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TECHNOLOGIES AND COSTS FOR THE REMOVAL OF RADON FROM DRINKING WATER

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This Technology and Costs for the Removal of Radon From Drinking Water document was prepared by Science Applications International Corporation (SAIC), under the auspices of Mr. William Labiosa (Work Assignment Manager) of the U.S. Environmental Protection Agency's (USEPA) Office of Ground Water and Drinking Water (OGWDW). SAIC wishes to gratefully acknowledge the support of the EPA WAM. SAIC Contract No. 68-C6-0059, Work Assignment No. 1-22, SAIC Project No. 01-0833-08-3566-000. SAIC contract and work assignment managers are: James Parker, Contract Project Manager; and Faysal Bekdash, Work Assignment Manager. Individuals who prepared this T&C document are: Faysal Bekdash, Ph.D., Senior Environmental Engineer; Pravin Rana, Environmental Engineer, Tracy Scriba Environmental Scientist, Pat Ransom, Environmental Engineer, Mary Waldron, Environmental Scientist, Abhjit Palit, Jr. Environmental Engineer, and Djamel Benelmouffok Ph.D. QA reviewer.

PRELUDE

The purpose of this document is to assist the U.S. Environmental Protection Agency (EPA) in updating the radon-relevant portions of its "Technologies and Costs" (T&C) documents[1,2] developed to support the 1991 proposed radionuclides rule. Therefore, much of the background information, description of technologies, and valid design parameters sections were taken from the above referenced T&C documents. Subsequent to this Prelude, this document is organized as follows:

- **List of Abbreviations**
- **List of Definitions and Conversion Units**
- **Table of Contents**
- **List of Figures**
- **List of Tables**
- **Chapter 1.** ***Introduction:*** Presents general information on the chemical and physical properties of radon and the regulatory background, and defines the objectives of this document.
- **Chapter 2.** ***Removal of Radon from Drinking Water:*** Discusses technologies and techniques for removing radon from drinking water sources. Technologies presented include various aeration technologies, granular activated carbon (GAC) treatment, and other low technology radon removal techniques. Also, this chapter discusses pre- and post treatment requirements for selected radon removal technologies.
- **Chapter 3.** ***Best Management Practices:*** Presents an overview of best management practices (BMPs) for removing moderate amounts of radon from drinking water sources.
- **Chapter 4.** ***Radon Removal Costs:*** Provides information on available cost models used for costing various radon removal technologies and presents costs for various system size categories and types.
- **Appendix A.** Provides supporting information for cost analysis and possible off-gas emissions regulations.

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[1] U.S. EPA. (1987). Technologies and Costs for the Removal of Radon from Potable Water Supplies (Fourth Draft). Prepared by Malcolm-Pirnie (January 8, 1987).

[2] U.S. EPA. (1992) Technologies and Costs for the Removal of Radionuclides from Potable Water Supplies. Prepared by Malcolm-Pirnie (July, 1992).

ABBREVIATIONS LIST

A:W	air:water ratio (quantity of air provided compared to the quantity of water)
atm	atmosphere
atm-m^3/M	atmosphere-meter cubed per mole
avg	average
°C	degrees Celsius
cc	cubic centimeters
cm	centimeter
CO_2	carbon dioxide
CT	concentration time
DBA	diffused bubble aeration
EPA	U.S. Environmental Protection Agency
°F	degrees Fahrenheit
Fe	iron
ft.	feet
ft^3/min.	cubic feet per minute
gal.	gallon
gm/M	grams per mole
gpd	gallons per day
gpm	gallons per minute
gpm/sq ft.	gallons per minute per square foot
hp	horsepower
hr	hour
in.	inch
K	Kelvin
K$	$1,000
L/hr.	liters per hour
Mn	manganese
MCL	maximum contaminant level
m^2/s	square meters per second
m^3K/M	cubic meter Kelvin per mole
mg/L	milligrams per liter
MGD	millions of gallons per day
mW/cm^2	milliwatts per square centimeter
mWs/cm^2	milliwatts-seconds per square centimeter
MSBA	multi-stage bubble aeration
NOM	natural organic matter
PCE	Perchloroethylene
PTA	packed tower aeration
ppm	parts per million
pCi/L	picocuries per liter
pE	electron activity; -log of the electrons exchanged in a redox reaction; -log[e]
pH	negative logarithm of the hydronium ion concentration in mol/L; -log [H_3O^+]

POE	point of entry
POU	point of use
psi	pounds per square inch
SDWA	Safe Drinking Water Act
s	second
sf	square foot
scfm	standard cubic feet per minute
μg/L	micrograms per liter
VOC	volatile organic compound

DEFINITIONS AND CONVERSION UNITS

Aerosol is a suspension of solid or liquid in air.

Alpha particles are positively charged particles, consisting of two protons and two neutrons. Emitted by decaying radon.

Becquerel (Bq) is a unit of activity in the international system of units (SI) that is equal to one disintegration per second. 1 Bq is equivalent to about 27 pCi.

Concentration Time (CT) is the product of the residual disinfection concentration in mg/L © and the disinfectant contact time in minutes (T). Disinfectant contact time is the time needed for water being treated to flow from the point of disinfectant application to a point before or at the first customer during peak hourly flow (U.S. EPA, 1997).

Curie is a unit of activity that equals 3.7×10^{10} disintegrations/second. 6.48 mg of radon has an activity of one curie.

Dose equivalent is the product of the absorbed dose from ionizing radiation and such factors which account for differences in biological effectiveness due to the type of radiation and its distribution in the body as specified by the International Commission on Radiological Units and Measurements (ICRU).

Henry's Law is p = kc, where p is the partial pressure (in atm) of the gaseous solute above the solution, c is the concentration (in mol/L) of the dissolved gas, and k is a constant (in L-atm/mol) that is characteristic of the particular solution.

Henry's Constant is an indicator of the transfer efficiency of a gas from a liquid solution. It is expressed in atmosphere (atm) or in m^3atm/mole. To convert Henry's Constant from atm to m^3atm/mole, the following equation applies $H_{atm}=H_{m3atm/mole} \times P/RT$, where P is pressure in atmosphere, T is temperature in Kelvin (K), and R is the universal gas constant 8.205×10^{-5} m^3atm/mole.

1 Picocurie = 10^{-12} curies, which is approximately two disintegrations per minute.

Radiation Absorbed Dose (Rad) is a unit representing deposition of energy in matter. One rad equals the deposition of 100 ergs per gram of irradiated material. 100,000 rads are equal to one watt.

Radioactivity is the nuclear transformation of a radioactive substance which occurs in a specific time interval.

Roentgen Equivalent in Man (Rem) is the dose equivalent from ionizing radiation to the total body or any internal organ or organ system that will produce the same biological effect as one rad of high-

penetrating x-rays. It is equal to the absorbed dose in rads multiplied by a quality factor (rem = rad × Q). The quality factor is a measure of the relative biological effectiveness, which depends on the part of the body irradiated and the type of radiation.

Sievert (sv) is an SI unit of dose equivalent from ionizing radiation to the total body or any internal organ or organ system, and is equal to 100 rem.

1 Standard atmosphere = 1 atm = 760 mmHg = 101,325 Pascal = 14.7 lb/in^2

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Introduction

1.0 INTRODUCTION

Radon-222 (radon) is a noble gas that is formed by the radioactive decay of the immediate parent element radium-226. Noble gases (Periodic Group 8A) are inert, odorless, and colorless. Radon-222 undergoes further radioactive decay emitting alpha particles in the process. The half life of radon is about 3.82 days. The decay products of radon, called radon progeny or radon daughters, are short half-life radioactive isotopes that emit alpha and beta particles, and gamma radiation. The concentration of radon dissolved in water is extremely small in comparison to its activity. For example, a volume of water containing 6.48×10^{-10} mg/L of radon gas contains 100,000 pCi/L.

The physical properties of radon are listed in **Table 1-1.**

Table 1-1. Physical Properties of Radon[1]

Molecular Weight	222 gm M^{-1}
Boiling Point	211 K (-62 °C)
Melting Point	202 K (-71 °C)
Solubility in Water	230 cm^3/L @ 20 °C
Air Diffusion Coefficient	1.2×10^{-5} m^2 Sec^{-1}
Water Diffusion Coefficient	1.2×10^{-9} m^2 Sec^{-1}

(1) Chemical Engineer's Handbook 6th Edition (Perry, 1984) and The Merck Index Eleventh Edition (Budavari, 1989).

The rate and amount of gas that transfers in and out of water is greatly impacted by its solubility. Gases either react with water or do not chemically react with water. For gases such as radon which do not react with water, the attraction that water molecules have to themselves opposes solubility since a gas must be more attracted to the water than are other water molecules in order for it to solubilize. Since radon does not bond to water molecules, it is not solubilized. Radon's low solubility and its high vapor pressure mean that it strongly partitions into the air by diffusion.

Since it easily transfers from water to air, radon is rarely found in surface waters and is primarily an issue in ground waters. Radon enters drinking waters supply sources from the decay of naturally occurring radium-226 in the rock and soil matrix. Radon levels can vary greatly from one region to the next because of differences in the local geology. Radon in well water also varies due to local, site specific factors such as well depth, distance from the radon source, pumpage patterns, and the characteristics of the radon source. For example, the relationship between granite bedrock and high radon levels has been observed in sections of the United States and other parts of the world (Michel, 1990; Land and Water Resource Center, 1983; Castren, 1977; Sasser and Watson, 1978). In addition to the relationship between granite bedrock and the occurrence of radon, radon has been detected in thermal springs at concentrations of 100 to 30,000 pCi/L and in regions of phosphate mining (Hess, et al., 1985; Partridge et al., 1979; Smith et al., 1961).

The National Inorganics and Radionuclides Survey (NIRS) conducted by EPA in 1988 indicated that the concentration of radon in ground water supplies ranged from the minimum reporting level of 100 pCi/L to 25,700 pCi/L (Longtin, 1988). Levels of radon in ground water supplies were in the range of 100 to 1,000 pCi/L for 61.5 percent of the 978 sites sampled in the NIRS. The highest levels of radon observed in the NIRS were in small system supplies serving fewer than 500 people. Atoulikian, et al. (1995) estimates that about 83 percent of ground water systems have a radon concentration of less than 500 pCi/L and that about 10 percent of ground water systems have a radon concentration between 500 and 1,000 pCi/L.

The concentration of radon in drinking water may increase or decrease in the distribution system as it travels from the treatment plant to customers. The decay of radon during transit or storage in the distribution system has been shown to generally reduce radon levels by 10-20% (NRC, 1998). However, radon levels in the distribution system can also increase due to the decay of radium that has accumulated in iron-based pipescale (NRC, 1998; Valentine and Stearns, 1994).

Once radon in water supplies reaches consumers, it may produce human exposure via two routes: inhalation and direct ingestion. Radon in water transfers into the air during normal water uses such as showering, flushing toilets, washing dishes, and washing clothes. For inhalation, the

main risk from exposure to radon gas is not from the gas itself, but the radioactive progeny it produces. This is because radon is an inert gas while the progeny are chemically active and associate readily with aerosols (suspension of solid or liquid in air). The aerosols tend to deposit in the lungs where they release radiation that has been shown to increase the likelihood of lung cancer. Radon is second only to cigarette smoking as a leading cause of lung cancer in the United States (U.S. EPA, 1994a).

Some of the radon and its progeny also reach body tissues through ingestion, resulting in radiation exposure to the internal organs. Ingested radon is thought to move from the gastrointestinal tract to the bloodstream, and from there is carried to the liver, lungs, and general body tissue (Crawford-Brown, 1990). Crawford-Brown (1990) notes that studies have shown that radon is generally retained in the body with a half-life of 30 to 70 minutes, and leaves the body mostly through exhalation from the lungs. Ingested radon is believed to increase the risk of stomach cancer and, to a smaller degree, the risk of other cancers, but this is based on indirect evidence (Mills, 1990).

A study prepared for the American Water Works Association Research Foundation (Deb, 1992) examined the effect that reducing waterborne radon concentrations had on indoor air radon concentrations. The study found that a reduction of 1.3×10^{-4} pCi/L of indoor air radon occurred for every 1 pCi/L reduction in waterborne radon (Deb, 1992). For example, a reduction in waterborne radon concentration from 2000 pCi/L to 200 pCi/L (1800 pCi/L reduction, which is 90 percent) would result in a reduction of 0.234 pCi/L in the airborne radon concentration in a home. This relationship corresponds well with those found in other research (Deb, 1992).

1.1 PURPOSE OF THIS DOCUMENT

The objective of this document is to support the EPA Office of Ground Water and Drinking Water (OGWDW) in its preparation of requisite technology and cost documentation for rule development and regulatory impact analysis for the radon rule. This document presents information on various radon removal technologies and techniques and provides information on expected removal efficiencies based on peer reviewed literature and documented case studies. The

technologies and techniques discussed in this document include various aeration technologies, granular activated carbon (GAC), and storage and other best management practices as means to remove and reduce radon in drinking water. This document also provides unit treatment cost estimates for a range of plant sizes, and cost estimate for regionalization. In addition, it provides guidance on how regional cost variations may affect unit treatment cost estimates.

Removal of Radon from Drinking Water

2.0 INTRODUCTION TO TREATMENT TECHNOLOGIES

The feasibility of technologies for radon removal from water is largely determined by radon's chemistry. Other factors include secondary risks from treatment and site-specific considerations (e.g., physical space constraints). Radon is virtually inert, has a short half-life (3.82 days), and is a soluble gas at normal temperature and pressure (20°C, 1 atm). Because of its short half-life, 2 days of storage removes about 30 percent of the initial mass and radioactivity of radon in water by decay alone.

Henry's Law states that the amount of gas that dissolves in a given quantity of a solution, at constant temperature and total pressure, which is directly proportional to the partial pressure of the gas above the solution (Zumdahl, 1989). Henry's Law is expressed by the following equation:

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

where:

p = mole fraction of gas in air = mol gas/mol air

C = mole fraction of gas in water = mol gas/mol water

H = Henry's Law constant = atm

P_T = total pressure = atm (usually = 1).

Since P_T is usually defined as 1, the equation becomes p = HC and H becomes unitless. Thus, H=p/C, and the larger Henry's constant is, the larger the contaminant concentration in air is at equilibrium. When a contaminant is at saturation in both the liquid and vapor phase, the partial pressure of the contaminant is equal to the vapor pressure of the pure material and Henry's Law constant 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 means that a contaminant with lower solubility and/or higher

volatility (i.e., higher vapor pressure) will have a higher Henry's Law constant. (Faust and Aly, 1998)

The Henry's Law constant for radon in water at 20 °C is 2.26×10^3 ATM, or 40.7 L-atm/mole which is equivalent to 5.09×10^{17} pCi/L-atm[3] (Hess et al., 1983). Because of this large Henry's Law constant, radon easily transfers into air above water. At 20°C, ammonia (NH_3) has a Henry's Law constant of 0.76 atm, while carbon dioxide (CO_2) has a Henry's Law constant of 1.51×10^3 atm (AWWA and ASCE, 1998). Radon's relatively high Henry's Law constant indicates that it can transfer from water into the air faster than both ammonia and carbon dioxide, which are readily strippable gases.

