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Review Article

Aeration Process for Removing Radon from Drinking Water – A Review

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Abstract: This paper presents information on various radon elimination techniques and presents knowledge on anticipated elimination performances following literature. The technologies assessed in this review comprise different aeration techniques and granular activated carbon (GAC) as tools to eliminate and decrease radon in potable water. Because radon does not bound to water molecules, it is not dissolved. Radon's low solubility and its elevated vapor pressure imply that it strongly partitions into the air through diffusion. For the reason that it readily diffuses from water to air, radon is scarcely observed in surface waters and is firstly trouble in groundwater and radon is easily removed through aeration processes. Aeration transmits the radon pollution from water to air, so precautions should be taken to avoid such air contamination hazards. Aeration is not sufficient for removing radon from drinking water; it should be supported by adsorption method. Air is mainly composed of nitrogen ($N_{2(gas)}$, ~80%) and oxygen ($O_{2(g)}$, ~20%). N_2 is hydrophilic and O_2 is hydrophobic. Injecting pure O_2 into water would be more efficient than air (i.e., $N_2 + O_2$) in removing radon from water, thanks to its hydrophobicity. At the opposite extreme, injecting pure N_2 would be less performant, due to its hydrophilicity. Research should be made on this direction.

Keywords: Radon, Drinking Water, Water Treatment, Aeration, Granular Activated Carbon (GAC), Waterborne Radon

1. Introduction

Radon-222 (radon) is a noble gas that is generated through the radioactive disintegration of the direct parent element Radium-226 [1-4]. Noble gases (Periodic Group 8A) are inert, odorless, and colorless. Radon-222 goes through additional radioactive disintegration, transmitting alpha particles during the phenomenon [5]. The half-life of Radon is around 3.82 days [6]. The disintegration products of radon, named radon progeny or radon daughters [7, 8], are short-life radioactive isotopes that transmit alpha and beta particles, and gamma radiation. The concentration of radon solubilized in water is very little comparatively with its activity [9]. As an illustration, an amount of water comprising 6.48×10^{-10} mg/L of radon gas includes 100,000 picoCuries per liter (pCi/L). Table 1 lists some physical properties of radon [3].

Table 1. *Physical properties of radon [3, 10].*

Molecular Weight	222 g/mole
Boiling Point	211 K (-62°C)
Melting Point	202 K (-71°C)
Solubility in Water	230 cm^3/L at 20°C
Air Diffusion Coefficient	1.2×10^{-5} m^2/s
Water Diffusion Coefficient	1.2×10^{-9} m^2/s

The rate and quantity of gas that transports in and out of water are highly influenced by its solubility. Gases either interact chemically with water or do not. For gases like radon do not interact with water, the attraction that water molecules have to themselves opposes solubility because a gas must be more attracted to the water than are other water molecules in order for it to solubilize. Because radon does not bound to water molecules, it is not dissolved. Radon's low solubility and its elevated vapor pressure imply that it strongly partitions into the air through diffusion [3, 11].

For the reason that it readily diffuses from water to air, radon is scarcely observed in surface waters and is firstly trouble in groundwater [3]. Radon comes into drinking waters supply sources from the disintegration of naturally present radium-226 in the rock and soil matrix [12]. Radon concentrations may change importantly from one region to the following due to dissimilarities in the local geology [13]. Radon in well water as well changes because of local, site-specific parameters like the well depth, the gap from the radon source, pumping patterns, and the features of the radon source [14, 15]. As an illustration, the links between granite bedrock and high radon concentrations have been detected in parts of the United States and other areas of the world [16-21]. Moreover than the link among granite bedrock and the presence of radon, radon has been found in thermal springs at levels of 100 to 30,000 pCi/L and in sections of phosphate mining [22-24].

The National Inorganics and Radionuclides Survey (NIRS) undertaken by the Environmental Protection Agency (EPA) in 1988 pointed out that the level of radon in groundwater supplies varied from the minimum reporting concentration of 100 to 25,700 pCi/L [25]. Concentrations of radon in groundwater supplies were in the span of 100 to 1,000 pCi/L for 61.5 percent of the 978 sites evaluated in the NIRS. The highest concentrations of radon found in the NIRS were in small system supplies serving fewer than 500 people. Atoulikian et al. [26] assessed that around 83 percent of groundwater systems have a radon level of less than 500 pCi/L and around 10 percent of groundwater systems have a radon level among 500 and 1,000 pCi/L [3, 27-30].

The level of radon in potable water can augment or diminish in the distribution system since it passes from the treatment plant to customers [3, 31-33]. The disintegration of radon through transport or storage in the distribution system has been observed to usually decrease radon concentrations by 10-20% [34]. Nevertheless, radon concentrations in the distribution system may as well augment because of the disintegration of radium that has accumulated in the iron-based pipescale [34-37].

The moment that radon in water supplies attains consumers, it can form human exposure through two paths: inhalation and direct ingestion [3, 38-40]. Radon in water passes into the air through ordinary water usages like showering, flushing toilets, washing dishes, and washing clothes [41, 42]. For inhalation, the major hazard from exposure to radon gas is not from the gas itself, but the radioactive progeny it generates [43]. This is attributed to the fact that radon is an inert gas; however, the progeny are chemically kinetic and link quickly with aerosols (suspension of solid or liquid in air). The aerosols are inclined to deposit in the lungs where they liberate radiation that has been found to augment the probability of lung cancer. Radon is second only to cigarette smoking as a leading cause of lung cancer in the United States [44, 45].

Some of the radon and its progeny also attain body tissues during ingestion, conducting to radiation exposure to the internal organs [3]. Consumed radon is believed to go from the gastrointestinal tract to the bloodstream, and from there is transported to the liver, lungs, and general body tissue [46]. Radon is usually kept in the body with a half-life of 30-70 min and quits the body frequently during exhalation from the lungs [46]. Absorbed radon is thought to augment the danger of stomach cancer and the hazard of additional cancers [47, 48].

