattern disappears, and the wake become turbulent.

By proper arrangement of the lamps, i.e. their number and relative distance to each other, an optimum photo-system having the most uniform light intensity distribution and highest  $SO_2$  conversion is obtained.

FIG. 2A depicts a cross-sectional view **300** of a preferred light source assembly for in-situ flue-gas fly-ash conditioning. FIG. 2B depicts a side view of the preferred light source assembly of FIG. 2A along arrow B. Referring to FIGS. 2A–2B, the embodiment **300** has fly-ash **350** with exhaust gases **360** entering an exhaust ductwork **340** from a coal combustor **302** in the direction of arrow B. In-situ conditioning of the fly-ash **350** with  $SO_2$  occurs by passing the fly-ash **350** in the ductwork along arrow **310** by Ultra-Violet (UV) light. Individual lamps **331** have lead wires **202**, **204** connected to ballast **210** such as but not limited to 120 V, 60 Hz, 0.625 A such as the one shown in FIG. 2D and connected to main power supply **209** (i.e., 120 volt). The UV light comes from the low pressure mercury vapor lamps **330** which are positioned horizontally against the incoming gases **360** and **350**. Any number of commercially available low-pressure or medium/high-pressure mercury vapor lamps having approximately one to five foot length, such as but not limited to Voltarc's G36T6Ultra V Base and GE 40BL lamps or others such as Model #Philips HOK 140/120, HTQ14 or Hanovia 6850A431 lamps. A single UV lamp **331** contains an external reflective coating **380** that can include an aluminum surface having a diameter,  $d$ . The lamp **331** has a grounded shield at **370** which is the same as coating **380**. Angle  $\phi$  is approximately 80 degrees. This angle designates the angular positions on the cylindrical surface in a cross flow at which flow separation occurs.

The lamps are separated from one another by a vertical height,  $h$ , represented between lamps **332** and **334** of FIG. 2A. The height,  $h$ , has a value of approximately  $d$  to  $2d$ . The lamps can further be separated by a length,  $l$ , represented between lamps **332** and **333**. Length,  $l$ , can have a value of between approximately  $d$  and  $3d$ . Arrow **320** represents the direction of conditioned flue gas having passed through embodiment **300**. The unit  $d$ , can range from approximately  $\frac{5}{8}$  inches to approximately 2 inches. The total number of lamps used is a function of the flue gas flow rate, the concentration of the  $SO_2$  and the particulate matter and ash particles within the ductwork.

From the laboratory measurements, the inventors have discovered that residence times of few seconds are needed to achieve approximately 7 to approximately 15% conversion of  $SO_2$  to  $SO_3$  for fly-ash conditioning, using a 16 W low-pressure mercury lamp. For a typical power plant of 500 MW capacity, the gas flow rate is roughly 4,890,000  $m^3/hr$  (cubic meters per hour) or 1358  $m^3/s$  (cubic meters per second). Assuming a residence time of 1 s, requires 1360  $m^3$

of reaction volume for full conditioning of the flue gas. This corresponds to duct work dimensions of approximately 25' by 25+ by 75' volume. The total number of UV lights required depends on the lamp type and quantum efficiency of  $SO_3$  formation. Thus, if 25 ppmv of  $SO_3$  is needed, approximately 1.3875 mol/s of sulfur trioxide conversion will be needed. For large-scale applications, the use of high-pressure mercury vapor lamps will be more advantageous. With electrical to photon efficiency of about 35% and quantum efficiency of  $SO_3$  formation of 30%, roughly 10% of a lamp's power input will be useful. Assuming an average photon energy of about 500 kJ, approximately 6.61 MW of power will be required to reform 1.3875 mol/s of  $SO_3$  in the flue gas in order to accomplish ash conditioning. This corresponds to about 1.32% of the plant output power generated.

FIG. 2C is a perspective view of a preferred embodiment **400** to run high-pressure mercury vapor lamps **331** suitable for large-scale fly-ash conditioning applications using the components of FIGS. 2A–2B in a novel feedback operation. Flue gas **310** containing fly-ash and exhaust gasses (such as **350**, **360** discussed previously) from a boiler **290** enters via pipe **295** into ash conditioning photo-duct **340** (also described previously in relation to FIGS. 2A–2B). Duct **340** contains UV lamps **331** with a total output power capable of producing  $SO_3$  levels needed for proper ash conditioning. FIG. 2D shows a conventional wiring diagram for constant wattage ballast used in FIGS. 2A–2C. FIG. 2E shows a conventional wiring diagram for a capacitor used in FIGS. 2A–2C. FIGS. 2D and 2E represent schematics of a commercially available high-pressure mercury vapor lamp circuitry for the Philips model HTQ-14, 4 kW lamp, of which the circuitry is nonessential subject matter which is incorporated by reference. Other appropriate UV lamps include Philips model HOK series with output power exceeding 17 kW.