If a water storage tank is left open to the atmosphere and undisturbed, the radon-contaminated water will lose virtually all radon through diffusion and decay. Dixon and Lee (1987) noted that, while filling a stand pipe, volatilization and seepage (diffusion) of radon into the air is a far more important factor than the decay of radon. Data from the 2-day experiment show that radon levels in the 0.032 MG steel stand pipe effluent were 15 percent less than the influent radon levels about one hour after pumping well water into the tank. The well water radon levels were in the 4,600 pCi/L range. Aeration hastens the diffusion process by providing a larger air/water surface area and a higher degree of turbulence.

Because of the physico-chemical characteristics of radon and natural processes (e.g., natural diffusion and decay, turbulence), radon levels in surface waters are typically much lower than those found in ground water. Since radon has the above-mentioned properties, options for removing radon from drinking water sources include aeration, adsorption onto another media (e.g., GAC), and storage.

[3] 6.48 mg of radon has an activity of 1 Curie. For conversion of Henry's Constant from atm to L-atm/mole, refer to page iv.

Table 2-1. Summary of Technologies for Radon Removal and Removal Efficiencies

Treatment Method	Percent Removals[1]	Comments
Packed Tower Aeration	78–99.9	– Proven technology – Low maintenance – Pretreatment may be required – Potential emissions concerns – Potential temperature concerns – Potential aesthetic concerns
Diffused Bubble Aeration	71–99.9	– Proven technology – Low maintenance – Low profile and compact – Pretreatment may be required – Potential emissions concerns – Potential temperature concerns
Point of Entry Diffused Bubble Aeration	92–99.9	
Spray Aeration	35–99	– Multiple passes required for high removals – Operational problems in cold conditions
Point of Entry Spray Aeration	82–93	
Slat Tray Aeration	70–94	– Pretreatment may be required – Potential temperature concerns
Low Technology Aeration [2]	10-96	– Footprints maybe larger than those needed for other technologies – Potential temperature concerns
Granular Activated Carbon	70–99	– EBCT of 30–130 minutes (longer than that needed for the removal of taste and odor and volatile organic compounds) – Radiation concerns.

(1) Removals as high as these ranges have been reported in literature.
(2) 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.

Table 2-1 shows various technologies available for the removal of radon. These technologies are water treatment processes within the technical and financial capability of most public water systems. Prior to implementing a technology, site specific engineering studies of the methods identified to remove radon should be performed. The engineering study should evaluate technically feasible and cost effective methods for the specific location where radon removal is required. In some cases a simple survey may suffice, while in other cases, extensive chemical analysis, design, and performance data will be required. The study may include laboratory tests and/or pilot-plant operations to cover seasonal variations, preliminary designs, and estimated capital and operation costs for full-scale treatment. The evaluation of other options, such as point of use/point of entry devices and spraying in storage tanks, as well as best management practices

(BMPs) such as extended atmospheric storage, may be included. Cost estimates for such engineering studies will vary based on factors such as raw water quality, system size, and the number of options.

Radon removal techniques can be divided into three categories:

- Aeration
- Granular Activated Carbon (GAC)
- Simple techniques and best management practices.

The sections that follow in this chapter contain a description of these technologies, discussion of removal efficiencies achieved, issues related to pretreatment, post treatment, and off-gas emissions, and information gathered from treatability/case studies. Simple techniques and best management practices are discussed in Chapter 3.

2.1 AERATION

2.1.1 Process Description

Aeration may be described as the process of bringing air and water into close contact with each other for the purposes of transferring undesirable water constituents to air, oxidizing some natural organic matter (NOM), and improving the treatability of water. Aeration has been used effectively in water treatment to reduce the concentration of taste and odor-producing compounds such as hydrogen sulfide and certain synthetic volatile organic compounds (VOCs), to remove carbon dioxide to reduce corrosivity and lime demand in lime softening treatment, and to oxidize iron or manganese. However, the use of aeration solely for the purpose of controlling radon is a relatively new concept in the drinking water industry.

The driving force for mass transfer of radon from water to air is the difference between the actual concentration in water and the concentration associated 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. Henry's Law ($p=Kc$) states that the amount of gas that dissolves in a given quantity of liquid (c), at constant

temperature and total pressure, is directly proportional (K) to the partial pressure of the gas above the solution (p). Thus, the Henry's Law constant (K) can be considered a partition coefficient which describes the relative tendency for a compound to separate, or partition, between the gas and liquid phases at equilibrium.[4] Aeration is used to increase the speed of the natural process of moving 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 move from water to air by exposing the water to a fresh source of air that has lower concentrations of the substances.

Equilibrium constants for radon and several other compounds which have been found in ground water supplies are presented in **Table 2-2**. 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 readily. Thus, high Henry's Law constant indicates equilibrium favoring the gaseous phase; i.e., the compound generally is more easily stripped from water than one with a lower Henry's Law constant. As shown in Table 2-2, radon has a larger Henry's Law constant than carbon dioxide and trichloroethylene which are known to be easily removed by air stripping.

Table 2-2. Henry's Law Constants for Selected Compounds (20°C)(1)

Compound	Henry's Law Constant(2) ($\frac{atm\text{-}m^3}{mole}$)	Henry's Law Constant(2) 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

(1) To convert from atm-m^3/mole to atm, the following equation applies: H (atm-m^3/mole) × 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).
(2) Hess et al., 1983.

[4] Henry's Law applies to most gases, particularly those that are slightly soluble and do not react with the solvent (e.g., dilute solutions like radon in ground water).

The following factors are key elements in controlling the transfer of volatile substances from water to air and must be considered in the design of aeration systems:

- Contact time (time of exposure)
- Area to volume ratio (available area for mass transfer, air to water ratio)
- Proper dispersal of waste gases into 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 phases)
- Physical chemistry of the contaminant
- Influent concentration of the contaminant
- Water and surrounding air temperatures.

The first three factors are aeration unit dependant, while the last three are contaminant and site specific.

Aeration may also have other effects besides radon and VOC removal. These secondary effects may be either beneficial or adverse and may include the following:

Beneficial

- Removal of hydrogen sulfide and other taste and odor-causing compounds.
- Removal of some carbon dioxide which results in increased pH and lower corrosivity.
- Potential reduction in the amount of chlorine needed to treat water. Since aeration removes sulfide, it can significantly reduce the amount of chlorine needed to oxidize sulfide (Dell'Orco, et al., 1998). However, there may be no net reduction in chlorine dose since aeration also increases pH and thus increases chlorine requirements.
- Partial oxidation of iron and manganese that may be removed by subsequent filtration.

Adverse

- Permitting procedures may be required for off-gas emissions containing radon in some urban locales; although, a properly designed system would not pose a significant risk to the public due to the dispersion of gases containing radon and its progeny (as discussed in Section 2.1.5.2 of this report).

- Increased potential for scaling in the distribution system due to the increase in pH.
- Increased corrosivity due to higher dissolved oxygen levels.
- Need to disinfect treated water and aeration equipment.
- Need to prevent deposition of iron and manganese in the distribution system.

Aeration technologies can be divided into four basic categories:

- waterfall aerators,
- diffusion or bubble aerators,
- mechanical aerators, and
- pressure aerators.

Some of the more common types of waterfall aerators are packed tower/column, spray, tray, cone, and cascade aerators (AWWA and ASCE, 1998). Several aeration technologies can be applied both at water treatment plants to treat full water supplies and at homes as point of entry (POE) devices.

Technologies in the first two categories, including their application as POE devices, and the emerging technologies of gas-permeable membranes and sparging are presented in this section. Some of the technologies in the first two categories, such as spray aeration and cascade aeration, can be applied using simpler structures in what can be considered a low technology manner. Similarly, technologies in the third category can be classified as low technology. These lower technology aeration techniques are described in Section 2.2. Pressure aerators, used to aerate water that is under pressure, are available 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, so they are not discussed further in this document.

2.1.1.1 Packed Tower Aeration

Radon is readily volatilized from water and thus is easily stripped like many VOCs. Packed towers have been shown to be the most efficient form of aeration for VOC removal, therefore packed towers have been applied for radon removal. In countercurrent flow packed towers, packing materials are used which provide high void volumes and high surface area. The water flows downward by gravity while air is forced upward. The untreated water is usually distributed on the top of the packing with sprays or distribution trays and the air is blown up the column by forced or induced draft. This design results in continuous and thorough contact of the water with air and minimizes the thickness of the water layer on the packing, thus promoting efficient mass transfer. The design of air stripping equipment has been extensively developed in the drinking water industry for VOC and hydrogen sulfide removal and in the chemical engineering industry for stripping concentrated organic solutions.

The removal of radon using packed tower aeration is determined by the following factors:

- Air to water (A:W) ratio
- Contact time
- Available surface area for mass transfer
- Surface loading rate
- Physical and chemical characteristics of radon (an inert gas with a high Henry's Law constant)
- Radon concentrations in the influent water and air
- Temperature of the water and the air.

The design of a packed tower aerator plays a major role in establishing the effects of the first four factors, while the last three factors are established by the contaminant, source water, and location of the tower (AWWA and ASCE, 1998).

The air flow requirements for a packed tower depend on the Henry's Law constant for the particular compound(s) to be removed from the water. In a perfect aeration system, the minimum A:W ratio which will achieve complete removal of a contaminant is dependent on Henry's Law

constant. The greater the Henry's Law constant, the less air is required to remove the compound from water. Because aeration systems are not perfect and the contaminant concentration in the feed air may not be zero, actual A:W ratios to achieve a given removal efficiency are greater than the ideal or theoretical relationship between radon removal and the A:W ratio (Spencer and Brown, 1997).

The contact time is a function of the depth and type of the packing material. An increase in the depth of packing material results in a greater contact time between the air and the water, and consequently, higher removals are achieved. The depth of the packing material is determined by the height of the packing in the tower.

The available surface area for mass transfer is a function of the packing material. Various sizes and types of packing material are available including ¼-inch to 3-inch sizes and metal, ceramic and plastic materials. In general, the smaller packing materials provide a greater available area for mass transfer per volume of material thus increasing the mass of contaminant removed. However, the resulting increased pressure drop for air passing through the column must also be considered.

The surface loading rate is the amount of water that passes through the tower and is largely a function of the diameter of the tower and the system design flow. The surface loading rate typically ranges from 25 to 30 gpm/ft^2 (AWWA and ASCE, 1998).

Temperature affects the solubility of radon in water and its Henry's Law constant. As the temperature increases, radon's solubility in water decreases. However, radon, as an inert gas, is not expected to show a large margin of difference in solubility between near freezing temperature and 20°C. Although removal efficiencies usually increase as water temperature increases for packed tower aerators, heating influent water is generally not cost effective (AWWA and ASCE, 1998).

Packed tower aeration can generally be used with systems of all sizes. A typical packed tower installation consists of the following:

- **Packed Tower**—Either metal (stainless steel or aluminum), fiberglass-reinforced plastic, or concrete construction. Internals (packing, supports, distributors, mist eliminators) are generally made of metal or plastic. Packing can be random or structured.

- **Blower**—Typically centrifugal type, either metal or plastic construction. Noise control may be required depending on the size and system location.

- **Effluent Storage**—Generally provided as a concrete clearwell (also called airwell) below the packed tower. Typical storage time is 5-15 minutes of design flow with the higher storage capacity at small systems (U.S. EPA, 1979).

- **Effluent Pumping**—Generally required since effluent is at atmospheric pressure. Vertical turbine pumps mounted on clearwell are typical.

Packed towers are often installed outdoors, potentially creating temperature, aesthetic, and noise concerns. In cold climates, piping should be protected from freezing, especially during low flows that occur during periods of lower demand for water. Fog and surface icing may also be cold weather concerns. Aesthetic problems due to the height and appearance of a packed tower may necessitate special artistic touches and architectural designs. Some large outdoor facilities may need to locate the blowers in a building when noise is a concern. In addition, public perception about off-gas emissions may require a public relations/outreach program.

2.1.1.2 Diffused Aeration

Aeration is accomplished in the diffused-air type equipment by injecting bubbles of air into the water by means of submerged diffusers. Diffusers are usually either porous plates or tubes, or perforated pipes. The older, more traditional applications included a deep tank. The more recently developed diffused-bubble aeration systems include a shallow depth tank. Ideally, diffused aeration is conducted counterflow with the untreated water.[5] 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 produced by the diffusers rise through the water, creating turbulence and providing an opportunity for the transfer of volatile materials. Gas transfer can generally be improved by increasing basin depth, producing smaller bubbles, improving contact basin geometry, and by using a turbine to reduce bubble size and increase bubble holdup (EPA, 1992).

[5] Since some mixing results from aeration, flow is rarely this straightforward.

Diffused aeration generally provides less interfacial area for mass transfer but greater liquid contact time when compared to packed towers (AWWA and ASCE, 1998). Diffused aeration provides an optimum treatment system for the dissolution of a soluble gas in the water (i.e., oxygenation or ozonation), while packed tower aeration provides an optimum system for the removal of volatile contaminants from the water.

A viable option for small and medium sized systems is a variation of diffused aeration technology called multi-stage bubble aeration (MSBA). MSBA units are available commercially. Typical commercial units consist of a high-density polyethylene vessel partitioned into multiple stages with stainless steel and polyethylene divider plates. Each stage is provided 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 typically less than 1.5 ft (compared to depths of 10 to 20 ft for typical aeration basins).

Diffused aeration may be adapted to existing storage tanks and basins. The air diffusers may be placed on the side of the tank to further induce turbulence and assist in gas transfer. When porous plates are used, they are located at the bottom of the tank. If porous tubes or perforated pipes are used, they may be suspended at about one-half depth of the tank to reduce compression heads. Diffusers are designed to produce bubbles of certain sizes. Smaller bubbles create more total area for mass transfer, thus increasing the exchange of volatile substances. When porous diffusers are used, incoming air should be filtered carefully through an electrostatic unit or a filter of metal wool or glass in order to minimize clogging. Static tube aerators have also been used in a variety of applications and have provided adequate aeration when properly designed.

The design of diffused aeration equipment has been developed extensively in the chemical processing industry for handling concentrated organic solutions. The procedures found in the chemical engineering literature can be applied to water treatment for radon. The rate at which radon is removed from water by diffused aeration depends upon many of the same factors as for packed tower aeration:

- Temperature of the water and the air

- Physical and chemical characteristics of radon
- Radon concentrations in the influent air and water
- A:W ratio
- Contact time (e.g., flow rate)
- Available area for mass transfer (e.g., bubble fineness).

The first three factors are fixed by the liquid stream and the contaminant; the last three are dependent upon the equipment and operating conditions and can be evaluated in a pilot testing program.