Research investigated the impact that decreasing waterborne radon levels had on indoor air radon levels [3, 49]. The survey established that a decrease of 1.3×10^{-4} pCi/L of indoor air radon happened for every 1 pCi/L decrease in waterborne radon [50]. As an illustration, a decrease in waterborne radon level from 2000 to 200 pCi/L (90 percent) would conduct to a lowering of 0.234 pCi/L in the airborne radon level in a home [50].

US EPA and various states have recommended drinking water standards for radon in water ranging from 300 to 10,000 pCi/L but no standard currently exists [51]. One study of radon in over 900 Pennsylvania water wells found that 78% exceeded 300 pCi/L, 52% exceeded 1,000 pCi/L and 10% exceeded 5,000 pCi/L [51, 52].

This paper offers data on different radon elimination techniques and gives knowledge on anticipated elimination performances following literature. The technologies assessed in this review comprise different aeration techniques and granular activated carbon (GAC) as tools to eliminate and decrease radon in potable water.

2. Treatment Techniques

The likelihood of methods for radon elimination from water is greatly imposed by radon's chemistry [53]. Additional parameters comprise secondary hazards from treatment and site-specific indicators (such as physical space restrictions) [54, 55]. Radon is practically inert, has a short-lived half-life (3.82 days), and is a soluble gas at usual temperature and pressure (20°C, 1 atm). Due to its short half-life, 2 days of storage eliminates around 30 percent of the initial mass and radioactivity of radon in water by disintegration alone [3].

Henry's Law explains that the quantity of gas that dissolves in a given amount of a solution, at constant temperature and total pressure, which is directly proportional to the partial pressure of the gas above the solution [56]. Henr's Law is expressed by Eq. (1):

$$p = \frac{HC}{P_T} \tag{1}$$

where: p = mole fraction of gas in air (mole gas/mole air); C = mole fraction of gas in water (mole gas/mole water); H = Henry's Law constant (atm); P_T = total pressure (atm, usually = 1) [3].

Because P_T is frequently described as 1, Eq. (1) becomes:

$$p = HC \tag{2}$$

and H becomes unitless. Thus,

$$H = p/C \tag{3}$$

or

$$C = p/H \tag{4}$$

and the larger Henry's constant is, the larger the pollutant level in air is at equilibrium. When a pollutant is at saturation in both the liquid and vapor phase, the partial pressure is proportional to P_v/S (where P_v is the vapor pressure of the liquid and S is the solubility of the contaminant in water). This implies that a pollutant with lower solubility and/or higher volatility (i.e., higher vapor pressure) will have a higher Henry's Law constant [3].

The Henry's Law constant for radon in water at 20°C is 2.26 × 10^3 atm, or 40.7 L-atm/mole that is equivalent to 5.09 × 10^{17} pCi/L-atm (6.48 mg of radon has an activity of 1 Curie) [57]. Due to this considerable Henry's Law constant, radon readily passes into air above water. At 20°C, ammonia (NH_3) has a Henry's Law constant of 0.76 atm, whereas carbon dioxide (CO_2) has a Henry's Law constant of 1.51 × 10^3 atm [58]. Radon's relatively Henry's Law constant shows that it can diffuse from water into the air faster than both ammonia and carbon dioxide, which are easily strippable gases [3, 59].

If a water storage tank is left open to the air and undisturbed, the radon-polluted water will collapse substantially all radon by diffusion and disintegration. Researchers [60] observed that, during filling a standpipe, volatilization and seepage (diffusion) of radon into the air is a far more significant parameter than the disintegration of radon. Information from the 2-day test proves that radon concentrations in the 0.032 MG steel standpipe effluent were 15 percent less than the effluent radon concentrations in the 4,600 pCi/L extent. Aeration accelerates the dispersal operation by giving a bigger air/water surface area and a bigger level of turbulence [3].

Thanks to the physicochemical features of radon and natural processes (such as natural disposal and disintegration, turbulence), radon concentrations in surface waters are frequently much lower than those detected in groundwater [21, 61]. Because radon has the previously mentioned features, solutions for eliminating radon from potable water sources comprise aeration, adsorption onto another media (like GAC), and storage [3, 62].

Table 2 presents several technologies ready for the elimination of radon. These technologies are water treatment methods [63] within the technical and financial capability of most public water systems. Before applying technology, site-specific engineering investigations of the techniques established to eliminate radon must be realized. The engineering investigation has to assess technically practical and cost-effective techniques for the specific location where radon elimination is needed. In several situations, a simple study may be sufficient, while, in other situations, extensive chemical analysis, design, and performance data will be necessitated. The survey may comprise laboratory tests and/or pilot-plant operations to cover seasonal changes, preliminary designs, and estimated capital and operation costs for full-scale treatment [64]. The assessment of other choices, like the point of use/point of entry (POE) devices and spraying in storage tanks, as well as BMPs like extended atmospheric storage, can be comprised [3].

Table 2. *Summary of technologies for radon elimination and elimination performances [3, 65].*

Treatment Method	Percent Removals*	Comments
Packed Tower Aeration (PTA)	78-99.9	1) Proven technology 2) Low maintenance 3) Pretreatment may be needed 4) Potential emissions concerns 5) Potential temperature concerns 6) Potential aesthetic concerns
Diffused Bubble Aeration (DBA)	71-99.9	1) Proven technology 2) Low maintenance 3) Low profile and compact 4) Pretreatment may be needed 5) Potential emissions concerns 6) Potential temperature concerns
Point of Entry (POE) DBA	92-99.9	
Spray Aeration (SA)	35-99	1) Multiple passes required for high removals 2) Operational problems in cold conditions
POE SA	82-99	
Slat Tray Aeration	70-94	1) Pretreatment may be needed 2) Potential temperature concerns
Low Technology Aeration**	10-96	1) Footprints may be larger than those needed for other technologies 2) Potential temperature concerns
Granular Activated Carbon (GAC)	70-99	1) EBCT of 30-130 min (longer than that needed for the removal of taste and odor and volatile organic compounds (VOCs)) [66] 2) Radiation concerns

*Removals as high as these ranges have been reported in litearture.