Referring again to FIGS. 2C–2E, conditioned flue gas **320** passes to a conventional electrostatic precipitator (ESP) **410** (such as the ones described in the background section above). A ESP power meter **420** picks up power signals in kW (kilowatts) from ESP **410** to lamp power controller/computer **430**. The opacity sensor **480** is a light beam device that detects the amount of transmitted light being blocked by an exhaust plume **475**. The opacity sensor **480** can be an off-the-shelf component such as but not limited to a Datatest single or double pass opacity sensors model #1000 MPS, 1000 MPD or 900 RMD. Conditioned gas from ESP **410** passes through lines **460**, **465** into an emitting stack **470** and finally dispensed into the atmosphere as a plume **475**. Opacity sensor **480** measures and passes signals to the lamp power controller/computer **430**. Output signals **432**, **485** from the electrostatic precipitator electrodes power sensor **420** and an opacity sensor **480** installed on stack **470** are processed by a computer controller **430** that regulates total output photonic power within the photo-duct as a feedback to meet the requirements of ash conditioning as the process conditions change. The computer **430** used for controlling the UV lamps can be an IEEE 488 Board and an IBM compatible 586, with a National Instrument Systems data acquisition and control board. The controlling can be done by turning on or off the appropriate number of UV lamps **331** which are used to accomplish ash conditioning in the duct work **340**. FIG. 2F illustrates an optional circuit **900** for turning on and off UV lamps **331** which includes opacity sensor **480** connected to an OP-AMP voltage divider **910**, through resistor **920** (approximately 500–1000 ohms, preferably 720 ohms), to a semiconductor switch **930** such as an



NPN transistor and resistor **940**(approximately 10–100 ohms, preferably 55 ohms) through a 12VDC, 115VAC, 350 mA relay **950** to control the turning on and off of lamps **331**. All lamps **331** are connected in parallel and each require a capacitor **210** FIG. 2D and a constant wattage ballast **250** 5 shown in FIG. 2E. Ballast **250** and capacitor **210** can be an off-the-shelf Philips 4XVG3/HTQ Ballast with 5  $\mu$ g farad capacitor, and are nonessential subject matter which are incorporated by reference. The lamp power controller/computer **430** can be further utilized to control rheostat type 10 switches for adjusting the brightness and effective fly-ash conditioning effects of the individual UV lamps **331** in the system **400**. Optionally the invention can substitute medium/high pressure mercury vapor lamps, such as Model #Philips HOK140/120, HTQ14 or Hanovia 6850A431 lamps have a built-in rheostat type power modulator for varying and 15 controlling the intensity of each of the lamps, instead of the mercury vapor lamps **331** previously discussed.

FIG. 3 shows a flow chart depicting the operational feedback logic steps of the preferred embodiment of FIG. 2C. The system is started **510** and reset **515** on each pass. From the reset **515**, the computer **430** of FIG. 2C reads the ESP power consumption **520** to determine if ESP power usage is within preselected ranges **525**. If the answer is no the next step is to increase the number of UV lamps that are lit, **540**, followed by signaling to UV lamp power controller **430** to turn on the lamps **331**, shown by step **544**. Next a timer **536** restarts the beginning of the flow chart measuring after a preselected time period **536**. If ESP power usage is determined at step **525** to be within a preset range, then step **520** occurs where the opacity meter is read. The next step is determining whether the opacity reading is within a preset range at step **533**. If the answer from step **533** is no the next step is **540**, if the answer is yes the system passes to step **536**, and so forth. 20

In all flue gas treatment methods the objective is a substantial reduction in the concentration of the flue gas contaminants, most desirably at 90% levels. Thus, for SO<sub>2</sub> treatment, a conversion efficiency of at least 90% would be most desirable. Unlike processes aimed at the treatment of the flue gas constituents, fly-ash conditioning only requires approximately a 5% to 10% SO<sub>2</sub> conversion. 5

While the invention has been described, disclosed, illustrated and shown in various terms of certain embodiments or modifications which it has presumed in practice, the scope of the invention is not intended to be, nor should it be deemed to be, limited thereby and such other modifications or embodiments as may be suggested by the teachings herein are particularly reserved especially as they fall within the breadth and scope of the claims here appended. 15

We claim:

**1.** A method of in-situ conditioning fly-ash particles produced by a coal burning power plant upstream to an electrostatic precipitator without injecting sulfur trioxide, comprising the steps of: 20

producing a flue gas containing fly-ash particles and SO<sub>2</sub>, the fly-ash particles having catalytic surfaces; photocatalytically converting approximately 5% to approximately 10% of the SO<sub>2</sub> to SO<sub>3</sub>; and 25 conditioning the fly-ash with the photocatalytically produced SO<sub>3</sub>.

**2.** The method of conditioning fly-ash particles of claim **1**, wherein the photocatalytic step includes supplying the ultraviolet radiation. 30

**3.** The method of conditioning fly-ash particles of claim **2** wherein the ultraviolet lamp further includes supplying the ultraviolet radiation with vertical and horizontal adjacent ultraviolet lamps.

\* \* \* \* \*

UNITED STATES PATENT AND TRADEMARK OFFICE  
**CERTIFICATE OF CORRECTION**

PATENT NO. : 5,935,538  
APPLICATION NO. : 09/128443  
DATED : August 10, 1999  
INVENTOR(S) : Ali Tabatabaie-Raissi et al.

Page 1 of 1

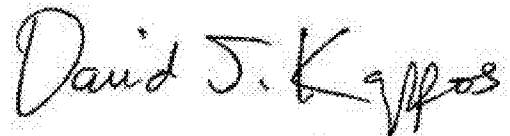
It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Col. 1, lines 13-14 should read,

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

This subject invention was made with government support under the DOD/Navy/NSWC, federal contract number N0017491C0161. The government has certain rights in this invention.

Signed and Sealed this  
Eighth Day of March, 2011

A handwritten signature in black ink that reads "David J. Kappos". The signature is written in a cursive style with a large initial "D" and "K".

David J. Kappos  
*Director of the United States Patent and Trademark Office*