This technology has a number of advantages and disadvantages relative to packed tower aeration (PTA). The advantages include the potential for modifying an existing basin or storage tank with diffused aeration, and marginal savings due to no packing costs, reduced pumping costs, and generally lower energy costs. MSBA in particular offers the advantage of being compact and thus is favorable for aesthetic reasons and often involves lower building costs. The disadvantages include the requirement of increased contact time (which could rule out the use of a given modified basin or storage tank), the possibility of needing a greater A:W ratio, and overall less efficient mass transfer. MSBA is also limited in treating larger flows.

2.1.1.3 Spray Aeration

Spray aerators direct water upward, vertically, or at an inclined angle, in such a manner that the water is broken into small drops. Installations commonly consist of fixed nozzles on a pipe grid. The small droplets formed expose a large interfacial surface area through which the radon migrates from the liquid phase to the gaseous phase.

Design factors that impact the effectiveness of spray aration include:

- Nozzle design and operating pressure (e.g., velocity of spray)
- Nozzle orientation (e.g., size, number, and spacing of multiple spray nozzles; nozzle trajectory)
- Distance of water droplet free fall
- Water droplet size

- Amount of ventilation (including the effects of wind on the movement of rising and falling water droplets).

Although the use of many small spray nozzles that each produce very small water droplets may provide the greatest area-volume ratio (i.e., most available area for mass transfer), these small nozzles tend to clog and require high maintenance. Spray aerator nozzles generally have a diameter of 1.0–1.5 in., discharge ratings of 75–150 gpm (at about 10 psi), and are installed every 2–12 feet apart. (AWWA and ASCE, 1998)

Spray aeration, like diffused aeration, has a number of advantages and disadvantages in comparison to other aeration technologies. The advantages include the capability of achieving efficient mass transfer due to the small water droplets created by the fixed nozzles, the lack of any packing costs, and potentially lower maintenance costs. The disadvantages include the need for a large operational area, which translates into increased building construction costs, potentially increased operating problems during the cold weather months when the temperature is below the freezing point, short exposure time between air and water, and high pressure requirements (AWWA and ASCE, 1998).

2.1.1.4 Tray Aeration

A slat tray or multiple tray aerator consists of a series of trays (usually 3–9 trays spaced 12–30 in. apart) equipped with slats, or perforated or wire-mesh bottoms, over which water is distributed and allowed to fall to a collection basin at the base of the unit. Distribution of the water over the entire tray area is important from an efficiency standpoint. In many tray aerators, coarse media such as coke, stone, or ceramic balls ranging from 2 to 6 inches in size are placed in the trays to improve the efficiency of gas exchange and distribution. Radon removal occurs as the water falling through the trays contacts air and radon is transferred from the water to the air. Air can be supplied to tray aerators either with a natural draft or a forced draft from a blower.

A cascade tray aerator is essentially a slat tray aerator without a blower to force air through the aerator. Instead, the water is allowed to flow over the trays and fall to a basin through naturally induced air.

If tray aerators are placed in a poorly ventilated building, performance will be impaired and operator safety may be of concern. Artificial ventilation is a requirement under these conditions. Artificial ventilation is provided in certain types of tray aerators by enclosure and provision of a forced draft. Such aerators generally employ the countercurrent flow principle. The air is supplied at the bottom of the aerator enclosure by a blower and travels upward through the aerator counter to the downward flow of the water. The counterflow of air and water is advantageous, and such aerators have shown excellent oxygen absorption and carbon dioxide removal capabilities. More research is needed to determine how the use of counterflow impacts radon removal capabilities.

Another variation of this technology is shallow tray aeration, where the primary component is a shallow tray module that has one to six compartments or stages of limited depth (e.g., 18 to 30 inches). Water is pumped through the module as air is pumped in through diffusers at the bottom. Since these units are generally modular, they are compact (yielding a smaller footprint) and are considered relatively simple to install for both retrofits and new construction.

A type of multiple tray aerator, the crossflow tower, has been extensively utilized in cooling applications. In this system, water is allowed to fall over the tray area while air is forced or induced to flow across the slats perpendicular to the water path. In some crossflow columns, air is drawn in from the sides and expelled out the top of the aerator. This type of column is actually a hybrid of the countercurrent and crosscurrent units. The reviewed literature did not provide data on radon removal rates for crossflow tower tray aerators.

Tray aerators can generally be used with systems of all sizes. One disadvantage of tray aerators is that slime and algae can grow on the trays, possibly necessitating the addition of copper sulfate or chlorine to control growth (NRC, 1997).

2.1.1.5 Point of Entry (POE)/Point of Use (POU) Devices

Point of entry (POE)/Point of use (POU) treatment devices are installed at residences where only household water is treated. POU systems generally treat only water used for drinking and cooking, while POE systems treat the entire supply entering a household. POU treatment is provided at the tap by devices that can be faucet mounted or with line-bypass units. As the name implies,

faucet-mounted units are devices which attach to an existing faucet. Line-bypass units supply treated water to a special tap or third faucet which is usually located at the kitchen sink. These treatment devices themselves are generally located under the sink and are usually larger and treat a greater volume of water than faucet-mounted units. POE devices can be installed in the basement or outside the home. The health risk associated with airborne radon would necessitate that all of the water entering a house be treated for radon removal. Therefore, a POE system would be more appropriate than a POU treatment device from an exposure standpoint.

Diffused bubble, bubble plate, and spray aeration are adaptable to individual family homes or, in some cases, buildings serving more than one family, or a small community. Packed tower aeration is not generally used in POE systems because of its greater cost and aesthetic and installation concerns due to tower height. MSBA and shallow tray aeration can be installed as POE systems, but may be cost prohibitive. POE devices may require pretreatment and post treatment to avoid operational problems.

POE treatment devices provide a technically feasible alternative to centralized treatment facilities, and may be more economical than a central treatment system. POE treatment may be most economically competitive in very small water systems where the economies of scale for the larger centralized facilities are not apparent. Another advantage of POE treatment is the small capital investment relative to centralized treatment for many technologies. In some cases, POE treatment may provide more effective contaminant reduction than the use of a central treatment system.

However, even though as a treatment technology POE devices may be capable of removal efficiencies equal to those achieved with full scale systems, this treatment alternative has some disadvantages. These include:

- Increased complexity of controlling treatment, monitoring, maintenance, and regulatory oversight of the devices.
- Concern for possible bacterial colonization on the treatment devices.
- Potential for high operation, monitoring, and maintenance costs.
- Standards have only been developed for a limited number of POE devices.

- Potential for radiation hazards at homes.
- Liability associated with failure of the devices.

Responsibility for the use of POE devices rests with the public water system. The Safe Drinking Water Act (SDWA), as amended in 1996, specifies that POE and POU treatment units "shall be owned, controlled and maintained by the public water system or by a person under contract with the public water system to ensure proper operation and maintenance and compliance with the maximum contaminant level or treatment technique and equipped with mechanical warnings to ensure that customers are automatically notified of operational problems." (SDWA, Section 1412(b)(4)(E)(ii))

Standards and a certification program for some POE devices have been developed by the National Sanitation Foundation (NSF International). Initially prompted by State drinking water administrators (and later by U.S. EPA), NSF began developing standards and a certification program for the contaminant reduction claims (both health and aesthetic) made by manufacturers. NSF is currently working on standards for GAC POE devices. Manufacturers can submit their products and product information to NSF to apply for certification. (NSF, 1998)

The Water Quality Association has also developed a certification program, however, its equipment assessments are not independent since it is a trade association for POE and POU equipment manufacturers. Regulations for certifying POE devices have been developed by several States. California only allows POE devices to be installed when other alternatives have been evaluated and determined to be infeasible. (NRC, 1997)

2.1.1.6 Cone Aeration

Cone aerators consist of a stack of pans, with inverted cone-shaped protrusions extending from the bottom of each pan. Water fills the top pan, then drains down through the inverted cones to cascade down to the succeeding pan. As water flows through the inverted cones (wider at the top, narrower at the bottom), it increases in velocity and splashes down onto the pan below, generating

bubbles and greater contact with the air. A review of literature did not find any studies using cone aerators for radon removal.

2.1.1.7 Gas-Permeable Membrane Aeration

Gas-permeable membranes have the potential to achieve the highest removal efficiencies, but their long-term performance has not been sufficiently evaluated to consider this technology more than emerging. For this technology, water flows through tubes made of highly porous fiber membranes that allow gases but not liquids to escape. The membranes provide a very large area for air and water contact compared to other aeration systems of similar size and thus may prove to be very efficient for removal of both semivolatile and volatile organic chemicals. (NRC, 1997) At this point, no literature is available on the application of gas-permeable membrane aeration for radon removal.

2.1.1.8 Air Sparging

Air sparging is the injection of pressurized air into water reservoirs or directly into well water or an aquifer. For reservoir sparging, air is injected, under pressure, near the bottom of the reservoir, creating air bubbles in the reservoir. Radon is transferred from the reservoir water to the air bubbles and then carried to the surface by the air bubbles and released to the atmosphere. For aquifers and wells, air is injected under pressure below the water table. The air bubbles, pushing in three dimensions through the soil column, carry radon into the vadose zone. From the vadose zone, radon migrates to ground surface and continues its movement into the atmosphere.

Like air stripping and diffused bubble aeration, air sparging will volatilize radon. Radon removal efficiency using air sparging varies and depends on the amount and pressure of the air injected, reservoir or well column depth, surface area of water in direct contact with the atmosphere, and venting conditions in the reservoir or well column. Design of an air sparging system may require pilot tests to determine the radius of influence of the air sparging point(s) and the effectiveness of the system. For reservoir sparging, design of the air sparging system requires knowledge about reservoir venting, water inlet and outlet conditions, and mixing conditions. For

aquifer sparging, design of the air sparging system requires knowledge about the hydrogeology of the aquifer.

Some of the complications from air sparging include biological growth and precipitation of metals, particularly in hard or iron and manganese-containing ground waters. Water sparged with air maintains high dissolved oxygen which enhances biological growth. Biological growth might create water quality problems including the formation of slime material and odor and color problems. Air sparging also enhances precipitation of metals, which may cause pitting and corrosion of the pump and motor. Moreover, pressurizing air and delivering pressurized air to water in wells, aquifers, and reservoirs is energy demanding.

The application of air sparging to well ground water for radon removal has been limited. Experimental trials have not been encouraging because of the problems mentioned above (Hess, 1998). A feasibility study of in-well aeration conducted by the North Penn Water Authority found this treatment technology to have relatively low efficiency and identified several disadvantages, including causing the water to appear milky as a result of dissolving large quantities of air into the water (AWWA and ASCE, 1998).

2.1.2 Removal Efficiency and the Effect of Key Design Criteria

Reviewed studies on aeration technologies provide data on removal efficiencies for radon. These data are summarized in **Table 2-3**. Removals for packed tower aeration ranged from 78.6 to greater than 99 percent, with most removals reported at 90 percent or greater. For the two diffused bubble aeration facilities, removal efficiencies were 93 and 95 percent. Removal efficiencies for multi-staged bubble aerators ranged from 71 to 100 percent. These studies showed wide variation in removal efficiencies for spray aerators, with removals ranging from 35 to 99 percent depending on operating conditions. For tray aeration, the studies evaluated reported radon removals of 70 to 99 percent. POE systems using diffused bubble and multi-stage diffused bubble aerators technologies achieved radon removals of 92 to 99.9 percent. Spray aerators installed in homes have shown radon removals of 82 to 93 percent.

Table 2-3. Removal Efficiency Data for Aeration Technologies

Source	Influent Radon Level (pCi/L)	Source WQ Parameters	System Design, Size, and Other Design Parameters	Removal Efficiency	Comments
Packed Tower Aeration					
AWWSC (1989)	1,700–2,700	VOCs also analyzed	Packed tower of 23-inch diameter, 16 feet high, packing depth – 10 feet; tower has an orifice type water distributor, stainless steel knitted-mesh mist eliminator, expanded aluminum support tray; packing material of 2-inch polypropylene Jaeger tripacks; blower powered by gas engine to provide air volumes of up to 600 cubic feet per minute; can aerate water directly from well pump or subsequent to a treatment process	93–98% for loading rates of 25.5 and 50 gpm/sf and A:W ratios of 3:1, 8:1, 12:1, 30:1	– Tested on water drawn from 1 well – Similar removals at all A:W ratios; – Packing height had greatest effect on removals; – Strong correlation between concentration of CO_2 and radon in raw and treated water, so CO_2 could be a surrogate for testing radon removal; – Minimal maintenance; several possible retrofitting options; lack of redundancy causes service stoppage; aesthetics concerns
Drago (1998)	NA	NA	Packed tower – 9 to 9,000 gpm flow rate – 2.6 to 13 min detention time	79–99+%	11 systems evaluated Compact system, but aesthetic concerns due to tall towers (some >25 ft)
Lenzo (1990)	1,500	NA	Packed tower – 450 gpm flow – 14 ft high, 5 ft diameter – 0.5 blower horsepower	90%	Design recommendations for full-scale system based on results of pilot test; Packing bed depth is key factor in determining removal efficiency
Lenzo (1990)	1,400	NA	Packed tower – 350 gpm flow – 14 ft high, 5 ft diameter – 0.33 blower horsepower	90%	Design recommendations for full-scale system based on results of pilot test; Packing bed depth is key factor in determining removal efficiency
Lenzo (1990)	3,000	25 µg/L of tetrachloro-ethene (PCE)	Packed tower – 450 gpm flow – 21 ft high, 5 ft diameter – 0.75 blower horsepower	95% 96% removal of PCE	Design recommendations for full-scale system based on results of pilot test; Packing bed depth is key factor in determining removal efficiency
Hodsdon (1993)	1750	NA	Packed tower – tower 33+ ft tall – supply capacity 450 gpm – counter current flow	99+% (effluent <15 pCi/L)	System designed and installed for VOCs Avg daily consumption 87,000 gpd Gas chlorination disinfection

Table 2-3. Removal Efficiency Data for Aeration Technologies (Continued)

Source	Influent Radon Level (pCi/L)	Source WQ Parameters	System Design, Size, and Other Design Parameters	Removal Efficiency	Comments
Hodsdon (1993)	4,621 avg (1,143-10,244)	NA	Packed tower – supply capacity 365 gpm – concurrent flow	94.2% (effluent = 268 pCi/L)	Avg daily consumption 150,000 gpd Liquid disinfection
Hodsdon (1993)	9,000	NA	Packed tower – supply capacity 75 gpm – counter current flow	99% (effluent=90-100 pCi/L)	Avg daily consumption 14,000 gpd Chlorine hypochlorite disinfection
Hodsdon (1993)	1,400	NA	Packed tower – supply capacity 85 gpm – counter current flow	78.6% (effluent=300 pCi/L)	Avg daily consumption 46,000 gpd Liquid chlorine disinfection 3 bag filters installed to remove precipitated iron (result of radon retrofit) Water passes through ion exchange unit before tower to reduce iron and hardness
Hodsdon (1993)	3,150–3,750	NA	Packed tower – supply capacity 150 gpm – 33 ft tower height – counter current flow	99+% (effluent <15 pCi/L)	Avg daily consumption 82,000 gpd Gas chlorination disinfection Major retrofit to existing system
Hodsdon (1993)	2,200	NA	Packed tower – supply capacity 9 gpm – counter current flow	86.4% (effluent =300 pCi/L)	Avg daily consumption 5700 gpd Liquid chlorine Retrofit for radon removal 2 bag filters remove precipitated iron after tower Water passes through ion exchange unit before tower to reduce iron and hardness
Hodsdon (1993)	1,208–1,473	NA	Packed tower – supply capacity 400 gpm – concurrent flow	94% (effluent = 83 pCi/L)	Avg daily consumption 240,000gpd Chlorination Retrofit for CO2 removal
Hodsdon (1993)	1,575–1,790	NA	Packed tower – supply capacity 450 gpm – concurrent flow	89% (effluent = 198 pCi/L)	Avg daily consumption 300,000-400,000 gpd Chlorination Major retrofit for radon removal & storage – new high lift station & clearwell