**Low technology processes include relatively simple techniques such as the use of free-fall aeration, spray nozzles, or Venturi laboratory devices to deliver influent to an atmospheric storage tank, or mechanical surface aeration to agitate the water in a tank or basin.

Radon elimination techniques may be divided into three categories:

1) Aeration,

2) Granular Activated Carbon (GAC),

3) Simple techniques and BMPs [3].

The Sections that follow in this paper include an explanation of these techniques, investigation of elimination performances attained, problems linked to pretreatment, post-treatment, and off-gas emissions, and data collected from treatability/case studies. Simple techniques and BMPs are also reviewed.

2.1. Aeration

2.1.1. Method Definition

Aeration may be defined as the method of bringing air and water into approaching contact with each other for the objectives of diffusing unwanted water pollutants to air, oxidizing several natural organic matter (NOM) [67, 68], and enhancing the treatability of water. Aeration has been employed efficiently in water treatment to decrease the level of taste and odor-producing constituents like hydrogen sulfide and some synthetic VOCs, to eliminate carbon dioxide to decrease corrosivity and lime demand in lime softening treatment, and to oxidize iron [69] or manganese. Nevertheless, employing aeration just for the target of controlling radon is a relatively new idea in the potable water industry [3, 70, 71].

The driving force for mass transfer of radon from water to air is the gap between the actual concentration in water and the concentration linked with equilibrium between the gas and liquid phases. The equilibrium concentration of a solute in air is directly proportional to the concentration of the solute in water at a given temperature according to Henry's Law. As seen above, Henry's Law (Eq. (4)) mentions that the quantity of gas that solubilizes in a certain amount of liquid (C), at constant temperature and total pressure, is directly proportional ($1/H$) to the partial pressure of the gas above the solution (p). Thus, the Henry's Law constant (H) can be viewed as a partition coefficient. This coefficient shows the relative tendency for a compound to separate, or partition, between the gas and liquid phases at equilibrium (Henry's Law applies to most gases, particularly those that are slightly soluble and do not react with the solvent, such as dilute solutions like radon in groundwater). Aeration is employed to enhance the speed of the natural process of displacing toward equilibrium between dissolved, volatile substances in the water and the same substances in the air to which the water is exposed. Aeration also enables more of the dissolved, volatile substances to diffuse from water to air by exposing the water to a fresh source of air that has lower concentrations of the substances [3, 72].

Equilibrium constants for radon and some other compounds that have been detected in groundwater supplies are listed in Table 3. A Henry's Law constant is a measure of the relative escaping tendency of a compound; a compound with a high vapor pressure and a low aqueous solubility tends to volatilize more easily. Therefore, an elevated Henry's Law constant shows equilibrium favoring the gaseous phase; i.e., the compound usually is more readily stripped from water than one with a lower Henry's Law constant. As illustrated in Table 3, radon has a bigger Henry's Law constant than carbon dioxide and trichloroethylene which are known to be readily eliminated through air stripping [3].

Table 3. *Henry's Law constants for selected compounds (20°C)* [*] *[3, 57].*

Compound	Henry's Law Constant (atm-m^3/mole)	Henry's Law Constant (atm)
Vinyl Chloride	$6{,}295 \times 10^{-3}$	3.5×10^{5}
Oxygen	773×10^{-3}	4.3×10^{4}
Radon	40.7×10^{-3}	2.26×10^{3}
Carbon Dioxide	27.2×10^{-3}	1.51×10^{3}
Tetrachloroethylene	19.8×10^{-3}	1.1×10^{3}
Trichloroethylene	9.89×10^{-3}	5.5×10^{2}
Ammonia	0.0137×10^{-3}	0.76

[*]To convert from atm-m^3/mole to atm, the following equation may be applied: $H(atm - m^3/mole) \times P/RT = H(atm)$, where P is pressure in atmosphere, T is temperature in Kelvin, and R is the universal gas constant (8.205×10^{-5} atm-m^3/mole.)

Table 4 presents the fundamental parameters in controlling the transfer of volatile substances from water to air that must be taken into account in the design of aeration systems [3].

Table 4. *Essential factors in controlling the transfer of volatile substances from water to air [3].*

Factor	Description
Factor #1	Contact time (residence time)
Factor #2	Area to volume ratio (accessible area for mass transfer, air to water ratio)
Factor #3	Appropriate propagation of waste gases into the atmosphere (gas transfer resistance, particularly due to liquid film and gas film resistance at the air-water interface; partial pressure of gases in the aerator atmosphere; turbulence in gaseous and liquid phase)
Factor #4	Physical chemistry of the pollutant
Factor #5	Influent concentration of the pollutant
Factor #6	Water and surrounding air temperatures.

The first three parameters depend on aeration unit, whereas the remaining three are pollutant and site specific [3].

Aeration can as well have different impacts apart from radon and VOC elimination. These additional influences can be either useful or opposite and can comprise those listed in Table 5 [3].

