USING OZONE INSTEAD OF CHLORINE IN A TYPICAL WATER TREATMENT PLANT IN EGYPT: A CASE STUDY

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ABSTRACT

Ozone is now used as an oxidant and disinfectant in water treatment plants worldwide. Ozone is extremely faster and more powerful than chlorine in removing organic and inorganic matter, bacteria, viruses, pesticides, turbidity, odour, taste and color from potable water production. Some of these substances exist as by-products of using chlorine such as trihalomethanes in the treatment process. In this paper, the use of ozone instead of chlorine in water treatment plants and associated processes has been discussed. The advantages of using ozone as an oxidant and disinfectant in the pre-oxidation process are detailed. The Mansoura city main water treatment plant (a typical Egyptian plant) has been taken as a case study. The concentration time value (CT) for both chlorine and ozone for cryptosporidium inactivation is represented graphically and in correlation form. Results have shown that the most suitable point of ozone injection is the same that of pre-chlorination and the suitable ozone doze is 3 mg/l. For a higher Log credit value of 4, the CT value will be 10.54 (mg/l) min; the required contact time is only 3.54 min which is very small compared to that of chlorine (27 min). However, the operating cost of ozone is 23.5 % larger than that chlorine. The operating ozone concentration and exposure time makes it safe in handling.

Keywords: Ozone, Chlorine, Water treatment plant, Egypt, Case study

INTRODUCTION

Surface water treatment includes coagulation, flocculation and solid sedimentation in the first stages. Coagulation and flocculation processes are necessary to remove solids that may include minerals, organic materials and bacteria. Heavier solids will settle out of the water by sedimentation, but suspended solids are removed through physical and chemical treatment. Chemicals are added to raw water to cause coagulation. The coagulants bind the solid particles and draw them together forming floc that settle out of water. Coagulants include metallic salts such as aluminum sulfate (Alum), poly aluminum chloride, ferrous sulfate and synthetic polymers. Removing these solids reduces the filtration load and prevents bacteria from surviving. Intake point must be correctly situated to limit the algae, organics and warm water near the surface, as well as the hydrogen sulfide, iron, and manganese that may exist in deeper water.

Following coagulation and flocculation, water flows into sedimentation basins that remove the solids and thus much of turbidity. Water treatment plants (WTPs) should have at least two sedimentation basins so that maintenance, cleaning and inspection can be conducted without shutting down the plant. The sedimentation process is controlled by observing changes in turbidity and monitoring sludge depth. A well functioning sedimentation basin will remove most solids and thus reduce loading on the filters.

Following sedimentation, water passes through filters. The filters are made of sand, coal, or other granular substances (media) that remove suspended solids and floc, which may include silt, clay, bacteria and plankton. In filters, the solids are removed through deposition on the filter media, adsorption, absorption and biological action. Solids adhere to the media as the water passes through it. In gravity filtration, water is passed through a media made up of a combination of sand, anthracite coal and mineral sands. The water level above the media pushes the water through the media. Activated carbon may be added to the media to remove odours, improve taste and adsorb organic compounds.

Backwashing cleans the filters by reversing the flow of water through them to remove trapped solids. Filters backwashing is performed before clogging and break-through can occur. The wash water, which contains solids, passes to dewatering and solids handling and may then be returned to the treatment process. The filtration process is controlled by monitoring pressure loss across the filter. Filter-aid chemicals such as polymers may be added to improve the filter's solids removal efficiency.

Chlorine is often used in Egypt as a drinking water disinfectant. Chlorine is a dangerous chemical, usually stored in cylinders as a concentrated liquid and is released directly into the water in measured amounts to provide disinfection. Pre-chlorination of source water prior to treatment is also useful in controlling algae growth, improving taste and odours. Post-chlorination is the addition of chlorine to the water after treatment. Drinking water should be sufficiently chlorinated to maintain a minimum concentration of 2 mg/l throughout the distribution system. However, chlorine may combine with organics to form trihalomethanes which are carcinogenic. For this reason, other disinfectants such as iodine, bromine, lime and ozone are attracting great interest. Destroying pathogens by using ultraviolet rays is also effective, although very expensive.