Table 2-3. Removal Efficiency Data for Aeration Technologies (Continued)

Source	Influent Radon Level (pCi/L)	Source WQ Parameters	System Design, Size, and Other Design Parameters	Removal Efficiency	Comments
Diffused-Bubble Aeration – Multi-Stage					
AWWSC (1989)	1,700–2,700	VOCs also analyzed	Multi-stage bubble aeration system – diffused aeration system of rotomolded polyethylene, capable of treating 150 gpm; 6.5 ft long, 2 ft wide, 3 ft high; 5 stainless steel partitions inside to achieve a staged-flow regime and 6 aerator assemblies; can aerate water directly from well pump or subsequent to a treatment process	97–100% for flows of 50 gpm at A:W ratios of 33.2:1, 22.2:1, 11.1:1 and 100 gpm at 16.6:1, 11.1:1; 86% for flow of 100 gpm at 5.5:1	Tested on water drawn from 1 well; Strong correlation between concentration of CO2 and radon in the raw and treated water so CO_2 could be a surrogate for testing radon removal; minimal maintenance; redundancy possible with standby blowers
Drago (1998)	NA	NA	Multi-stage bubble aeration -12 to 1,200 gpm flow rate - 0.6 to 7.6 min detention	71–99+%	8 systems evaluated Less compact than PTA
Lowry (1990)	2,000	NA	Stripper Aeration Model PS25 (multi-stage diffused bubble aerator) – 1 to 30 gpm flow rate – 1 module – A:W of 6.7	90%	At A:W=10, effluent is 100 pCi/L (instead of 200)
Lowry (1990)	2,000	NA	Stripper Aeration Model PS150 (multi-stage diffused bubble aerator) – 31 to 325 gpm flow – 1 module – A:W of 5.7	90%	At A:W=8, achieve effluent of 100 pCi/L (instead of 200) up to 230 gpm
Lowry (1990)	2,000	NA	Stripper Aeration Model PS150 (multi-stage diffused bubble aerator) – 326 to 650 gpm flow – 2 modules – A:W of 5.7	90%	For A:W $\leq$4.2, single PS150 can go up to 450 gpm; For each additional modules, can get 200 pCi/L for up to 325 gpm more
Wright Pierce (1998)	5,400$\pm$100	NA	- Capacity of 350 gpm -A:W of 11.26	97%	Avg daily consumption 100,000 gpd Sodium hypochlorite for disinfection

Table 2-3. Removal Efficiency Data for Aeration Technologies (Continued)

Source	Influent Radon Level (pCi/L)	Source WQ Parameters	System Design, Size, and Other Design Parameters	Removal Efficiency	Comments
Wright Pierce (1998)	800±100	NA	-Capacity of 450 gpm -A:W of 6.77	89%	Avg daily consumption 250,000 gpd Sodium hypochlorite for disinfection
Diffused-Bubble Aeration – Single Stage					
Drago (1998)	NA	NA	Diffused bubble aeration – 79 gpm flow rate – 60 min detention	93%	1 system evaluated Significantly longer detention time than MSBA
Hodsdon (1993)	20,000	NA	Diffused aeration – supply capacity 60 gpm – 3 clearwells, 2 w/diffusers supplied by a single blower	95% (effluent=1000 pCi/L)	Avg daily use 45,700 gpd Chlorination Retrofit
Spray Aeration					
Drago (1998)	NA	NA	Spray aeration – 173 gpm flow rate	88% (theoretical based on VOC removal data)	1 system evaluated Low technology for moderate removal
AWWSC (1989)	1700-2700 3700-4600	VOCs also analyzed	Turbojet air stripping system – pressurized water stream enters perpendicular to the main body of the unit while air enters at one end, causing mixing of air and water and stripping – third trial evaluated removal efficiency under four conditions: single pass through the Turbojet, multiple passes (water is circulated through the unit several times), remote mountings of Turbojet (nondirect discharge into a collection vessel), decrease in flow rate with increase in A:W to 27.4:1.	76% at 6:1 A:W (effluent of 473 pCi/L); 89% – for A:W varied from 3:1 to 17:1 (effluent of 203 pCi/L ±40 pCi/L); 68% – 1 pass @ A:W of 26.8:1, 99% – 4 passes, 35% – remote mounting, 69% – 1 pass A:W 27.4:1	3 sets of tests on water drawn from 2 wells; orifices plugged by iron and iron carbonate compounds lowered removals on last 2 days of sampling Varying the A:W ratio from 3:1 to 17:1 only had a marginal effect on radon removal (87% removal to 91% removal)

Table 2-3. Removal Efficiency Data for Aeration Technologies (Continued)

Source	Influent Radon Level (pCi/L)	Source WQ Parameters	System Design, Size, and Other Design Parameters	Removal Efficiency	Comments
Slat Tray Aeration					
Drago (1998)	NA	NA	Slat tray aeration – 365 to 450 gpm flow rate – 3.3 to 10 min detention	86–94%	6 systems evaluated Less compact than PTA, but shorter towers
US EPA (1988)	NA	NA	Slat tray aerators – 1 of 3 has a cascade aerator – used for oxidation of iron and manganese	77–91% (80–81% for cascade aerator)	Data from 3 sites
Brown (1995)	283±12	NA	Induced draft tray aerator – aluminum unit 1 ft, 9 in square, 14 ft high – internals: 10 ft of triangular PVC slats on 4 in. vertical centers – 15 to 150 gpm flow – 2,550 cfm capacity for 0.5 hp induced draft blower	89.8% @ A:W of 3:1 92.2% @ A:W of 4.5:1 91.9% @ A:W of 6:1	Manufacturer noted that removals were higher than expected based on calculated values of 65%
Brown (1995)	496±16	NA	Forced draft tray aerator – aluminum unit 8 in square and 7 ft 2 in. high – internals: 7 ft of redwood slats on 2 in. vertical centers – 0 to 5 gpm flow – A:W of 3:1 – forced draft blower of 1/30 hp with capacity of 110 cfm @0.5 in and 30 cfm @0.9 in static pressure – 17.5 gpm/sf loading rate	93.8%	Manufacturer noted that removals were higher than expected based on calculated values of 65%
Shallow Tray Aeration					
Hodsdon (1993)	4,800	NA	Shallow tray aeration[1] – supply capacity 440 gpm – 3 shallow tray system – air filtered before passing through water and is vented directly to outside air after use	95% (effluent =196 pCi/L)	Avg daily use 180,000gpd Sodium hypochlorite disinfection Put in w/new groundwater supply-pumping & separate clearwell added

Table 2-3. Removal Efficiency Data for Aeration Technologies (Continued)

Source	Influent Radon Level (pCi/L)	Source WQ Parameters	System Design, Size, and Other Design Parameters	Removal Efficiency	Comments
Hodsdon (1993)	NA	NA	Shallow tray aeration[1] – supply capacity 12 gpm – air filtered before passing through water and is vented directly to outside air after use	99%	Avg daily use 9,000 gpd Chlorine disinfection Part of new groundwater supply-pumping & separate clearwell added
Hodsdon (1993)	550 avg (450–600)	NA	Shallow tray aeration[1] – supply capacity 25 gpm – single treatment unit – air filtered before passing through water and is vented directly to outside air after use	70% (effluent=160 pCi/L)	Avg daily use 3,000 gpd Sodium hypochlorite disinfection Part of new groundwater supply system
Hodsdon (1993)	2,194 avg (2,000–2,200)	NA	Shallow tray aeration[1] – supply capacity 39 gpm – single treatment unit – air filtered before passing through water and is vented directly to outside air after use	95% (effluent=108 pCi/L)	Avg daily use 5,400 gpd Sodium hypochlorite disinfection Part of new groundwater supply system
Hodsdon (1993)	5,200 avg (4,500–6,000)	NA	Shallow tray aeration[1] – supply capacity 375 gpm – 3 shallow tray system – air filtered before passing through water and is vented directly to outside air after use	96% (effluent=200 pCi/L)	Avg daily use 250,000 gpd Sodium hypochlorite disinfection Part of expanded groundwater supply
Hodsdon (1993)	8,810	NA	Shallow tray aeration[1] – supply capacity 25 gpm – single treatment unit – system is 8'wide × 15' long and includes a water softener (for manganese removal), shallow tray aerator, polyethylene tank used as a clearwell, high lift pumps, and hydropneumatic tanks	97% (effluent=200 pCi/L)	Avg daily use 2,500 gpd No disinfection Part of new water supply

Table 2-3. Removal Efficiency Data for Aeration Technologies (Continued)

Source	Influent Radon Level (pCi/L)	Source WQ Parameters	System Design, Size, and Other Design Parameters	Removal Efficiency	Comments
Hodsdon (1993)	1,800 avg (1,600–2,000)	NA	Shallow tray aeration[1] – supply capacity 720 gpm – 4 shallow tray system – air filtered before passing through water and is vented directly to outside air after use	91% (effluent=160 pCi/L)	Avg daily use 720,000 gpd Sodium hypochlorite disinfection Part of new groundwater supply Pumping & separate clearwell added
Slatted Tray Tower Aeration					
Hodsdon (1993)	900	NA	Slatted tray towers – 2 redundant towers w/ total supply capacity of 800 gpm – counter current flow – A:W of 50:1 – 8'×8'×10' towers with redwood horizontal slats (not packed media)	92% (effluent = 75 pCi/L)	Avg daily use 145,000gpd Gas chlorination disinfection Towers installed to remove H_2S
Hodsdon (1993)	900	NA	Slatted tray tower – supply capacity 435 gpm – tower is specially built unit w/wooden horizontal slats instead of packed media	67% (effluent=298 pCi/L)	Avg daily use 40,000 gpd Liquid chlorine disinfection before stripper Slat tower first put in for hydrogen sulfide removal
Cascade Aeration					
Hodsdon (1993)	1261	NA	Cascade (splash) aeration – supply capacity 1,000 gpm – water cascades down a set of wood steps that create a 1 ft drop	81% (effluent=236 pCi/L)	Avg daily use .7–1.0 mgd Chlorination, polyphosphate, fluoride disinfection Low technology
POE Aeration					
Lowry et al. (1988)	20,000–500,000	NA	Multi-staged diffused bubble POE aeration system (Stripper model) – 3 stages (compartments) in 1 module	92–99.9% 99.5–100% for 0–10 gpm flow (98% for tests run @ flows up to 20 gpm, 0.5 hp blower, A:W of 15.7)	22 prototype systems installed and monitored Multiple modules can be used to achieve higher removals at greater flows

Table 2-3. Removal Efficiency Data for Aeration Technologies (Continued)

Source	Influent Radon Level (pCi/L)	Source WQ Parameters	System Design, Size, and Other Design Parameters	Removal Efficiency	Comments
Kinner et al. (1993)	35,620±6,727 avg (22,837-54,765)	NA	POE diffused bubble aerator – vessel with 3 compartments in series, each with an internal diffuser from a common header – .02 in diameter holes variably spaced – A:W of 119/1 for water flow rate = 2.3 gpm and air flow rate =38 cfm	>99%	Effluent ≤ 200 pCi/L even when air flow rate restricted due to iron precipitation accumulated on diffusers For very high concentrations, monitoring may be needed to see if higher A:W (more dilution) or treatment of off gas is needed Iron oxidation occurs readily – leads to precipitation and release or gradual decrease in air flow rate, so iron treatment probably required More expensive O&M than GAC, extra pump needed for repressurization, blowers possibly needed for ventilation (noise issue)
Kinner et al. (1993)	35,620±6,727 avg (22,837–54,765)	NA	POE bubble-plate aerator – 315cfm capacity blower to direct air through .19in diameter holes spaced .75in apart – A:W ratio = 156/1, water flow rate = 6.0gpm, air flow rate of 125cfm	>99%	Problem with clogging of air intake filter for blower For very high concentrations, monitoring may be needed to see if higher A:W (more dilution) or treatment of off gas is needed Iron oxidation occurs readily – leads to precipitation and release or gradual decrease in air flow rate, so iron treatment probably required More expensive O&M than GAC, extra pump needed for repressurization, blowers possibly needed for ventilation (noise issue)

[1]For the Hodsdon (1993) study, shallow tray aerators were defined to consist of a shallow tray module with an aeration component of 18 to 30 in. depth. The module could have a single aerator compartment or could be divided into as many as 6 stages.

2.1.2.1 Packed Tower Aeration

Packed tower aeration can achieve very high removals of radon ranging from 90 percent to higher than 99.9 percent. The design parameters that affect the removal of radon include packing height, A:W ratio, packing type, and loading rate. Systems installing packed tower aeration should also consider issues such as pretreatment, additional disinfection requirements, and pump retrofitting (discussed in Sections 2.1.3 and 2.1.4).

Effect of Packing Height—Packing height is the most critical design parameter for radon removal (Dixon et al., 1991; Cummins, 1988). Dixon et al. (1991) suggest a minimum packing height of 10 feet.

Effect of A:W Ratio—The removal of radon is not very sensitive to A:W ratio as long as the ratio is sufficiently high. Typical A:W ratios for packed towers in drinking water treatment plants range from 30:1 to 100:1 (AWWA and ASCE, 1998). Cummins (1988) noted radon removals drop rapidly for A:W ratios lower than 2:1. Kinner et al. (1988) observed that radon removal efficiencies were similar at A:W ratios of 5:1, 10:1, and 20:1, and were only slightly lower for an A:W ratio of 2:1, so increasing the A:W ratio beyond the range of 2:1 to 5:1 impacted removals very little. Kinner et al. (1988) also noted that using an A:W ratio of 1:1 provided a significantly lower removal. Dixon et al. (1991) showed that radon removal is not sensitive to A:W ratio. Dixon et al. (1991) reported radon removals greater than 93 percent for an A:W ratio of 3:1 and a packing height of 10 feet. Based on Dixon et al. (1991), an A:W ratio of 5:1 should be sufficient for obtaining high radon removals. More recent research on radon removal efficiencies shows that radon removal is sensitive to the A:W ratio over a wider range of ratios than reported above. Spencer and Brown (1997) showed that radon removals tend to level off at an A:W ratio of about 10:1, and that increasing the A:W above 10:1 has minimal effect on radon removal. According to Spencer and Brown (1997), the theoretical A:W ratio necessary to remove more than 90 percent of the radon from water is about 5:1, while the practical A:W ratio is 6.5:1 for 90-percent removal. An A:W ratio of 19:1 should be sufficient to remove nearly 100 percent of the radon, as shown in **Figures 2-1** and **2-2**.