Table 5. *Aeration secondary effects [3].*

Beneficial	Adverse
Elimination of hydrogen sulfide and different taste and odor-causing constituents.	Permitting procedures may be needed for off-gas emissions carrying radon in certain urban locales; even if, a duly conceived system would not pose a considerable danger to the people because of the diffusion of gases carrying radon and its progeny (as discussed in Section 2.1.5.2 of [3]).
Elimination of some carbon dioxide that conducts to augmented pH and lower corrosivity.	Augmented possibility for scaling in the distribution system because of the elevation in pH.
Possible decrease in the quantity of chlorine required to treat water.	
Because aeration eliminates sulfide, it may importantly diminish the quantity of chlorine necessitated to oxidize sulfide. Nevertheless, there may be no clear decrease in	Augmented corrosivity because of higher solubilized oxygen concentrations.

Beneficial	Adverse
chlorine dose because aeration also augments pH and therefore grows chlorine needs [73,74].	
Partial oxidation of iron and manganese that may be eliminated during the following filtration [75].	The necessity to disinfect treated water and aeration equipment [76].
	The requirement to prohibit deposition of iron and manganese in the distribution system.

Aeration engineering may be classified into four primary groups: (1) Waterfall aerators, (2) diffusion or bubble aerators, (3) mechanical aerators, and (4) pressure aerators [3, 77].

Some of the more popular sorts of waterfall aerators are packed tower/column, spray, tray, cone, and cascade aerators [58]. Many aeration methods may be used both at water treatment plants to treat full water supplies [78] and at homes as POE devices [3].

Technologies in the first two classes, comprising their use as POE devices, and the emerging technologies of gas-permeable membranes [79-81] and sparging [82] are described in this Section. Some of the technologies in the first two classes, like spray aeration (SA) and cascade aeration, may be used employing simpler structures in what can be considered a low technology process. In the same way, technologies in the third type are defined in Section 2.2 of [3]. Pressure aerators, employed to aerate water that is under pressure, are accessible in two types. One type sprays water into the top of a closed tank while the tank receives a continuous supply of compressed air; aerated water leaves from the bottom of the tank. With the second type, compressed air is injected directly into a pressurized pipeline to add air bubbles to the flowing water. Pressure aerators are applied in iron and manganese oxidation but are not used for radon removal [3].

(i) Packed tower aeration (PTA)

Radon is promptly volatilized from water and therefore is facilely stripped such as several VOCs. Packed towers have been proved to be the most performant form of aeration for VOCs elimination; consequently, packed towers have been used for radon elimination. In countercurrent flow packed towers, packing materials are employed which furnish elevated void volumes and increased surface area. The water flows downward via gravity while air is forced upward. The untreated water is usually distributed on the top of the packing with sprays or distribtion trays and the air is blown up the column by forced or induced draft. This conception conducts to continuous and full contact of the water with air and reduces the thickness of the water film on the packing, thus enhancing performant mass transfer. The plan of air stripping equipment has been largely expanded in the potable water industry for VOCs and hydrogen sulfide elimination and in the chemical engineering industry for stripping concentrated organic solutions [3, 83-85].

Table 6 lists the main parameters which directly affect the reduce of radon through packed tower aeration (PTA) [3].

Table 6. *Parameters determining the elimination of radon employing PTA [3].*

Parameter	Description
Parameter #1	Air to water (A:W) ratio
Parameter #2	Residence time
Parameter #3	Available surface area for mass tranfer
Parameter #4	Surface loading rate
Parameter #5	Physicochemical feature of radon (an inert gas with a high Henr's Law constant)
Parameter #6	Radon levels in the influent water and air
Parameter #7	Temperature of the water and the air.

The conception of a packed tower aerator has a great contribution in defining the impacts of the first four parameters, while the last three factors are dictated by the pollutant, source water, and location of the tower [3, 58].

The air flow needs for a packed tower are function of the Henry's Law constant for the specific constituent(s) to be eliminated from the water [3]. In an ideal aeration device, the minimum A:W ratio which attain total elimination of a pollutant is function of the Henry's Law constant. The bigger the Henry's Law constant, the less air is necessitated to eliminate the constituent from water. Since aeration devices are not ideal and the pollutant level in the feed air may not be zero, actual A:W ratios to attain a chosen elimination performance are more important than the ideal or theoretical relationship between radon elimination and the A:W ratio [86].

The residence period depend on the depth and kind of the packing material. An augmentation in the depth of packing material conducts to a more important residence time between the air and the water, and as a result, bigger eliminations are obtained. The depth of the packing material is determined by the height of the packing in the tower [3].

The accessible surface area for mass transfer depends on the packing material. Different sizes and types of packing material are accessible comprising 0.635 to 7.62 cm sizes and metal, ceramic and plastic materials. Largely, the smaller packing materials furnish a greater available area for mass transfer per volume of material so augmenting the mass of pollutant eliminated. Nevertheless, the resulting elevated pressure drop for air traveling over the column must also be taken into account [3].

The surface loading rate is the quantity of water that travels over the tower and greatly depends on the diameter of the tower and the system design flow [3]. The surface loading rate usually ranges from 61.1 to 73.3 m/h [58].

Temperature influences the solubility of radon in water and its Henry's Law constant. As the temperature augments, radon's solubility in water diminishes. Nevertheless, radon, as in inert gas, is not anticipated to display a wide interval of distinction in solubility between near freezing temperature and 20°C [3]. Even if elimination performances frequently augment as water temperature augments for packed tower aerators, heating influent water is usually not cost-effective [58, 87].

PTA can usually be employed with devices of all sizes. Table 7 presents the main features of packed tower installation [3].

Table 7. *Characteristics of packed tower installation [3].*

Feature	Description
Packed Tower	Either metal (stainless steel or aluminium), fiberglass-reinforced plastic, or concrete construction. Internals (packing, supports, distributors, mist eliminators) are usually made of metal or plastic. Packing may be random or structured.
Blower	Usually centrifugal type, either metal or plastic construction. Noise control can be necessitated following the size and system location.
Effluent Storage	Frequently furnished as a concrete clearwell (as well known as airwell) below the packed tower. Usual storage period is 5-15 min of design flow with the higher storage capacity at small systems.
Effluent Pumping	Typically needed because effluent is at atmospheric pressure. Vertical turbine pumps mounted on clearwell are usual.