Ozone is now used in WTPs for the removal of source water contaminants and to improve water quality. With the increasing concern regarding chlorination by-products such as trihalomethanes and haloacetic acids, ozone is becoming widely adopted as an efficient pre-oxidant before coagulation instead of chlorine [1-3]. Pre-ozonation can eliminate taste, odour, color and several mineral compounds. It can also be utilized for natural organic matter (NOM) degradation and microorganism inactivation. Pre-ozonation has a marked effect on the subsequent treatment processes, particularly the coagulation, Li et al. [4]. There are many contradictory reports about the effects of pre-ozonation on the removal of NOM and particles via coagulation [5 and 6]. However, a pilot-scale investigation was conducted to examine the impact of pre-ozonation on coagulation for particle and NOM removal as reported by Yan et al. [7]. Ozone can simultaneously aggregate fine particles and break down large ones, making them more mineralized and easier to remove. NOM with intermediate molecular weight and hydrophobic neutral property increases at lower ozone dosage, favoring removal by coagulation. At higher ozone dosages, NOM becomes more hydrophilic and the molecular weight becomes smaller, decreasing its removal.

In Egypt, there is no information about using ozone as a disinfection agent in any of WTPs. This is may be due to the lack of data available for the decision makers. In this paper, the using of ozone in a typical Egyptian WTP as a pre-oxidant is studied. The advantages and disadvantages of using ozone instead of chlorine are highlighted. A discussion of the best point of ozone application and the most suitable ozone concentration is reported. The ozone handling and operating cost is also studied.

Typical WTP in Egypt

Figure 1 shows the flow diagram of a typical Egyptian WTP. In Egypt, chlorine is almost used as a pre-oxidant and Alum is also added in this stage as a coagulant agent where fast mixing is carried out. Flocculation is allowed to predicate out of water in a sedimentation process. Suspended solid matters are trapped in a series of sand filters. Post-chlorination is carried out by the addition of chlorine to the water after filtration at a concentration of 2.5 mg/l throughout the distribution system.

Chlorine stock is stored in site and is added to water in liquid form where a risk of handling may exist. Moreover, using chlorine in WTPs yields many harmful byproducts that are responsible of most known waterborne diseases. Therefore, thousands of WTPs all over the world start to use ozone instead of chlorine since it is 3125 times faster and 50-100% powerful than chlorine [8]. Although more expensive, its positive impact on the water treatment processes and human health and environment increases the ozone attraction.

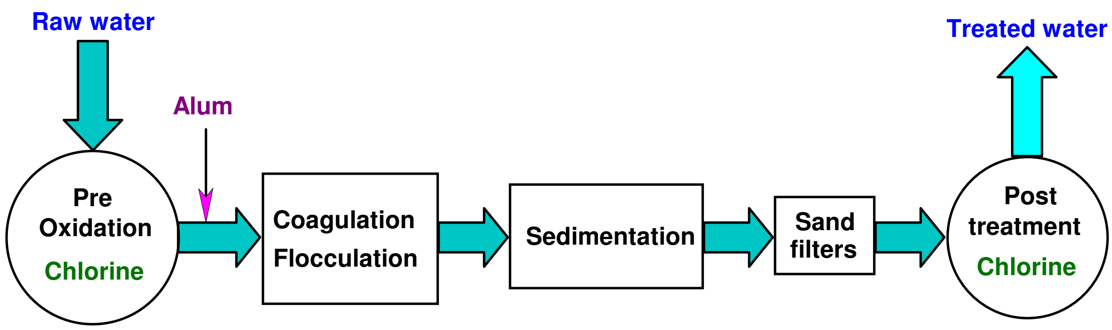

Fig. 1. The main processes of a typical WTP in Egypt

Ozone Generation

In practice, ozone can be generated by three methods; ultra violet radiation, corona discharge and cold plasma method. Ozone generation with corona discharge is the most suitable method (from the technical and economical point of view) in WTPs. It is not practical to store ozone as a liquid or gaseous form in site. Therefore, it can be generated in site from oxygen or air as shown in Fig. 2. It is recommended to use air as a feed gas since it is readily available everywhere with no cost. In this case, the air must be subjected to a pre-treatment procedure such as filtration, drying and compression before feeding to the generator. Air cooling may also be used. These processes help in increasing the efficiency and productivity of the ozone generator.