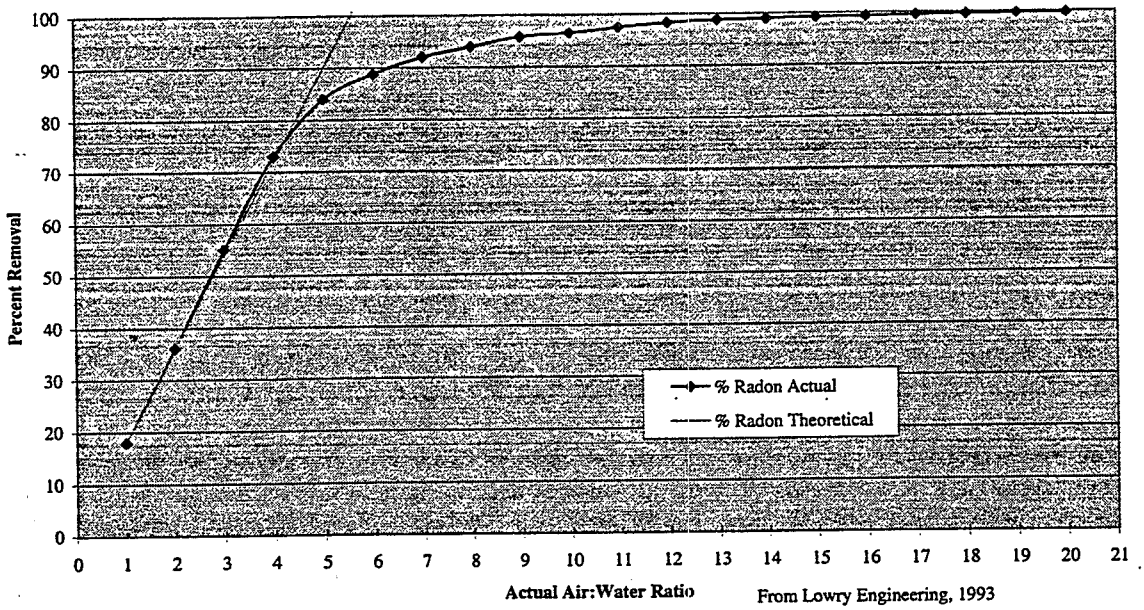


Figure 2-1. Practical Radon Removal with Increasing Air:Water Ratio for PTA (Source: Spencer and Brown, 1997)

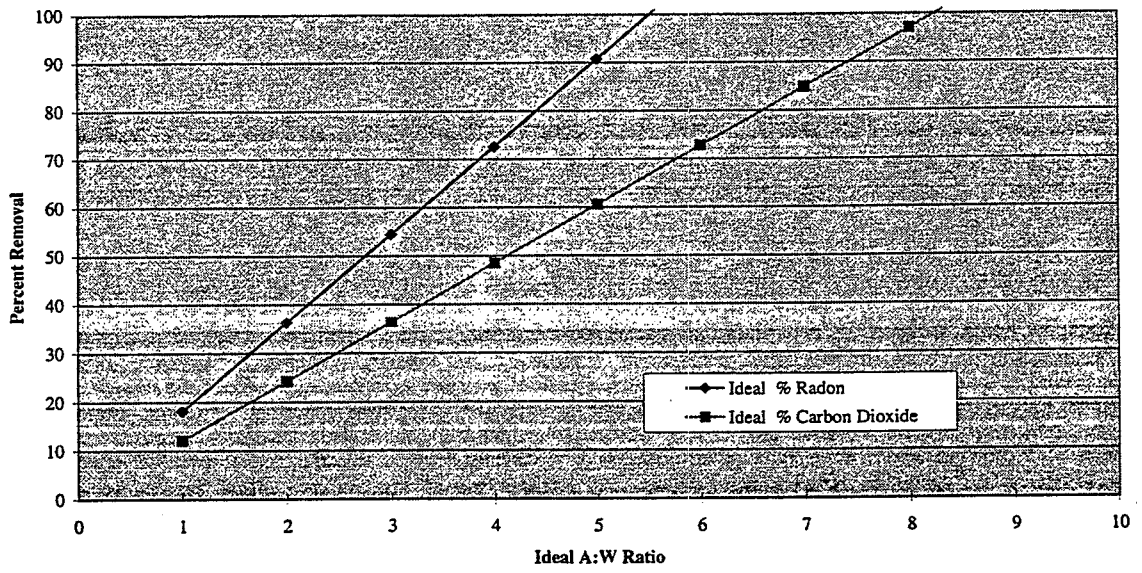


Figure 2-2. Theoretical Radon Removal with Increasing Air:Water Ratio for PTA (Source: Spencer and Brown, 1997)

Effect of Packing Type—Kinner et al. (1988) observed that radon removals with saddle packing were slightly lower than removals achieved with pall rings; however, radon removals were above 90 percent with either packing type for a similar packing height and A:W ratio.

Effect of Loading Rate—Dixon et al. (1991) reported high removals of radon at loading rates of 50 gpm/sq ft. However, in order to prevent potential flooding, a loading rate of 25-30 gpm/sq ft may be a practical limitation.

Other Considerations—Other considerations such as pretreatment for iron and manganese removal, additional disinfection requirements, and pump retrofitting are relevant to ground water systems that currently do not have any treatment in place. These factors are discussed in Sections 2.1.3 and 2.1.4. In addition, if the treatment facilities are located indoors, dehumidification and ventilation needs must be addressed.

2.1.2.2 Diffused Bubble Aeration

Diffused bubble aeration (DBA) can achieve very high removals of radon ranging from 71 to >99 percent, with removals often greater than 90 percent. The design parameters that have been studied for their effect on the removal of radon for this technology include the A:W ratio and flow rate. Systems installing DBA should also give consideration to pretreatment, disinfection, and pump retrofitting requirements.

The removal of radon by MSBA does not vary significantly with A:W ratio and flow rate (Dixon et al., 1991). A slight increase in radon removal occurred by increasing A:W ratio or decreasing the flow rate. According to Dixon et al. (1991), designs of MSBA permit a maximum flow of 800 gpm for radon removals greater than 95 percent, and 1,800 gpm for removals of less than 85 percent. Industry brochures claim treatment capacity of more than 1,000 gpm (Lowry Engineering, 1989).

2.1.2.3 Spray Aeration

Kinner et al. conducted pilot tests using spray aeration and reported the following removal efficiencies (U.S. EPA, 1988), presented in **Table 2-4.**

Table 2-4. Radon Removal for Spray Aeration Pilot Tests

Detention Time (hr)	Percent Removal of Radon	
	Decay	Total
9	7	63–73
12	9	62–65

Dixon et al. (1991) noted that variations in A:W ratio had a negligible effect on radon removal efficiency. Dixon et al. achieved 77-percent radon removal rates using a baffled steel tank with a flow of 70 gpm, an A:W ratio of 6:1, and a detention time of 20 minutes. For the same system with a flow of 50 gpm, Dixon et al. achieved radon removals of 83-91 percent for A:W ratios ranging from 3:1 to 17:1 (removal was 88 percent at A:W ratio of 6:1). Further investigation is needed to assess how removal efficiency is affected by design parameters, including water drop size, spray height, and ventilation.

2.1.2.4 Tray Aeration

Radon removals across tray aerators at three different plant sites are reported in a 1987 report by the American Water Works Service Company, Inc. Each of the plants use tray aerators for the oxidation of iron and manganese, with one site using a slat tray cascade aerator. The radon removal efficiencies of the aerators were between 77 and 91 percent. The site with the cascade aerator achieved 80- to 81-percent radon removal (U.S. EPA, 1988).

Other studies have shown radon removals of 86 to 94 percent for slat tray aerators with flow rates of 365–450 gpm and detention times ranging from 3.3–10 minutes (Drago, 1998). Brown (1995) reported radon removals of 89.8 to 93.8 percent for two pilot test systems. One pilot system contained an inducted draft aerator that was tested at A:W ratios ranging from 3:1 to 6:1; the radon removals were similar for all three A:W ratios. The second system was a forced draft aerator with an A:W ratio of 3:1 and a hydraulic loading rate of 17.5 gpm/sf (Brown, 1995).

For shallow tray aerators, the key design parameters are residence time and A:W ratio. Radon removals of 90 percent and higher are expected using a residence time of 30 to 60 seconds and an A:W ratio between 5:1 and 15:1. (Hodsdon, 1993 draft)

2.1.2.5 Point of Entry Devices

Studies and pilot tests of POE systems have focused on diffused bubble and spray aeration devices, since packed towers have generally been considered impractical for home use because of their size and cost. Radon removals from 95 percent to more than 99 percent are reported for diffused bubble aeration devices installed at the point of entry to homes (Lowry et al., 1984; Kinner et al., 1990; Kinner, et al., 1993). Kinner et al. (1993) note that the diffused bubble and bubble plate aerator POE units tested had high A:W ratios (which is common since POE units are generally overdesigned) and therefore the units should handle changes in influent radon activity and the water flow rate without a significant increase in effluent radon activity. For spray aeration systems installed in homes and tested, radon removals have ranged from 82 to 93 percent (Rost, 1981).

2.1.2.6 Comparison of Technologies

There is little difference between PTA and DBA in terms of radon removal. Both PTA and DBA achieve high removals of radon and are available commercially. Although shallow tray aerators can achieve radon removals of greater than 90 percent, removals are generally lower than those obtained from PTA and DBA. The maintenance requirements for both PTA and DBA are low. While DBA is favored for aesthetic reasons, PTA is favored for large flows for both practical and economic considerations. MSBA is also limited in treating larger flows. Dixon et al. (1991) and industry brochures show an upper limit capacity of 800 to 1,000 gpm for currently available DBA units based on practical considerations. Shallow tray aerators also offer aesthetic advantages since they are compact. The units are generally modular, so they can generally be used with systems of all sizes since multiple units can be used together to increase capacity.

The costs of PTA and MSBA are generally comparable for flows below 1 mgd, while the process costs of MSBA are higher than PTA for larger flows (based on Cummins, 1992; Lowry,

1990). Construction, engineering, operations and maintenance, and other indirect costs play a major role in determining the feasibility of a treatment technology. Building costs for compact aerators, like MSBA, should be much lower than for PTA. Other considerations such as pretreatment for iron and manganese, disinfection, pump retrofitting, and obtaining air permits are site-specific and may be required for either technology. For tray aerators, copper sulfate or chlorine may need to be added to control the growth of slime and algae on the trays.

2.1.3 Pretreatment

Some radon removal systems may require pretreatment, particularly treatment for iron and manganese, to reduce operational problems associated with aeration.

2.1.3.1 Iron and Manganese

Iron (Fe) and manganese (Mn) in influent water can precipitate when a water supply is aerated. Precipitation can foul packing in aeration units, thus decreasing the efficiency of these processes.

Existing ground water systems that will be required to reduce radon may not need additional treatment for iron and manganese since water systems normally treat their water to reduce iron and manganese levels below their secondary MCLs of 0.3 mg/L and 0.05 mg/L, respectively. This is confirmed by the results of an analysis of NIRS data (WMA, 1992) which correlated the occurrence of radon-222 with combined Fe and Mn levels. These results are summarized in **Table 2-5.**

Table 2-5. Correlation of Occurrence of Fe and Mn with Radon

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

As detailed in the subsequent sections, suggested treatment techniques that can be applied to avoid fouling in aeration units depend on the concentrations of iron and manganese in the influent water to aeration units, and are presented in **Table 2-6.**

Table 2-6. Treatment Levels for Iron and Manganese

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

Sequestration

Sequestration is a treatment method by which iron and manganese are prevented from causing objectional turbidity and color without actually removing iron or manganese from the treated water. Typical sequestering agents are sodium silicate and polyphosphate and other phosphate-containing compounds. Sequestrant chemicals are normally used simultaneouly with chlorine. For manganese-containing waters, polyphosphate is a more effective sequestrant than sodium silicate (Robinson et al., 1990).

The Ten State Standards (the Standards) recommend the use of polyphosphates only when iron, manganese, or a combination of both metals does not exceed 1 mg/L (GLUMRB, 1997). The Standards also limit the use of polyphosphates to 10 mg/L as phosphate. Because phosphates may enhance fouling of the distribution system, the Standards require a disinfectant residual in the distribution network. The Standards also require that polyphosphate stocks be disinfected and maintain about 10 ppm of free chlorine residual for solutions with pH above 2. The Standards strongly recommend the addition of chlorine or chlorine dioxide with or before the addition of the sequestrant agent sodium silicate. Maintaining a residual disinfectant in the distribution network is also strongly recommended by the Standards to avoid biological breakdown of the sequestered iron (GLUMRB, 1997).

States may have different limits for using sequestration. For example, in New Jersey sequestering limits are 0.6 mg/L for iron and 0.1 mg/L for manganese (Dixon, 1999). At greater concentrations of iron and manganese, removal treatment is required.

High doses of sequestrants (>2.5 mg/L) may cause turbidity particularly in very hard waters. Kleuh and Robinson, as cited in Malcolm Pirnie (1992), found that 1 mg/L of polyphosphate is

sufficient to sequester iron (1-2 mg/L). However, the turbidity level in hard waters (100 mg/L calcium hardness) treated with 2.5-10 mg/L of polyphosphate was above 1 NTU. Robinson and Reed (1990), as cited in Malcolm Pirnie (1992), reported that 1 mg/L iron can be sequestered without excessive silicate dosage even when high levels of hardness are present.

Greensand Filtration

Greensand filtration consists of a conventional filter box using greensand instead of sand or anthracite as the principal filtration medium (U.S. EPA. 1993a). Manganese greensand filtration has been successfully used for iron and manganese treatment for many years. Manganese greensand[6] media is prepared by treating glauconite[7], a natural zeolite, with manganous sulfate and potassium permanganate to coat the media with manganese oxide. This process gives the media adsorptive characteristics, which allows for the removal of soluble materials through adsorption, as well as filtration of insoluble materials (U.S. EPA, 1993a). The manganese oxide acts as a catalyst in the filtration process to assist in the complete oxidation of iron and manganese. Potassium permanganate is typically added to water ahead of greensand filtration. This serves to oxidize contaminants to insoluble forms for subsequent filtration, provides disinfection, and restores adsorptive capacity to the media. Greensand filtration is particularly advantageous when using potassium permanganate to oxidize iron and manganese. If reasonable dosages of potassium permanganate are used, greensand filtration will remove any excess potassium permanganate from water, preventing pinkish water from entering the distribution system (U.S. EPA, 1993a).