Packed towers are frequently installed outdoors, importantly generating temperature, aesthetic, and noise worries. In cold climates, piping should be protected from freezing, particularly through low flows that happen over times of lower demand for water. Fog and surface icing may also be cold weather problems. Aesthetic issues because of the height and appearance of a packed tower may require particular artistic touches and architectural designs. Some large outdoor facilities may necessitate to locate the blowers in a building when noise is a concern. Moreover, public perception of off-gas emissions may need a public relations/outreach program [3].

(ii) Diffused aeration (DA)

Aeration is realized in the diffused-air type device through injecting bubbles of air into the water by means of submerged diffusers. Diffusers are frequently either porous plates or tubes, or perforated pipes. The older, more conventional usages comprised a deep container. The more recently developed diffused-bubble aeration systems comprise a shallow depth container. In theory, diffused aeration (DA) is performed counterflow with the untreated water. The untreated water enters the top of the basin and exits from the bottom treated, while the fresh air is blown from the bottom and is exhausted from the top. The air bubbles formed by the diffusers rise through the water, producing turbulence and allowing a chance for the transfer of volatile materials. The gas transfer may usually be enhanced via augmenting basin depth, forming smaller bubbles, ameliorating contact basin geometry, and through employing a turbine to decrease bubble size and augment bubble retardation [3].

DA frequently gives a less interfacial area for mass transfer but greater liquid residence period if compared to packed towers [58]. DA supplies optimum treatment equipment for the dissolution of a soluble gas in the water (oxygenation or ozonation), while PTA gives an optimum system for the removal of volatile pollutants from the water [3].

An applicable choice for small and medium sized equipment is a variation of DA technologically named multi-stage bubble aeration (MSBA). MSBA units are obtainable commercially. Typical commercial units contain a high-density polyethylene vessel subdivided into multiple stages with stainless steel and polyethylene divider plates. Each stage is supplied with an aerator. Individual aerators are connected to a supply manifold. The units are compact and low profile. Water depths are shallow for MSBA, with sidewater depths usually less than 45.72 cm (compared to depths of 304.8 to 609.6 cm for typical aeration basins) [3].

DA may be adapted to present storage tanks and basins. The air diffusers may be placed on the side of the tank to further make turbulence and aid in gas transfer. When porous plates are employed, they are placed at the bottom of the tank. If porous tubes or perforated pipes are employed, they may be suspended at about one-half depth of the tank to decrease compression heads. Diffusers are destined to generate bubbles of certain sizes. Smaller bubbles form more total area for mass transfer, thus augmenting the exchange of volatile substances. If porous diffusers are employed, incoming air should be filtered carefully through an electrostatic unit or a filter of metal wool or glass with a view to minimize blocking. Static tube aerators have also been employed in a set of usages and have given sufficient aeration if duly intended [3].

The design of DA device has been expanded largely in the chemical processing industry for handling concentrated organic solutions. The steps observed in the chemical engineering references may be used in water treatment [88, 89] for radon removal. The rate at which radon is eliminated from water by DA depends upon many of the same parameters (Table 8) as for PTA [3, 90].

Table 8 lists the main parameters which directly affect the reduce of radon through diffuse aeration [3].

Table 8. *Parameters influening the removal of radon using diffuse aeration [3].*

Parameter	Description
Parameter #1	Temperature of the water and the air
Parameter #2	Physicochemical characteristics of radon
Parameter #3	Radon concentrations in the influent air and water
Parameter #4	A:W ratio
Parameter #5	Residence period (flow rate)
Parameter #6	Accessible area for mass transfer (bubble fineness)

The first three parameters are imposed by the liquid stream and the contaminant; the last three are a function of the device and working situations and may be assessed in a pilot testing program [3].

DA has several benefits and disadvantages to comparatively with PTA. The benefits comprise the possibility for changing a present basin or storage tank with DA, and marginal savings due to no packing costs, reduced pumping costs, and usually lower energy costs. MSBA, especially, gives the merit of being compact and so is appropriate for aesthetic purposes and frequently implies lower building costs. The handicaps involve the necessity of augmented residence period (which may cancel the usage of a given modified basin or storage tank), the potential of requiring a bigger A:W ratio, and overall less efficient mass transfer. MSBA is also restricted in dealing with greater flows [3, 91].

(iii) Spray aeration (SA)

Spray aeration (SA) devices point water upward, vertically, or at an inclined angle, in such a fashion that the water is broken into small drops. Installations frequently contain settled nozzles on a pipe grid. The formed small droplets present a big interfacial surface area by which the radon migrates from the liquid phase to the gaseous phase [3].

Table 9. *Design parameters that influence the performance of SA [3].*

Parameter	Description
Parameter #1	Nozzle conception and working pressure (velocity of spray)
Parameter #2	Nozzle direction (size, number, and spacing of multiple spray nozzles; nozzle path)
Parameter #3	Distance of water droplet free fall
Parameter #4	Water droplet size
Parameter #5	Degree of ventilation (comprising the impacts of wind on the motion of rising and falling water droplets)

Even if the usage of several small spray nozzles that each form very small water droplets can give the greatest area-volume ratio (most accessible area for mass transfer), these small nozzles are inclined to clog and need high maintenance [3]. Spray aerator nozzles usually possess a diameter of 2.54-3.81 cm, discharge ratings of 17-34 m^3/h (at around 0.68 atm), and are installed every 61-366 cm apart [58].