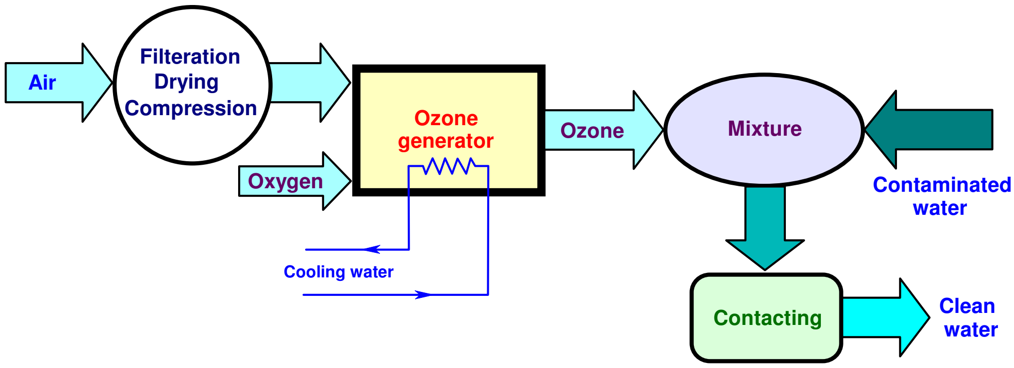

Fig. 2. Ozone generation system

The produced ozone (or ozone-air mixture) is bubbled in the water through a venture injector tube, turbine diffuser or a contactor tank with baffle. On the other hand, ozone generation is an exothermic process and it is power consuming. Therefore, the generated heat should be released. Usually cooling water is used as heat removal agent. A contact time of 4-8 minutes for ozone-water to insure disinfection action of ozone is recommended.

Practically the ozone dose at the pre-oxidation stage ranges from 2 to 5 ppm. Ozone can be injected with smaller dose at another point downstream the source water inlet, but this will need costly activated carbon (AC) filters after ozonation to remove little undesired byproducts as reported by Li et al. [4].

The CT value

Ozone disinfection power (like any other oxidant material) depends not only on its concentration in the treated water, but also on the contact time and water temperature. The concentration time (CT) value is an important measure for a certain amount of disinfection (Log credit). Tables (1) and (2) show the CT value, (mg/l) min for chlorine and ozone respectively at different temperatures for various values of Log credits for cryptosporidium inactivation as an example, US EPA [9]. The data in the tables are demonstrated graphically in Fig. 3.

Table (1) CT value for chlorine

Log Credit	Temperature, °C			
	5	**10**	**15**	**20**
0.25	107	69	45	29
0.5	214	138	89	58
1.0	429	277	179	116
1.5	643	415	268	174
2.0	858	553	357	232
2.5	1072	691	447	289
3.0	1286	830	536	347

Table (2) CT value for ozone

Log Credit	Temperature, °C			
	5	**10**	**15**	**20**
0.25	4.0	2.5	1.6	1.0
0.5	7.9	4.9	3.1	2.0
1.0	16	9.9	6.2	3.9
1.5	24	15	9.3	5.9
2.0	32	20	12	7.8
2.5	40	25	16	9.8
3.0	47	30	19	12

It is clear from the tables and Fig. 3 that that the relation between CT value and the Log credit value different temperatures is linear for both chlorine and ozone. At any given Log credit value, the CT value for chlorine is much larger than that of ozone especially at higher temperatures. In general, the CT value for both chlorine and ozone increases with decreasing water temperature. Lower ozone CT value means lower concentration and/or contact time, and hence smaller disinfection basins and quicker process. Therefore, if an existing WTP uses ozone instead of chlorine as a disinfection agent for cryptosporidium, the plant capacity can be increased for the same Log credit value. The CT values for chlorine, CT_{Ch} and that for ozone, CT_{O3} can be correlated from Fig. 3 in terms of Log credit, L and temperature, T (°C) as,