Iron and manganese are oxidized and converted to iron and manganese oxides before being filtered out by the greensand media. The catalytic properties of the manganese greensand assist in removing the iron and manganese. A short reaction time before filtration is desirable to avoid large growth of particle size which may clog the surface area of the filter media. To help prevent clogging of the greensand media, the greensand can be capped with anthracite. This prevents microbial growth on the greensand since organic matter is removed on the anthracite.

[6] greensand: a sedimentary deposit consisting of glauconite mingled with sand and clay

[7] glauconite: iron potassium-silicate mineral

The filters can be regenerated by two techniques, continuous regeneration and intermittent regeneration. Intermittent regeneration intermittently passes potassium permanganate through the greensand bed which usually requires about one hour. This includes washing and rinsing of the media. Intermittent regeneration allows for a higher flow rate and longer runs between regenerations. Intermittent regeneration is recommended when removal of only manganese or manganese with a small amount of iron is needed (U.S. EPA, 1993a). Continuous regeneration involves the constant feeding of potassium permanganate solution and other oxidizing chemicals to the raw water ahead of the filters. The filters are periodically taken off line for conventional washes that require approximately 20 minutes. If excess potassium permanganate is fed ahead of the filters, the filter media will pick up the excess and minimize leakage into the effluent, up to a point. Potassium permanganate breakthrough may occur. Continuous regeneration is recommended for water where iron removal is the main objective with or without the presence of manganese (U.S. EPA, 1993a).

For removal of iron and manganese, greensand filtration is very sensitive to pH. When the pH is lower than 7.1, deterioration of the bed occurs and the addition of a pH adjustor to the incoming stream is required. When pH is between 7.5 and 9, optimum conditions occur and the oxidation reaction with potassium permanganate is complete and rapid. The rate of reaction is very important as this process is usually employed in installations with direct pumping where the contact time is very short (i.e., from the well through the filters to the distribution system) (U.S. EPA, 1993a).

The entire process can be a closed process which does not require the water to be exposed to the air. Major components of the process include filtration with greensand backwash facilities, and potassium permanganate feed systems.

2.1.3.2 Other Factors

In addition to Fe and Mn, other factors that can affect fouling of aerators are microbial growth, pH, pE, and the hardness of the water. A potential but generally labor-intensive alternative to pretreatment is periodic replacement 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, or pressure washing).

For hard water with a high CO_2 concentration, precipitation of calcium carbonate can occur when aeration reduces the CO_2 concentration, also resulting in an increased pH level. As stated in NRC (1998), "In a study of the aeration units used for VOC treatment, the American Water Works Association (1991) reported that the effect of CO_2 removal, with the greater stability of $CaCO_3$ at the higher pH, negated the effect of the increased oxygen concentration in water. There was no increase in the corrosivity of water." NRC (1998) also reported that a very small water supply system in Colorado found that removing radon through aeration eliminated the need to add lime to prevent corrosion. In addition, a small system in New Hampshire experienced a decrease in corrosivity and a reduction in the lead and copper measured in the drinking water as a result of aeration. Although the effects of aeration can include decreased corrosivity of the water, it may not eliminate the need to add corrosion inhibitors. (NRC, 1998)

2.1.4 Post Treatment

2.1.4.1 Disinfection Following Aeration

During the aeration process, atmospheric air is blown into the water supply. The air blowers are equipped with influent screens to prevent any large particulate matter from entering the water supply. However, airborne bacteria or viruses are usually introduced into the supply. For ground water systems, this is likely to be the only contact with the air prior to the water reaching consumers. The exposure of a clean ground water supply to air increases the risk of microbiological contamination. In keeping with good engineering practice, ground water supplies that are aerated should be disinfected, even if the ground water supply may otherwise be classified as naturally disinfected. Based on this approach, if a ground water system currently does not disinfect and it adds aeration for radon removal, it would also need to install disinfection.

The Ten State Standards (GLUMRB,1997) state that the following features be provided when water is subjected to aeration:

- Disinfection application points both ahead of and after the tower to control biological growth.
- Disinfection and adequate contact time after the water has passed through the tower and prior to the distribution system.

Methods for disinfection include:

- Chlorination
- Ultraviolet light treatment
- Ozonation
- Chloramine addition
- Chlorine dioxide addition
- Mixed oxidant addition (anodic disinfection)

These methods are described in the sections below.

The Ten State Standards (GLUMRB, 1997) do not specify minimum contact times for disinfection, but specify that aerated water must receive chlorination as minimum additional treatment. It is difficult to estimate the extent of microbiological contamination that would result due to aeration. Insects such as chironomus fly may lay eggs in the stagnant portion of a tray aerator (U.S. EPA, 1991a). Also bacteria and viruses may be introduced into the water through the blown air. As a conservative estimate, affected groundwater systems that would install aeration for radon removal should provide adequate disinfection for 4-log (99.99%) inactivation of virus. Water systems with little or no distribution network and with minimal likelihood of cross-contamination do not need to provide residual disinfection. For other systems that need to install disinfection and provide a residual, UV and ozone should not be used.

Chlorination

Chlorination, in gaseous, solid, and liquid-feed forms, is the most widely used disinfectant at public water supplies (U.S. EPA, 1997). Chlorine can inactivate bacteria, *giardia,* and viruses. The level of inactivation is determined by the chlorine contact time, pH, temperature, and free chlorine residual. Chlorine feed systems can be either direct solution/dry chemical, gas to solution, or direct gas injection. Direct solution or dry chemical feed systems use commercially-available sodium or calcium hypochlorite to deliver the necessary chlorine dosage. Gas to solution systems inject compressed chlorine gas from cylinders into feedwater to form a chlorine solution which is then added to the process stream. Direct gas injection into the process stream is possible but is not a common procedure.

The size of the clearwell depends on the inactivation required, temperature, pH, chlorine residual, and requirements for efficient pumping. The inactivation concentration time (CT)[8] value from the *Guidance Manual for Compliance With the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources* (U.S. EPA, 1991) for chlorine disinfection to a level of 4-log (99.99%) inactivation of virus at a temperature of 10°C, and a pH between 6 and 9, is 6 mg-min/L. Assuming a chlorine dose of 1.5 mg/L, the contact time for this conservative case is 4 minutes. Assuming that the theoretical contact time is 70 percent of practical residence time (due to inadequate mixing or short circuiting in the clearwell) the clearwell should be sized to provide a contact time of about 5.7 minutes. For a chlorine dose of 1 mg/L, the theoretical contact time would be 6 minutes, so the practical contact time would need to be about 8.6 minutes.

For ground waters with low chlorine demand and a short distribution system, 3-log inactivation of viruses may be sufficient. A chlorine dose of 1 mg/L and a contact time of 4 minutes, at a temperature of 10°C, and a pH range of 6 to 9, will provide the needed CT value of 4 mg-min/L. To account for short circuiting and inadequate mixing, a practical residence time of 5.7 minutes in

[8] CT is the product of the residual disinfectant concentration in mg/L © and the disinfectant contact time in minutes (T). Disinfectant contact time is the time needed for the water being treated to flow from the point of disinfectant application to a point before or at the first customer during peak hourly flow (U.S. EPA, 1997).

clearwell will be adequate for disinfection. On the basis of disinfection considerations alone, systems would provide a theoretical residence time in the range of 5 to 10 minutes. The clearwell in a PTA system provides a theoretical residence time of about 14 minutes for very small systems and 7 minutes for systems treating 1 mgd (U.S. EPA, 1984). Minor improvements to the PTA clearwell, such as adding baffles, will improve mixing and disinfection conditions in the PTA clearwell.

Ultraviolet Light Treatment

Ultraviolet light treatment in drinking water involves the direct exposure of the water stream to ultraviolet light. Exposure to the ultraviolet light damages nucleic acids and changes their mode of action in microorganisms, thus preventing microorganisms from propagating or remaining active. Ultraviolet light is generated by striking an electric arc through mercury vapor. The inactivation of microorganisms in drinking water by means of ultraviolet light is a function of the intensity of the radiation, proper wavelength, exposure time, water quality, flow rate, type and source of the microorganisms (natural or culture), and the distance from the light source to the targeted microorganisms. The intensity is measured in milliwatts per square centimeter (mW/cm^2) and time is measured in seconds(s), resulting in a dose measurement in milliwatts-seconds per square centimeter (mWs/cm^2).

At sufficient intensity and appropriate wavelength and exposure time, ultraviolet light is an effective disinfection agent for drinking water. Since ultraviolet treatment is more suitable for clean water sources with little suspended matter, water should be pretreated (e.g., for iron removal) before reaching the ultraviolet disinfection unit (U.S. EPA, 1996). The scientific literature shows that, in general, under laboratory conditions and using distilled water, a 3-log reduction of bacteria is achieved using an ultraviolet light dose of 30 mWs/cm^2, a 4-log reduction of viruses is achieved at a dose of 50 mWs/cm^2, and a minimum 3-log reduction of bacterial spores is achieved at a dose of 60 mWs/cm^2 (without a safety factor). Studies conducted on ground water show that a 4-log reduction of bacteriophage MS-2 (a surrogate test organism) is achieved at about 90 mWs/cm^2 (Snicer et al. 1996 as cited in U.S. EPA, 1996). Based on their study of the practical experience of

ultraviolet disinfection in the Netherlands, Kruithof et al. (1992) recommended the use of ultraviolet light (without use of a secondary disinfectant) for disinfecting drinking water from all sources of water provided that two conditions are met: (1) the water has to be low in biodegradable compounds so regrowth would not occur; and (2) the distribution network does not need any additional protection (no biofilm growth is likely and no cross contamination is likely). For ground water systems with little or no distribution network, UV disinfection is very feasible.

Given the inconsistent sensitivity of microorganismsto UV light and assuming a safety factor of 1.5 for dose requirements, a dose of 90 mWs/cm^2 should produce a minimum 3-log reduction of pathogenic (and indicator) microorganisms (bacteria and viruses) that are in ground waters. In addition, a dose of 140 mWs/cm^2 should produce a minimum of 4-log reduction of microorganisms that are in ground water sources.

Ultraviolet systems come in two types, closed and open, with closed systems more commonly used in potable and sterile water applications and thus used in this analysis. The design and operation of an ultraviolet system needs to consider equipment operational factors (e.g., lamp output, fouling of unit surfaces), water quality factors (e.g., microbial and chemical characteristics), and hydraulic design elements (e.g., dispersion, flow rate). For small systems, multiple modular units are recommended and should be easy to install and operate. To be effective, ultraviolet light treatment must be applied after aeration. Information collected from case studies has shown that generally, ultraviolet systems require little supervision and users are satisfied with the performance of the equipment. For the case studies, the main factors cited for choosing ultraviolet technology over traditional disinfection technologies include minimum service time, low operation and maintenance costs, and the absence of a chemical smell and taste in finished water (U.S. EPA, 1996).

Ozonation

Ozone is a powerful disinfectant and has been used primarily at large drinking water treatment facilities, but is also applicable to small systems. Ozone is generated on-site from air or oxygen and introduced into water using mass transfer equipment. Ozone reacts quickly with organic

and inorganic substances in the water and auto decomposes, so its residual is much less stable than that of other disinfectants and dissipates rapidly. To prevent health risks, any excess dissolved or entrained ozone must be destroyed or removed before the water enters the distribution system. Every effort must be made to avoid exposure to plant personnel. This may require the use of a secondary disinfectant. (U.S. EPA, 1993b).

Design criteria include ozone residual, competing ozone demands, and minimum contact time. One study showed complete inactivation of bacteriophage MS-2 and Hepatitis A virus for a pH range of 6-10, temperature of 3-10°C, and ozone residuals of 0.3-2.0 mg/L. For a short contact time of 5 seconds, inactivations of >3.9-log to 6-log occurred. Other studies have shown inactivation of *Giardia muris* and enteroviruses of 3-log and 4-log removals, respectively, for 5 minutes contact time and ozone residuals of 0.5-0.6 mg/L. (U.S. EPA, 1997)

Chloramine Addition

Chloramines are formed when chlorine is added to water containing ammonia and the ammonia then reacts with hypochlorous acid. The three chloramine species that can form are monochloramine, dichloramine, and trichloramine (or nitrogen trichloride). The amount of each chloramine formed depends on pH, temperature, time, and the initial chlorine to ammonia ratio. Some of the characteristics of chloramine disinfection include a long residual effect, low production of disinfection byproducts, the need for careful management of the ratio of chlorine to ammonia to prevent odor and taste problems and biological instability in the water, and longer inactivation contact times than chlorine and ozone (since chloramines are less potent). Chloramines can be used as a primary disinfectant or as a secondary disinfectant, but their use as a primary disinfectant is limited by the long contact times necessary for adequate disinfection. The longer inactivation time translates into larger contact basins than those required for chlorination, chlorine dioxide, ozonation, or UV treatment. The CT value of 4-log removal of viruses using chloramine at 10°C is 1,491 mg-min/L (U.S. EPA, 1991). Information on the use of chloramination at small systems is limited. Theoretically, chlorination may be applicable to small systems. However, the relative stability of chloramines and their long residual effect in distribution systems makes them effective as a secondary disinfectant.

Chlorine Dioxide Addition

Chlorine dioxide can be used as a primary disinfectant, but is not applicable as a secondary disinfectant because its reactivity means it is rapidly consumed and there is little or no residual in the distribution system. Because of its instability and explosivity, chlorine dioxide cannot be transported and must be generated at the application site, usually by chlorinating aqueous sodium chlorite.

Since chlorine dioxide has more than 2.5 times the oxidizing capacity of chlorine, its CT requirements for *Giardia cysts* are lower than the CT requirements for free chlorine. However, for viral inactivation, chlorine dioxide has higher CT requirements than those for free chlorine. For 3-log and 4-log inactivation of viruses at 10°C, CT values are 12.8 and 25.1 mg-min/L, respectively, for pH between 6.0 and 9.0. CT values for the inactivation of viruses by chlorine dioxide are affected by temperature, but are independent of changes in pH over a range of 6.0 to 9.0 (U.S. EPA, 1993b).

As with chloramination, information on the use of chlorine dioxide disinfection at small drinking water treatment facilities is limited. This is because chlorine dioxide is an expensive technology requiring skilled labor, more careful handling than other forms of chlorine, and has high monitoring requirements. In addition, the production of chlorite and chlorate (disinfection byproducts or DBPs) can be problematic. Taste and odor can develop if the chlorite reacts with free chlorine used for residual disinfection.