Like DA, SA possesses many merits and disadvantages to compare with other aeration technologies [3]. The benefits comprise the capacity of attaining performant mass transfer thanks to the small water droplets formed through the attached nozzles, the lack of any packing costs, and greatly lower maintenance costs. The disadvantages involve the necessity for a big functioning area, which translates into augmented building construction costs, importantly elevated working issues through the cold weather period when the temperature is below the frezzing point, short exposure time between air and water, and high pressure needs [58].

2.1.2. Removal Performance and the Impact of Key Design Criteria

Consulted investigations on aeration methods give facts about removal performances for radon. These facts are recapitulated in the EPA report [3]. Eliminations for PTA varied from 78.6 to more than 99 percent, with most eliminations announced at 90 percent or bigger. For the two diffused bubble aeration (DBA) means, elimination performances were 93 and 95 percent. Elimination performances for MSB varied from 71 to 100 percent. These investigations displayed a large change in elimination results for SA devices, with performances varying from 35 to 99 percent following working parameters. SA devices built-up in homes have manifested radon decreases of 82 to 93 percent [3].

(i) Packed tower aeration (PTA)

PTA may attain extremely elevated eliminations of radon varying from 90 percent to more than 99.9 percent. Table 10 lists the conception factors that influence the elimination of radon comprising packing height, A:W ratio, packing type, and loading rate. Devices putting PTA have to as well take into account problems like pretreatment, supplementary disinfection [92] needs and pump retrofitting [3].

Table 10. *Design factors affecting the elimination of radon [3].*

Factor	Description
Packing height	Packing height is the most important conception factor for eliminating radon [93,94]. Dixon et al. [93] proposed a minimum packing height of 304.8 cm.
A:W ratio	Eliminating radon is not extremely responsive to A:W ratio provided that the ratio is enough elevated. Typical A:W ratios for PTA devices in potable water treatment plants vary from 30:1 to 100:1 [58]. Researcher [94] observed radon eliminations came down quickly for A:W ratios smaller than 2:1. Researchers [95] showed that radon decrease performances were identical at A:W ratios of 5:1, 10:1, and 20:1, and were only somewhat smaller for an A:W ratio of 2:1, so augmenting the A:W ratio beyond of 2:1 to 5:1 influenced eliminations very little. The same researchers [95] also observed that employing an A:W ratio of 1:1 assured an importantly lower removal. Dixon et al. [93] mentioned that radon elimination is not responsive to A:W ratio. They also announced radon eliminations bigger than 93 percent for an A:W ratio of 3:1 and a packing height of 304.8 cm. Following Dixon et al. [93], an A:W ratio of 5:1 must be adequate for achieving elevated radon eliminations. Freshest investigation on radon elimination performances proved that radon elimination is responsive to the A:W ratio through a larger domain of ratios than mentioned previously. Researchers [86] announced that radon eliminations tend to level off at an A:W ratio of 10:1, and that augmenting the A:W over 10:1 has less impact on radon elimination. Following them [86], the theoretical A:W ratio indispensable to eliminate more than 90 percent of the radon from water is around 5:1, as the practical A:W ratio is 6.5:1 for 90-percent removal. An A:W ratio of 19:1 must be enough to eliminate almost 100 percent of the radon.
Packing type	Researchers [95] noted that readon eliminations with saddle packing were somewhat smaller than eliminations attained with pall rings; nevertheless, radon eliminations were over 90 percent with either packing type for an identical packing height and A:W ratio.
Loading rate	Researchers [93] mentioned elevated eliminations of radon at loading rates of 122 m/h. Nevertheless, with a view to avoid potential flooding, a loading rate of 61.1-73.3 m/h may be a practical limitation.

(ii) Diffused bubble aeration (DBA)

DBA has the capacity to reach extremely elevated eliminations of radon varying from 71 to more than 99, with eliminations usually more impostant than 90 percent. The conception factors that have been investigated for their impact on the elimination of radon for this technique comprise the A:W ratio and flow rate. Equipment placing DBA have as well to take into account pretreatment, disinfection, and pump retrofitting needs [3].

Eliminating radon through MSBA does not change importantly with A:W ratio and flow rate [93]. A little augmentation in radon elimination happened via augmenting A:W ratio or diminishing the flow rate. Researchers [93] confirmed that conceptions of MSBA let a maximum flow of 181.69 m^3/h for radon eliminations bigger than 95 percent, and 408.82 m^3/h for eliminations of less than 85 percent. Industrials announced treatment potential of more than 227.12 m^3/h [3, 96].

(iii) Spray aeration (SA)

Researchers [95] performed pilot experiments employing SA and announced the next elimination performances, listed in Table 11.

Table 11. *Radon elimination for SA pilot experiments [3].*

Residence Period (hr)	Percent Elimination of Radon	
	Decay	Total
9	7	63-73
12	9	62-65

Researchers [93] observed that changes in A:W ratio had a minor impact on radon elimination performance. They attained 77-percent radon elimination rates employing a baffled steel tank with a flow of 15.89 m^3/h, an A:W ratio of 6:1, and a residence period of 20 min. For the identical equipment with a flow of 11.35 m^3/h, they obtained radon eliminations of 83-91 percent for A:W ratios varying from 3:1 to 17:1 (elimination was 88 percent at A:W ratio of 6:1) [3].

(iv) Point of entry (POE)

Investigations and pilot experiments of POE equipment concentrated on DBA and SA, because PTA devices have frequently been viewed unfeasible for home usage due their dimensions and price. Radon eliminations from 95 percent to >99 percent are mentioned for for DBA equipment placed at the POE to homes [97-99]. Researchers [99] observed that the diffused bubble and bubble plate aerator POE units examined had elevated A:W ratios (which is frequent because POE units are usually overdesigned) and consequently the units must treat variations in influent radon activity and the water flow rate without a considerable augmentation in effluent radon activity. For SA devices placed in homes and examined, radon eliminations have varied from 82 to 93 percent [3, 100].