For chlorine:

$$CT_{Ch} = (367.77 - 12.608\,T)\,L_{ch} \qquad T=10\text{-}15\ °C \qquad (1)$$

$$CT_{Ch} = (472.5 - 19.59\,T)\,L_{ch} \qquad T=15\text{-}20\ °C \qquad (2)$$

For ozone:

$$CT_{O3} = (13.428 - 0.473\,T)\,L_{O3} \qquad T=10\text{-}15\ °C \qquad (3)$$

$$CT_{O3} = (17.415 - 0.739\,T)\,L_{O3} \qquad T=15\text{-}20\ °C \qquad (4)$$

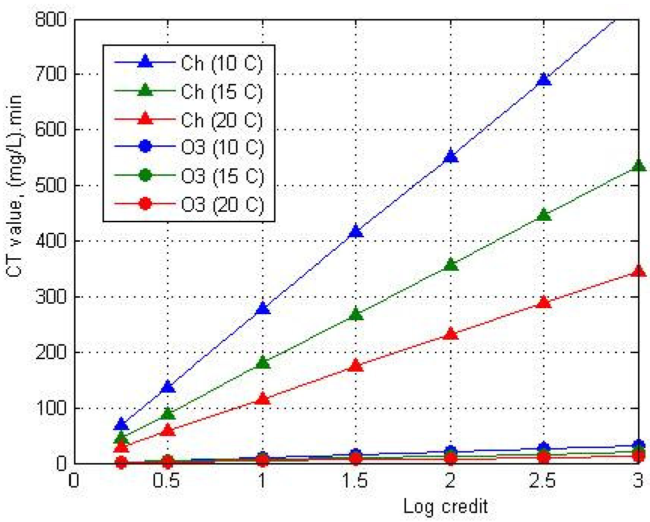

Fig. 3. CT value for chlorine and ozone for cryptosporidium inactivation, US EPA [9]

RESULTS AND DISCUSSION OF THE CASE STUDY

The Mansoura main WTP is considered as a case study in this work. The concerned operating technical data of this plant are as follows:

Plant capacity	120000 m^3/day
Water source	River Nile

Chlorine and Alum are added with hydraulic fast stirring in a 3x7 m basin

Chlorine dose (1)	4.5 mg/l	in the fast stirring basin
Chlorine dose (2)	2.5 mg/l	before sand filter
Alum dose	20 mg/l	in the fast stirring basin

The coagulation-flocculation process is carried out in 6 groups connected in parallel; each contains 5 basins with dimensions of 1.8x6 m and 4 m depth connected in series. The coagulation-flocculation process lasts about 27 min. There are two precipitation basins as shown in Fig. 4. Each basin has a dimension of 25x63 and 5 m depth. The precipitation process lasts about 130 min.
Chlorine price 1500 £/ton
Alum price 1200 £/ton