Mixed Oxidant Addition (Anodic Disinfection)

For mixed-oxidant disinfection, a solution containing oxidants (mostly free chlorine, but it may also contain ozone, chlorine dioxide, hypochlorite ion, and hypochlorous acid), is generated on-site by sending an electric current through a continuous-flow salt solution. This multiple oxidant solution is then added to the water for treatment. Mixed-oxidant disinfection can be more effective than a method using one oxidant since each oxidant provides different advantages. Advantages include broader ranges of conditions where they are effective and different residual effects,

production of potentially fewer disinfection byproducts, and combination effects (the presence of one disinfectant can make another more effective). This method may be particularly useful at sites where chemical supply is not reliable or where local codes do not permit the transportation of chlorine. Some of the limitations of mixed-oxidant disinfection include the difficulty of determining the relative ratios of each oxidant to include in the mixture, inability to significantly reduce color, questionable reliability for removing turbidity, and the limited data on the contact time necessary for adequate disinfection. Although it is expected that mixed-oxidant disinfection requires a shorter contact time than other technologies, EPA recommends that chlorine CT values be used until more data specific to mixed-oxidant disinfection are available. (Mixed oxidants have been used for disinfection and other full scale water treatment applicants.) Results from laboratory and pilot tests indicate that mixed-oxidant disinfection can achieve 3-log to 6-log inactivation for parasitic microorganisms at four hours contact time and 5 ppm residual, and 3-log to 4-log inactivation for *Giardia* (U.S. EPA, 1997).

2.1.4.2 Water Pump Modifications

When a ground water system installs a process that is open to the atmosphere, pumping modifications and additions may be necessary. Existing ground water systems normally provide minimal treatment—usually only disinfection—before pumping directly under pressure to the distribution system. If a process open to the atmosphere, such as aeration, is installed, the affected water system has the following options: (A) throttle existing well pumps; (B) restage existing well pumps; and © replace existing well pumps with pumps providing a lower head. In any case, finished water pumping will be needed to boost the pressure before distribution since most aeration technologies need to be operated at atmospheric pressure for radon to be released to the air. Some small water systems that choose to replace well pumps could use the old well pumps for pumping from the clearwell to the distribution system. Therefore, processes such as aeration will need both raw and finished water pumping, but often do not require more than one additional pump.

2.1.5 Off-Gas Emissions

2.1.5.1 Worker Radiation Exposure

Personnel in water treatment facilities that use PTA or other aeration techniques for radon removal may be exposed to higher-than-background radiation levels. This is because radon is

heavier than air and can build up in areas with stagnant air or in poorly ventilated facilities that house PTA or open DBA treatment units. Water treatment facilities should set work practices and monitoring to attain exposure levels as low as reasonably achievable in the work place (U.S. EPA, 1994). For example, areas immediately surrounding or immediately downwind of a PTA should be well-ventilated. Additionally, the water treatment plant buildings and areas where workers spend their time should be adequately ventilated all year round.

2.1.5.2 Air Emissions

Off-gas is not expected to be a regulatory or engineering concern for typical systems. There are no Federal regulations for off-gas emissions of radon from drinking water treatment plants. One source in the reviewed literature (Martin and Myers, 1992) cited a California State emissions standard for radon, but personnel at the California Department of Health Services (DOHS) said that California has no radon emission standards for water treatment facilities (Quinton, 1998). Martin and Myers (1992) stated that DOHS regulates the discharge of radionuclides and has a radon discharge standard that sets a 3 pCi/L concentration limit for radon "at the boundary of the controlled area" (California DOHS Regulations, Title 17, Section 30269). Using modeling, Martins concluded that compliance with a 3 pCi/L standard was not difficult to attain. For water with an influent radon concentration of 350 pCi/L and aeration treatment at an A:W ratio of 20:1, the stack discharge is estimated at 17.5 pCi/L. EPA's SCREEN model (which uses highly conservative default meteorology) predicts that this discharge at 60 ft above ground would dilute radon to less than 0.01 pCi/L at ground level (Martin and Myers, 1992).

No other potential State regulations setting limits for radon off-gas emissions were identified. The *Technology Transfer Handbook: Management of Water Treatment Plant Residuals* (U.S. EPA, 1996a) notes that some States have treatment requirements for radon off-gas and some States limit gas phase emissions from stripping processes and reactivation systems using GAC, but States are not identified and requirements are not given. In some cases, local and/or State restrictions could pose extra engineering or permitting requirements. Radon off-gas emissions regulations were being considered by the South Coast Air Quality Management District (SCAQMD) of California in 1991, but their development has been hindered by the unavailability of a unit risk factor for radon concentrations in ambient air (Balagopalan, 1998).

Although a human health risk may be created by radon emissions from aerators treating drinking water, this risk is far less (about 2 to 4 orders of magnitude smaller) than the risks from radon in homes due to untreated drinking water (U.S. EPA, 1994; U.S. EPA, 1993). In addition, by considering the location of off-gas emissions sources (e.g., on a roof) when designing an aeration system, the risks posed by human contact with these emissions can be minimized (U.S. EPA, 1993).

In a field evaluation of packed tower aeration using a 1-ft diameter stainless steel packed tower with 12 ft of plastic media packing, Kinner et al. (1990) reported off-gas emissions ranging from 2,410 to 21,200 pCi/L, which is 4 to 5 orders of magnitude higher than the average outdoor level of radon (0.2 pCi/L). The study used A:W ratios varying from 20:1 to 1:1 and water flow conditions of half and full. Kinner et al. (1990) noted that although the fate of the plume was not studied, it can likely be sufficiently diluted by proper venting (e.g., constructing the release point high enough off the ground). In an associated study using a diffused bubble aeration system, Kinner et al. (1990) found that the off-gas radon activity increased (4,167 to 18,600 pCi/L) as the A:W ratio decreased (less dilution), similar to findings with the packed tower system.

2.1.6 Treatability/Case Studies

2.1.6.1 Packed-Tower Aeration

PTA Blairsville, Georgia

EPA-TSD conducted a field evaluation of radon removal by packed tower aeration from a ground water supply in Blairsville, GA (Cummins, 1988). The key design parameters were as follows:

Diameter	2 feet
Tower Height	24 feet
Packing Height	18 feet
Packing Type	1" plastic saddles
A:W Ratio Range	0.05:1 to 15:1

The influent radon concentrations ranged from 4,000 to 6,200 pCi/L. Eight different runs were conducted with different air-to-water ratios. A profile of radon removal with packing height was obtained by sampling at different heights on the column.

The following observations were made:

- Radon removal ranged from 99.84 percent for an A:W ratio of 15:1 to only 17 percent for an A:W ratio of 0.05:1.
- The mass transfer coefficient decreased from 0.0225 sec^{-1} at an A:W ratio of 15:1, to 0.0027 sec^{-1} at an A:W ratio of 0.05:1.

Dixon and Lee Case Studies

Dixon and Lee (1988) performed studies for the removal of radon from ground water by packed-tower aeration. The key design parameters for the packed tower were as follows:

Diameter	4.5 feet
Tower Height	16 feet
Packing Height	14 feet
A:W Ratio	50:1

Although this column was originally designed to remove 70 percent of the VOCs present in the source water, the column removed greater than 95 percent of the radon present as shown in **Table 2-7.**

Table 2-7. Packed-Tower Aeration

Run	Type of Sample	Mean Radon Concentration pCi/L	Reduction Percent
1	Raw water Aerator effluent	783 20	97
2	Raw water Aerator effluent	649 21	97
3	Raw water Aerator effluent	646 24	96
4	Raw water Aerator effluent	646 34	95

Kinner et al. Pilot Studies

Kinner et al. (1988) performed pilot scale studies for the removal of radon from water by packed tower aeration. The stainless steel packed tower aerator was 18 feet in height and 1 foot in diameter. Glitsch mini-rings and saddles, and Koch pall rings packing media were tested. The overall packing height was 12.3 feet for both of the Glitsch media and 11.8 feet for the Koch media. Several runs were conducted at various A:W ratios, high flow rates between 4.25 and 17 gpm, and low flow rates between 0.1 and 7 gpm. The packed tower removed 97 to 99 percent when mini or pall rings media were used, and 90 to 94 percent when saddles were used. Temperature changes had little effect on radon removal efficiencies.

Dixon et al. Case Study in Pennsylvania

Packed-tower aeration was one of three aeration technologies evaluated for the removal of radon from a ground water supply in Pennsylvania (Dixon et al., 1991). The design and operating parameters of the packed tower were as follows:

Diameter	23 inches
Tower Height	16 feet
Packing Height	10 feet
Packing Type	2" Polypropylene Tripacks

Loading Rates	50 and 25.5 gpm/sq ft
A:W Ratios	3:1, 8:1, 12:1, and 30:1

The influent radon levels ranged from 1,700 to 2,700 pCi/L. Removal of radon ranged between 93 and 98 percent. The following observations were made from the study:

- Removals of radon were sensitive to packing height. The increase in removal efficiency by increasing packing height from 5 to 10 feet ranged from 17 to 22 percent at a loading rate of 50 gpm/sf, and from 14 to 16 percent at a loading rate of 25.5 gpm/sf.
- Removals of radon were insensitive to the A:W ratios tested in the study. The removal efficiencies radon ranged from 93 to 98 percent for A:W ratios ranging from 3:1 to 30:1, with a packing height of 10 feet.
- The removals were marginally improved (1- to 4-percent increase in removal) by decreasing the loading rate from 50 gpm/sf to 25.5 gpm/sf.
- A strong correlation was noted between the concentrations of carbon dioxide and radon in raw and treated water. Carbon dioxide was suggested as a potential surrogate parameter for assessing radon removal efficiency.

Hodsdon Case Studies

Data collected by A.E. Hodsdon (Hodsdon, 1993 draft) as part of a unpublished survey for the American Water Works Association (AWWA) showed removal efficiencies ranging from 78.6 percent to more than 99 percent for packed tower aerators, with three of the facilities reporting 99 percent or greater radon removals. The survey included eight operating packed tower aerators at drinking water treatment facilities of various sizes (supply capacities ranging from 9–450 gpm) in Wisconsin (3 sites), Pennsylvania and New Hampshire (2 sites each), and Colorado (1 site). Influent and effluent radon concentrations varied from 1,208 to 9,000 pCi/L and <15-300 pCi/L, respectively. The draft survey report did not provide information on air:water ratios or most tower heights (the two tower heights noted were both 33 feet). Five packed towers had counter current flow and three had concurrent flow, though this did not appear to be a significant factor. All of the facilities provided disinfection but did not install it as a result of radon treatment. Two facilities have ion exchange units before the tower to reduce iron and hardness and had this pretreatment in place prior

to installing radon removal equipment, but indicated that they installed post-tower bag filters to remove precipitated iron as a result of adding radon treatment.

Valley County Water District

Secondary Effects of Packed Tower Aeration

The Valley County Water District (VCWD) of San Gabriel Valley, California, provides water to the city of Baldwin Park and a portion of Irwindale about 30 miles east of Los Angeles. The water is drawn from ground water sources at 10 wells. A monitoring program revealed the presence of trichloroethylene (TCE) at levels greater than 1 mg/L. Since these levels exceeded action levels for TCE that were established by the State and would lead to the shutdown of wells, VCWD began evaluating the potential use of a packed tower aeration system and the secondary effects of aeration (Umphres and Van Wagner, 1986). The study covered several phases (pilot study; design, construction, and monitoring of the full-scale packed tower aeration facility) and examined the secondary effects of mineral scaling, corrosivity, microbiological quality, equipment noise, air pollution, and water particulates. Observations are reported below for each of these secondary effects evaluated.

Mineral Scaling—Calcium carbonate scaling occurred in the lower part of the tower and in pump casings downstream of the PTA. A dose of 1 mg/l of hexametaphosphate added to the aerator influent prevented further scaling.

Corrosivity—Copper corrosion rates were not influenced by aeration, while mild steel corrosion rates decreased slightly.

Microbiological Quality—Without chlorination of the PTA influent, standard plate counts of the effluent were higher than the influent. This suggests that microorganisms were growing in the oxygen-rich tower or were scrubbed from the influent air.

Equipment Noise—Instantaneous noise levels were measured with a Columbia Research Laboratory Model SPL-103 Sound Pressure Level meter. "A scale" readings taken indicated that

the blower contributed little to the base noise level for the area either during working hours or on the weekend. Noise levels of the centrifugal blower were well below OSHA standards and dropped to background levels 100 feet from the aerator.

Air Pollution—Computer modeling of the air emissions from the aerator prior to the detailed design indicated that ground level concentrations of organics as a result of aeration would be insignificant. Air samples were analyzed upwind and downwind of the aerator to check the findings of the model. At a detection level of 1 ppb (about 5.8 µg/L for TCE), TCE was not detected in any of the samples. Since 1 ppb (which was the standard detection level for that analyses) is considerably higher than the 21.8 ppt TCE predicted by the model, model estimates could not be fully verified.

The potential impact of ambient air concentrations of volatile organics on the pilot tower performance was examined. As the concentration of the volatile organics in the influent air increased, the driving force for transfer from water to air diminished. In the extreme case where the concentration in air is high enough and concentration in water is low enough, the aerator would function as an air scrubber by transferring the contaminant back into the water.

Water Particulates—Air stripping removal efficiency was increased by improving the distribution of water onto the packing and by adding packing to compensate for packing that settled as a result of start-up. Accumulated residue at the blower inlet indicated that dust and particulates were entrained into the PTA. Particle counts and turbidities did not increase significantly as a result of packed tower aeration.

Overall Conclusions of the VCWD Study—The impact of packed tower aeration on particulates, microbiological contaminants, and scaling is site dependent. Aeration facilities should be provided with the capability to feed chlorine to the influent and/or effluent to reduce the impact of microbiological growth. The water quality of a potential aerator site should be reviewed with respect to scaling. As a minimum, the design of the facility should provide for future installation of a chemical feed system to prevent scaling.

2.1.6.2 Diffused-Bubble Aeration

Lowry et al. Pilot Studies

Lowry et al. (1984) performed pilot scale shallow depth diffused aeration studies in a 120-gal (454-L) vessel. The aerator consisted of a series of fine bubble ceramic stones that achieved a practical aeration pattern. The process had a 60-minute aeration period and an aeration rate of 50 scfh (1,400 L/h), which provided an A:W ratio of 3:1. The unit was operated for 3 days with an average influent radon concentration of 76,000 pCi/L. The average effluent concentration was 4,900 pCi/L corresponding to a 93.6-percent removal.

Deep Tank DBA Belstone, England

A deep-tank diffused aeration system was installed in Belstone, England (Rafferty, 1983) to remove radon from a water supply with a capacity of 2.5 mgd. The water supply contained 10,000 pCi/L of radon. Designed and constructed in the early 1960s, the treatment facility consisted of an aeration tank that was divided into two parallel compartments Each compartment was 70 feet long by 10 feet wide and was equipped with a weir at each end to provide a 4-foot depth of water. The tank was equipped with 2,800 diffusers, each designed to diffuse air at a rate not to exceed 0.8 cubic feed per minute (cfm). Air was supplied by two of four 30-hp blowers, each capable of providing 1,125 cfm of air. At the design water flow rate of 2.5 mgd and air flow rate of 2,250 cfm, the plant operated with a 24-minute detention time and an A:W ratio of 8:1. This treatment resulted in a long term radon removal rate of 97 percent.