(v) Comparison of techniques

There is a small gap between PTA and DBA in terms of radon elimination. Both PTA and DBA attain elevated eliminations of radon and are accessible in the market [3]. Even if shallow tray aerators may reach radon eliminations of bigger than 90 percent, eliminations are usually less important than those attained from PTA and DBA. The maintenance needs for both PTA and DBA are small. Whereas DBA is preferred for aesthetic considerations, PTA is preferred for big flows for both practical and economic reasons. MSBA is as well restricted in dealing with bigger flows. Researchers [93] and industry documents display an upper limit potential of 181.69 to 227.12 m^3/h for presently obtainable DBA devices following practical reasons [3]. Shallow tray aerators as well give aesthetic benefits because they are compact.

2.1.3. Pretreatment

Several radon elimination devices can need pretreatment especially treatment for iron and manganese, to decrease functioning issues linked to aeration [3].

(i) Iron and manganese

Iron (Fe) and manganese (Mn) in influent water can precipitate if a water supply is aerated. Precipitation may foul packing in aeration equipment, therefore diminishing the performance of these methods [3].

Current groundwater devices that will be needed to decrease radon may not require supplementary treatment for iron and manganese as water devices usually treat their water to decrease iron and manganese concentrations further down their secondary Maximum Contaminant Levels (MCLs) of 0.3 mg/L and 0.05 mg/L, respectively. This is approved by the findings of an analysis of NIRS information which matched the presence of Radon-222 with combined Fe and Mn concentrations. These findings are listed in Table 12 [3].

Table 12. *Relationship of existence of Fe and Mn with radon [3].*

Total No. of Systems with Rn-222 >300 pCi/L	Percentage of Systems with Combined Fe and Mn		
	>0.3 mg/L	>1 mg/L	>2.5 mg/L
347	14.7	3.5	0.3

As well explained in the EPA Report [3], proposed treatment methods that may be used to bypass fouling in aeration units rely on the levels of iron and manganese in the influent water to aeration units, and are shown in Table 13.

Table 13. *Treatment concentrations for iron and manganese [3].*

Combined Fe and Mn (mg/L)	Suggested Treatment
<1	Addition of a sequestrant
>1	Oxidation/filtration or greensand filtration

Sequestration

Sequestration is a treatment technique during which iron and manganese are prohibited from producing undesirable turbidity and color without really eliminating iron or manganese from the treated water. Usual sequestering chemicals are sodium silicate and polyphosphate and additional phosphate-containing agents. Sequestrant products are frequently injected together with chlorine [101]. For manganese-containing waters, polyphosphate is a more performant sequestrant than sodium silicate [102].

Greensand Filtration

Greensand filtration includes a regular filter box employing greensand as an alternative to sand or anthracite as the main filtration medium. Manganese greensand filtration has been efficiently employed for iron and manganese treatment for several decades. Manganese greensand (a sedimentary deposit consisting of glauconite mingled with sand and clay) media is arranged via treating glauconite (iron potassium-silicate mineral), a natural zeolite, with manganous sulfate and potassium permanganate to coat the media with manganese oxide. This process confers the media adsorptive features, which lets for the elimination of dissolved materials by adsorption [103], as well as filtration of undissolved materials. The manganese oxide plays the role of a catalyst in the filtration operation to help in the complete oxidation [104] of iron and manganese. Potassium permanganate is frequently introduced to water ahead of greensand filtration. This helps to oxidize pollutants to undissolved forms for ulterior filtration, gives disinfection, and reestablishes adsorptive potential to the media. Greensand filtration is essentially profitable while employing potassium permanganate to oxidize iron and manganese. If moderate injections of potassium permanganate are employed, greensand filtration will eliminate any surplus potassium permanganate from water, prohibiting pinkish water from entering the distribution system [3].

(ii) Additional parameters

More than Fe and Mn, additional parameters that may influence fouling of aerators are microbial growth, pH, pE, and the hardness of the water [105, 106]. A possible but usually labor-intensive option to pretreatment is a cyclic change of packing, or cleaning of packing in aeration units (either by removing the packing for cleaning and replacing it with spare packing, or by cleaning the packing in place with acid, chlorine [107], or pressure washing) [3].

2.1.4. Post-Treatment

(i) Disinfection after aeration

In the course of the aeration operation, atmospheric air is blown into the water supply. The air blowers are armed with influent screens to avoid any big solids from entering the water supply. However, airborne bacteria or viruses are frequently inserted into the supply. For groundwater systems, this is probably to be the exclusive exposure with the air prior to the water reaching consumers. The contact of a clean groundwater supply to air augments the hazard of microbiological infection. By focusing on fine technology use, groundwater supplies that are aerated must be disinfected, even if the groundwater supply may otherwise be considered as inherently disinfected. Considering this strategy, if a groundwater system actually does not disinfect and it adds aeration for radon removal, it would also require to place disinfection [3, 108, 109].

(ii) Water pump changes

If a groundwater system places a technique that is open to the atmosphere, pumping changes and supplements may be required. Present groundwater systems usually give minimal treatment - frequently at most disinfection [110, 111] - before pumping directly under pressure to the distribution system. If a technique open to the atmosphere, like aeration, is placed, the influenced water system has the next choices: (a) throttle present well pumps; (b) restage present well pumps; and (c) substitute present well pumps with pumps giving a lower head. In any situation, finished water pumping will be required to rise the pressure before distribution because most aeration techniques necessitate being handled at atmospheric pressure for radon to be liberated to the air. Several small water systems that select to change well pumps may employ the old well pumps for pumping from the clearwell to the distribution system. Consequently, methods like aeration will require both raw and finished water pumping, however usually do not need more than one supplementary pump [3].