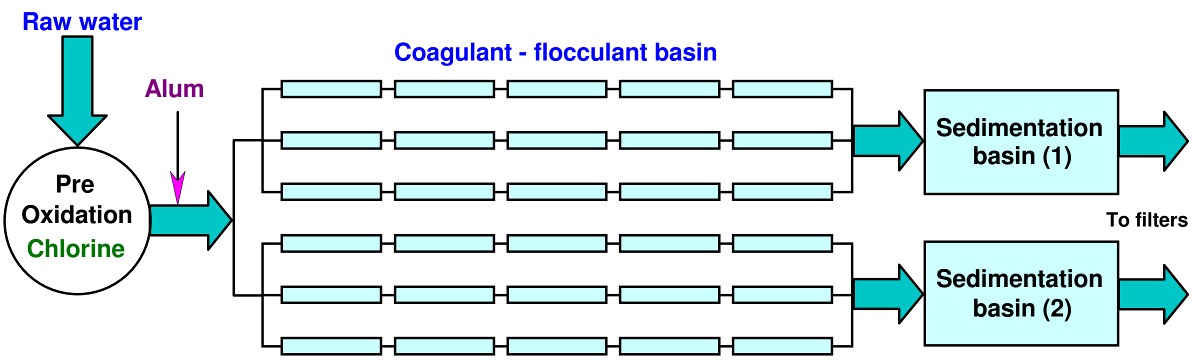

Fig. 4. Layout of coagulation-flocculation and sedimentation basins of the WTP

Points of Ozone Injection

According to the design of the plant as shown in Figs. 1 and 4 and the actual situation on the ground, the only suitable point of ozone injection is the same as that of pre-chlorination. The other possible injection point is usually taken before filters. But in this case, costly AC filters must be constructed after ozone injection. This type of filters is seldom used in the Egyptian WTPs because of its high operating costs. Therefore, the only possible ozone injection point (without major additional equipment) is the same as that of pre-chlorination.

Ozone Concentration

According to the above data, the CT value of chlorine is,

$$CT_{Ch} = \text{Conentration} \times \text{Time} = 4.5 \times 27 = 121.5 \quad (\text{mg/l})\,\text{min} \tag{5}$$

At this CT value and an average temperature of about 20 °C, the Log credit value can be calculated from equation (2) by,

$$L_{Ch} = 1.51$$

For the same temperature (20 °C) and Log credit value (1.51), the CT value for ozone can be calculated from equation (4) by about 4 (mg/l) min. This means that an ozone CT value of 4 (mg/l) min will give the same effect (Log credit) as chlorine CT value of 121.5 (mg/l) min. With the existing exposure time of 27 min, the required ozone concentration is,

$$\text{Ozone conentration} = \frac{CT_{O3}}{\text{Time}} = \frac{4}{27} = 0.148 \quad \text{mg/l}. \tag{6}$$

This concentration is practically very small as reported from Hoon et al. [10]. The optimum ozone concentration is better to be decided taking into account the impact on the coagulation-flocculation process. It is found that the ozone removal efficiency of the odorous materials depends mainly on the ozone concentration. In order to achieve high removal efficiency of the odorous compounds, high influent, ozone concentration C_{O3} must be larger than 3 mg/l, Muroyama et al. [11]. This concentration is also suitable for enhancing flocculation process. According to equation (4) and for L=4, the CT_{O3}= 10.54 (mg/l) min. The required contact time for this high credit value (L=4) will be only 3.54 min. According to plant technical specification, the available contact time is 27 min. This difference gives the possibility to increase the ozone concentration or the plant capacity. The increase of plant capacity of course needs a complete redesign of the whole plant infrastructure.

Power Consumption

Ozone generation is a power consuming process. In Japan (1995), the number of installed ozone generators is 2814, and the total designed power consumption of ozone generating systems is approximately 40,000 kW, Magara et al. [12]. There are minor power consumption sources in the ozone generation process such as air compression and cooling water circulation. However, the major source of power consumption is the corona discharge process which depends on the feed gas (oxygen or air), gas pressure, temperature and physical properties. The power increases almost linearly with the rate of ozone generated as reported by Alsheyab et al. [13]. Ozone formation efficiency varies depending on the oxygen content of the feed gas.

There is a great difference in ozone generator prices all over the world depending on the manufacturer and reliability. Ozone generators produced in USA are costly; while that produced in China are characterized by low price. However, in Europe the prices of ozone generators are reasonable. Figure 5 shows the power of ozone generators (kW) products of an Italian factory as a function of generator size (g/h) [14].