2.1.5. Off-Gas Emissions

Staf in water treatment stations that employ PTA or different aeration methods for radon elimination may be uncovered to higher-than-background radiation degrees. This is since radon is heavier than air and can build up in areas with stagnant air or in poorly ventilated stations that board PTA or open DBA treatment units. Water treatment plants have to regulate work practices and monitoring to achieve exposure degrees as low as reasonably attainable in the workplace [112, 113]. As illustration areas directly surrounding or immediately downwind of a PTA should be well-ventilated. Moreover, the water treatment factory buildings and areas where workers spend their time should be properly ventilated all year round [3, 114-116].

2.2. Granular Activated Carbon (GAC)

In potable water treatment industry, employing GAC through the world has been restricted mainly to purposes for monitoring synthetic organic chemicals and taste odor compounds. Nevertheless, since the discovery of radon in potable water supplies, several researches and pilot-scale investigations have been performed to assess the performance of GAC for monitoring radon [117]. Following the findings of these researches and pilot-scale works, GAC seems to be efficient in eliminating radon from water [3, 118].

Radon is eliminated from water through adsorption employing GAC. The adsorption process takes place when the radon molecules pass from the water to the surface of the GAC. Radon sorbs at the interface between the water and the carbon. Consequently, an elevated surface area is a fundamental parameter in the adsorption phenomenon. Even if the external surface of the carbon gives some accessible area for adsorption, the main part of the surface area is given in the pores inside the carbon texture [3].

Adsorption devices commonly function in a downflow mode where the polluted water is injected at the top of the carbon bed and flows across the bed to the bottom. As the water advances down out of the bed, the radon is adsorbed to the carbon until all the accessible interfacial area is saturated. The radon progresses with the water across the bed prior to there is an accessible area for adsorption to occur. Pollutant eliminations depend on the obtainable interfacial area between water and carbon, and also depend on time [3].

More technical details and case studies may be found in the EPA report [3].

On the other hand, the throwing away of consumed GAC filters employed in the practice of residential radon elimination from well water is a worry [119]. Remaining radioactivity gathered on the filter media, like natural uranium, radium, and lead require to be considered with a view to reduce issues at the disposal site [120]. It is established that well water comprises small amounts of uranium, radium, and radon, and the GAC filter has changing summation performances for each. Lead, a decay product of radon will also build up on the filter [121]. Different elimination problems necessitate being regarded [117, 122, 123].

2.3. Proccesses Combinations

In Sweden, several processes to remove radon in potable water were examined at the beginning of the 1980s [124]. SA under atmospheric pressure, DBA, aeration in the pressure tank and various installations of these processes were tested. Aeration in the drill hole and adsorption on granulated activated charcoal were also verified. The best findings, around 70% decrease, were achieved with aeration in the pressure tank with a spray system joined with diffused air bubbling. The Orebro project at the dawn of the 1990s comprised on-site testing of five various aeration techniques:

Aeration in the drill hole, aeration in the storage tank, ejector aeration, shallow tray aeration, and packed column aeration. The radon decrease performance changed between 20% and 99%. In 1994 an investigation proposed to assess the radon elimination potential of diverse water treatment apparatus was realized. The carried out quantifications proved that the only types of system that decrease the radon level importantly are radon separators and reverse osmosis filters. The radon elimination potential of the radon devices changed between 23 and 92%. In 1996, the nine most frequent radon devices on the Swedish market were evaluated. The findings established that the verified radon elimination apparatus functioned perfectly, even if the technical standard and adopted technical manners were not constantly the best. The radon elimination potential of the devices taking part in this trial was in most situations between 96 and 99%. In many situations, the potential surpassed 99%. With a view to obtain this radon removal ability, the water must be recirculated in a storage tank under atmospheric pressure [124, 125].

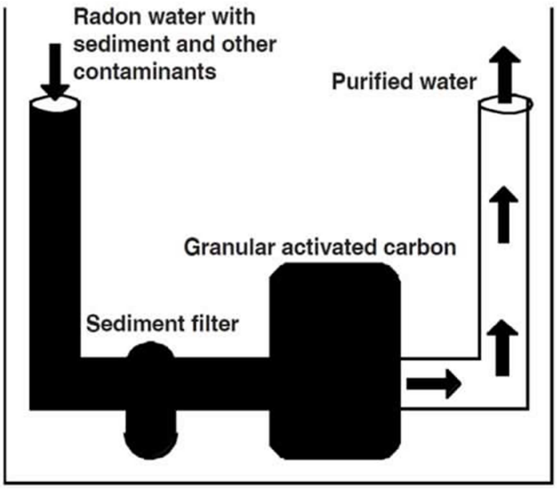

Figure 1. *Typical setup for a GAC filter treating radon [125].*

3. Conclusions

The main points drawn from this literature review may be given as:

Because radon does not bound to water molecules, it is not dissolved. Radon's low solubility and its elevated vapor pressure imply that it strongly partitions into the air through diffusion. For the reason that it readily diffuses from water to air, radon is scarcely observed in surface waters and is firstly trouble in groundwater and radon is easily removed through aeration processes. Aeration transmits the radon pollution from water to air, so precautions should be taken to avoid such air contamination hazards.

Air is mainly composed of nitrogen ($N_{2(gas)}$, ~80%) and oxygen ($O_{2(g)}$, ~20%). N_2 is hydrophilic and O_2 is hydrophobic. Injecting pure O_2 into water would be more efficient than air (i.e., $N_2 + O_2$) in removing radon from water, thanks to its hydrophobicity. At the opposite extreme, injecting pure N_2 would be less performant, due to its hydrophilicity. Research should be made on this direction.

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