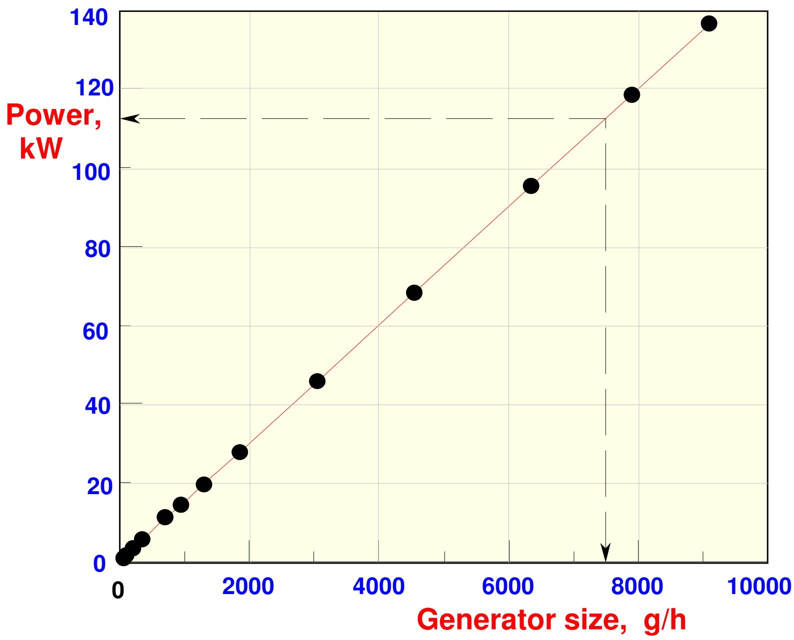

Fig. 5. Power vs. ozone generator size, [14]

Sizing the Ozone Generator

According to the above WTP technical specifications and the subsequent analysis, the ozone generator size can be determined as follows:
The water flow rate, m (kg/h) is given by:

$$m = \frac{\text{Plant capacicy } (m^3/\text{day})}{\text{Daily operation time (h/day)}} = \frac{120000}{24} = 5000 \quad m^3/h \tag{7}$$

$$m_{O3} = m\,(m^3/h) \times C_{O3} \;\; (g_{O3}/m^3) \quad g_{O3}/h \tag{8}$$

$$= 5000 \times 3 \times 10^{-3} = 15 \quad kg_{O3}/h$$

$$= 15 \times 24 = 360 \quad kg_{O3}/day$$

The calculated hourly ozone flow rate (15 kg_{O3}/h) can be supplied with two ozone generators; each has a capacity of 7.5 kg/h and a power of about 112 kW; with a total power of 224 kW as estimated from Fig. 5.

Operating Cost

For chlorine,

$$m_{ch} = m \times C_{ch} \quad g_{ch}/h \tag{9}$$

$$= 5000 \times 4.5 \times 10^{-3} = 22.5 \quad kg_{ch}/h$$

$$= 22.5 \times 24 = 540 \quad kg_{ch}/day$$

$$\text{Chlorine cost} = \frac{0.540\,(\text{ton/day}) \times 1500\,(\text{£/ton})}{5000\,(\text{m}^3/\text{day})} = 0.162\ \text{£/m}^3 \tag{10}$$

For ozone, considering the electric power cost 0.19 £/kWh, the ozone cost can be determined as,

$$\text{Ozone cost} = \frac{224 \times 24\,(\text{kWh/day}) \times 0.19\,(\text{£/kWh})}{5000\,(\text{m}^3/\text{day})} = 0.20\ \text{£/m}^3 \tag{11}$$

It is clear from equations (10) and (11) that the expected operating cost will increase by about 0.038 £/m^3, i.e. 23.5 %. The equipment cost for ozone is not considered in this work since it decreases rapidly with time. The prices of ozone generators also vary from place to another and the equipment reliability changes ... etc.

Safety

Chlorine can be blamed for thousands of deaths worldwide, while there is no evidence of any deaths to humans due to over exposure to ozone. This is because both the concentration and exposure time used in water ozonation put the operating point in the safe region as shown in Fig. 6. This figure shows the toxicity chart for ozone in terms of concentration (mg/l) and exposure time (min) [15].

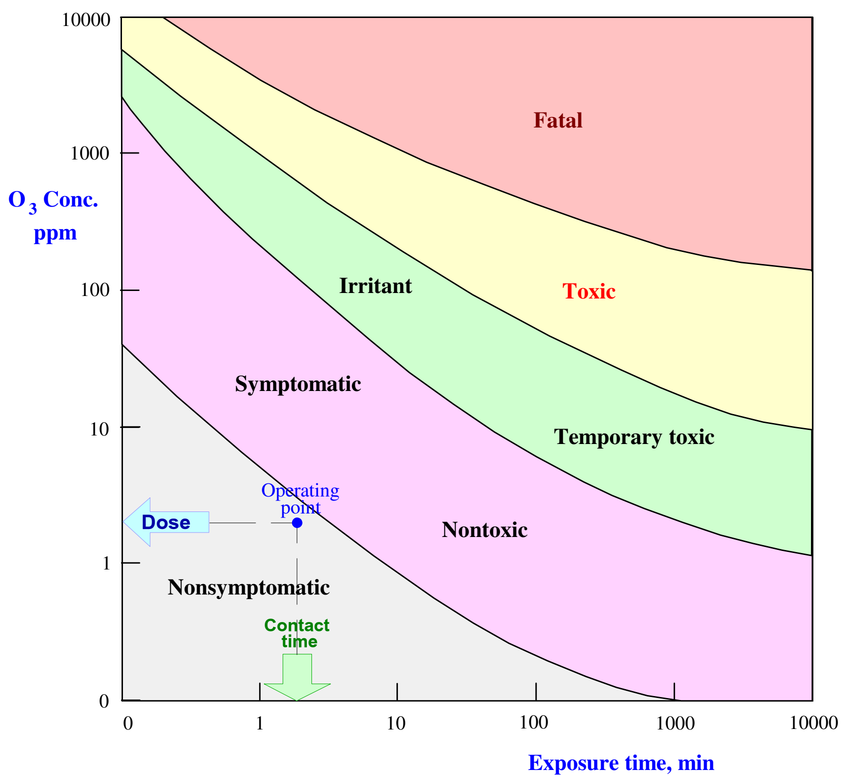

Fig. 6. Toxicity of ozone, [15]

CONCLUSIONS

In this paper, the use of ozone as an oxidant and disinfectant instead of chlorine in water treatment plants is discussed. Ozone generation, feed gas, power consumption, concentration, handling and possible points of injection are considered. The CT values for both ozone and chlorine for cryptosporidium inactivation are compared graphically and expressed in correlated linear equations. The results obtained from Mansoura main WTP as a case study for a typical Egyptian plant can be concluded in the following points:

1- The most suitable point of ozone injection is the same as that of chlorine addition at the source water inlet. Any other point requires costly AC filters.

2- Ozone gas is generated in site with air as a feed gas, and its handling is safe. The power consumption is proportional to the generator size.

3- According to the literature, a minimum ozone concentration of 3 (mg/l) min can be applied. This concentration is also suitable for coagulation-flocculation process enhancement.

4- For a higher Log credit value of 4 (compared to that of chlorine 1.51), the CT value will be 10.54 (mg/l) min (compared to 121.5 (mg/l) min for chlorine), the required contact time is only 3.54 min which is very small compared to the available (27 min).

5- Ozone generators prices are subjected to many factors; place of manufacturing, reliability and the feed gas. The prices are also decrease with time. However, the operating cost of ozone is 23.5 % larger than that of chlorine.

6- It is highly recommended to perform this work experimentally on a similar WTP for future study. The results of such work will be helpful for the decision makers in Egypt.

NOMENCLATURE

C	Concentration (mg/l),
CT	Concentration (mg/l) time (min) product, (mg/l) min,
L	Log credit value,
m	Mass flow rate of water (m^3/h),
ppm	Part per million = mg/l = g/m^3,
T	Temperature, (°C),
£	Egyptian pound.

Abbreviation

AC	Activated carbon,
WTP	Water treatment plant,
WTPs	Water treatment plants.

Subscripts

Ch Chlorine,
O3 Ozone.

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