Shallow Depth DBA Kinner et al. Case Study

Kinner et al. (1988) installed a shallow-depth diffused-bubble aeration system that consisted of three 270-gallon polyethylene tanks connected in series. Water flowed through each tank at a flow rate of approximately 9,960 gpd with an influent radon concentration of approximately 77,500 pCi/L. Air was provided through the spiral tube diffusers that contained holes of .0015 in. diameter and were placed 14 in. above the bottom of the tanks. The system was tested at A:W ratios ranging from 2:1 to 15:1 and two water flow rates (12 gpm and 27–33 gpm). At A:W ratios of 5:1 and greater (at both flow rates), the diffused bubble system obtained 91- to 99-percent radon removal and effluent levels ranged between 700 and 6,542 pCi/L.

MSBA Dixon et al. Case Study in Pennsylvania

Multi-stage diffused-bubble aeration was one of three aeration technologies evaluated for the removal of radon from a ground water supply in Pennsylvania (Dixon et al., 1991). The relevant design and operating parameters were as follows:

No. of Stages	6
Flow Rates	50 gpm, 100 gpm
A:W Ratio	16.6:1, 11.1:1, 5.5:1 for 100 gpm
	33.2:1, 22.2:1, 11.1:1 for 50 gpm

The influent radon concentration ranged from 1700 to 2700 pCi/L. The removals ranged from 97 to 100 percent, except for one run conducted with A:W ratio of 5.5:1 which achieved 86-percent removal. Neither flow rate nor A:W ratios (at or above 11.1:1) had a significant effect on removal efficiency.

2.1.6.3 Spray Aeration

Jet Aeration Case Study, Pennsylvania

Spray jet aeration was one of three aeration technologies evaluated for the removal of radon from a ground water supply in Pennsylvania (Dixon et al., 1991). Well water was pumped through a spray jet unit into a baffled steel tank with a detention time of 20 minutes. A series of tests were conducted to study the effect of air-to-water ratio, number of passes, remote mounting of the unit (attaching a 50-ft hose to the discharge end of the unit), and flow rate on the removal of radon. The following observations were made:

- The variation in the air-to-water ratio had only a marginal effect on radon removal efficiency. Radon removal of 87 percent was achieved at an A:W of 3:1, and different runs at A:W ratios of 6:1 to 17:1 achieved radon removals in the range of 83 to 91 percent.

- The removal of radon improved with increase in number of passes. Radon removal was 68-74 percent for a single pass and increased to 99 percent for four passes.

- Removal efficiency decreased significantly due to back pressure when the spray jet was remote mounted.

2.1.6.4 Slat or Cascade Tray Aeration

Shallow Tray Air Stripper, New Boston, New Hampshire

North East Environmental Products, Inc. installed a pilot air stripper with a 24x16 ft footprint at the New Boston Air Force Station, New Hampshire (Alexant, 1995). The design flow through rate for the air stripper was 80 gpm. The system included a 600 cfm air blower and four aeration trays. The unit was expected to achieve 99.9% radon removal; for a projected maximum influent radon concentration of 76,000 pCi/L, treated water projected concentrations would be 300 pCi/L or less. The A:W ratio was 56:1. Analyses done during trial operation of the pilot system showed removals greater than 99% (influent radon of 93,593 pCi/L and effluent values of 144, 138, and <100 pCi/L).

Wooden Slat Tray Aeration

Smith et al. (1961) evaluated the performance of a wooden slat tray aeration system for radon removal, although the aeration system had not initially been installed for radon removal. The height of the aerator and the water and air flow rates were not reported. The average influent radon concentration was 6,780 pCi/L. The slat tray aerator achieved an average removal of 71 percent, with the treated water having a radon concentration of 1,950 pCi/L.

Cascade Tray Aeration

Dixon and Lee (1988) studied the effect of cascade tray aeration on radon removal at three sites. Details of the setup were not provided. The cascade tray aerator removed greater than 75 percent of the radon as shown in **Table 2-8**.

Table 2-8. Cascade Tray Aerator

Site	Run	Type of Sample	Mean Radon Concentration pCi/L	Percent Removal
1	1	West aerator influent West aerator effluent	327 50	85
1	1	East aerator influent East aerator effluent	342 37	89
1	1	Raw water Effluent	465 108	77
2	2	Raw water Effluent	521 46	91
3	1	Influent Effluent	269 54	80
3	2	Influent Effluent	260 50	81

2.1.6.5 Point of Entry (POE) Devices

Several prototype home diffused-bubble aeration and spray aeration treatment devices have been field tested. These studies are described below.

Kinner et al. POE Diffused-Bubble and Bubble-Plate Case Study in Derry, NH

Kinner et al. (1993) evaluated the performance of diffused-bubble and bubble-plate aerators in POE applications. The study investigated radon removal efficiencies, potential problems (e.g., emissions and equipment malfunctions), and economic issues. The aeration devices were installed inside the pump house at an abandoned groundwater well in Derry, N.H. Radon activity in the influent ranged from 22,837 pCi/L to 54,765 pCi/L, with an average of 35,620 $\pm$ 6,727 pCi/L. The diffused-bubble device contained three compartments (each 24-cm long $\times$ 40-cm wide $\times$ 40-cm high) in series. Each compartment had an internal diffuser, with all diffusers fed from one header. The diffusers had variably spaced holes of 0.51-mm diameter, producing relatively small bubbles to provide a larger surface area for gas transfer. A 38-cfm capacity blower was used for the air feed and a water flow rate of 2.3 gpm was used to provide an A:W ratio of approximately 119:1. The

system consistently achieved radon removals higher than 99 percent (effluent radon < 200 pCi/L), even during periods of restricted air flow due to accumulated iron precipitation on the diffusers.

The bubble-plate unit was contained in a molded plastic casing (60-cm long × 38-cm wide × 23-cm high) with a 10-cm diameter PVC vent pipe. A 0.95-cm spiral diffuser fed water into a 7.6-cm wide polyethylene channel containing 4.8-mm diameter holes along the bottom, spaced 1.9 cm apart. Air was fed in through these holes, causing the influent water to rise up to 17 cm. At the end of the polyethylene channel, the treated water flowed over a weir and into a holding tank. With an air flow rate of 125 cfm and a water flow rate of 6.0 gpm, the unit had an A:W ratio of 156:1. The bubble-plate aerator generally achieved radon removals of more than 99 percent, but did have diminished effluent quality on a few occasions, particularly when there were problems with clogging of the blower's air intake filter.

Kinner et al. noted that pretreatment for iron would probably be needed since iron oxidation occurred readily in both aeration units, causing iron precipitate to accumulate in the diffusers (decreasing air flow rates) or to be released in pulses when the units were started. The study found that the plume from the off-gas emissions is diluted fairly rapidly, but venting should be set above the roof line to keep radon gas from entering the home. Treatment of off-gas emissions could be necessary in States where the emissions are regulated.

Lowry et al. POE Diffused Aeration Field Study

Lowry et al. (1984) tested a home diffused aeration unit during a field study. The basic components of the system were an aeration tank, a fine bubble diffuser, a liquid level pump control, and a timer-controlled air supply. A shallow well pump was provided to repressurize the treated water after aeration at atmospheric pressure. The diffuser was a composite of eight one-inch spherical ceramic porous diffusers made of fused crystalline alumina grains which were arranged uniformly within a 12-inch diameter area. The blower supplied an air flow rate of 30 scf/h to provide an A:W ratio of 3.4:1. The system reduced the influent concentration of radon from 50,000 pCi/L to an average 2,500 pCi/L in the treated water.

Kinner et al. POE Shallow Diffused-Bubble Pilot Study

Kinner et al. (1990a) conducted pilot scale studies for the removal of radon by shallow-depth diffused-bubble aeration applied at the point of entry to a home water system. Influent radon levels ranged between 22,900 and 54,800 pCi/L with an average of 35,700 pCi/L. The unit consisted of three aeration tanks (46 cm long, 40 cm wide, 24 cm deep). Each tank was fed by an interval diffuser from a common header. A 56-cfm capacity blower was used for the air feed to provide an A:W ratio of 119:1. The system achieved consistent radon removals higher than 99 percent.

Rost Spray Aeration POE Case Studies

Rost (1981) evaluated the performance of a spray aeration system built and tested in Hallowell, Maine by the Department of Human Resources. The unit was installed in a private home during the spring of 1981 and tested for a period of 4 months. The unit consisted of two atomizing spray heads and a 50 gallon receiving tank. The system provided 12 minutes of recirculation through the spray aerator prior to use. Influent radon concentrations ranged from 44,000 to 63,000 pCi/L. The process produced water with an effluent radon concentration ranging between 2,460 and 7,600 pCi/L, for an average removal of 93 percent.

As part of the same study (Rost, 1981), a separate spray aeration unit was installed in a single family house and operated for 1 month. This unit consisted of a stainless steel tank with two separate compartments of equal size, each with a capacity of approximately 100 gallons. The liquid volume in the first and second compartments was 30 and 60 gallons, respectively, to allow for air space. The raw water was introduced into the first compartment as a horizontal spray which impacted onto the vertical wall separating the compartments. A half horsepower pump, with its suction near the bottom of the first compartment, sprayed the water through a similar nozzle arrangement into the second compartment. The water was then pumped into the pressure tank for use in the home's water system as needed. The results of the study are summarized below:

Average Influent Radon Concentration	22,380 pCi/L
Effluent Concentration After 1st Spray	5,460 pCi/L
Effluent Concentration After 2nd Spray	2,290 pCi/L
Average Overall Removal	82 percent

After 20 days of operation, the unit was drained and thoroughly vented by blowing air through the system. The radon removal then increased from 82 to 87 percent for a period of 1 week. It was hypothesized that since radon is heavier than air, it was lying above the water surface in the two chambers and radon would re-enter the aerated water again as the spray passed through the layer of radon. A suction tree was substituted for the nozzle arrangement in Tank 2 for 1 day, with less effective results. The chamber removal efficiencies dropped first to 67 percent then to 47 percent and finally to 14 percent.

2.2 LOW-TECHNOLOGY AERATION METHODS

2.2.1 Process Description

Several low-technology aeration alternatives are available. These technologies provide some transfer between air and water. They include free-fall aeration, spray aeration and bubble aeration (both using simple devices), Venturi aeration, and mechanical surface aeration. These low-technology methods, however, will only provide low removals (relative to the aeration technologies discussed in Section 2.1). Therefore, for waters with high levels of radon, achieving the removals necessary to meet requirements might not be feasible with these methods.

Although several low technology radon treatment processes have achieved some degree of removal the following barriers might limit the implementation of any of these technologies in full-scale treatment:

- Existing storage tanks may not provide adequate headroom and ventilation to prevent the accumulation of a gaseous layer of radon, which can re-enter the aerated water.

- Existing pumps designed to discharge into an atmospheric clearwell would be inadequate to pump against the additional head imposed by distribution manifold piping and a spray nozzle system.
- Modifications to storage facilities may interrupt service.
- The capacity of existing storage tanks will probably be insufficient to provide the necessary detention time to reduce radon concentrations to acceptable levels if high influent levels are present.
- As stated earlier, these systems will probably not achieve removals that are sufficient to attain desired water qualities, if influent levels are extremely high.
- Rechlorination may be necessary after storage to provide a residual in the distribution system.

As with other aeration systems, off-gas emissions, iron and manganese precipitation, and corrosion control issues can be concerns and need to be addressed before implementing low technology aeration treatment systems.

2.2.1.1 Free-Fall Aeration

Free-fall aeration involves the flow of contaminated water over a weir or similar structure to provide a free-fall effect into a storage tank. This enhances the transfer of contaminants into the atmosphere due to the increased surface area exposed to the atmosphere and additional turbulence.

One type of free-fall aeration is cascade aeration, where water flows down over a set of steps or baffles that increase the time the water is exposed to air and the area-volume ratio. The simplest structures are basic sets of concrete steps, where the greater the number of steps the longer the exposure time. Baffles produce turbulence and can be used to increase the area-volume ratio. Limitations associated with these structures include the need to house them with adequate ventilation in cold climates, and the occurrence of slime and algae buildup and corrosion. (AWWA and ASCE, 1998)

2.2.1.2 Low Technology Spray Aeration

For low technology spray aeration, a simple spray nozzle is installed above an atmospheric storage tank or basin. The influent is then discharged into the tank or basin from the sprayer.

2.2.1.3 Low Technology Bubble Aeration

Low technology bubble aeration involves delivering air bubbles into a storage tank or basin using a simple device consisting of a hose or pipe with holes and a blower.

2.2.1.4 Venturi Aeration

For venturi aeration, a venturi laboratory device is installed above an atmospheric storage tank or basin to discharge the influent into the tank or basin.

2.2.1.5 Mechanical Surface Aeration

Mechanical surface aeration involves using a mechanical mixer to agitate the surface of water in a basin. The agitation brings more air into contact with the water to enable increased radon transfer from the drinking water to the air. One advantage of mechanical surface aeration is that it can often be retrofit to existing basins. There are several disadvantages to this technology, including the need for large basins, long residence times, and high energy inputs. (NRC, 1997)

2.2.2 Removal Efficiency

Since removal rates can vary considerably for low-technology methods, it may be necessary to pilot test the system to determine actual removal rates and avoid site-specific problems. For small systems with waters requiring 50-percent radon removal rates, low-technology spray aeration may be the best choice.

Removal efficiency data reported for various low-technology aeration techniques are presented in **Table 2-9**.

2.2.3 *Treatability/Case Studies*

Kinner et al. (1990) conducted pilot-scale studies of the effects of several low technology techniques that involved modifications to a simulated atmospheric storage tank. Most of the techniques involved simple aeration mechanisms. The techniques studied were:

- Water entry at the bottom of the tank

Table 2-9. Low-Technology Aeration Removal Efficiencies Observed

Technique	Percent Removals Observed	Source
Mechanical surface aeration	83–92%	Drago (1998)
Free-fall into a tank Free-fall and simple bubble aeration	50–70% 86–96%	Kinner et al. (1990) Kinner et al. (1987)
Simple spray aeration with free-fall	60–70%	Kinner et al. (1990)
Simple bubble aeration	80–95%	Kinner et al. (1990)

- Water entry at the bottom of the tank with minimal bubble aeration
- Water entry via free fall from 2 ft above the tank water level
- Water entry via free fall from 2 ft above the tank water level with minimal bubble aeration
- Water entry via free fall from garden spray nozzle 2 ft above the tank
- Water entry via free fall from laboratory venturi apparatus 2 ft above the tank.

For each of these techniques, the radon removal was measured for hydraulic detention times of 8 to 23 hours. The results are shown in **Table 2-10**.

Following the pilot-scale study, Kinner et al. (1990) installed a minimal aeration system to an existing storage tank at a housing development. The system consisted of 2 in. PVC pipes with 1/8 in. diameter holes and a blower injecting 20 cfm of air. The detention time for the system was 5.3 hours. Radon removal efficiencies ranged from 80 to 88 percent.

Table 2-10. Radon Removals for Low Technology Techniques

Technique	Radon removal % for 8 hr detention time (flow=0.9 gpm)	Radon removal % for 23 hr detention time (flow=0.24 gpm)
Bottom entry	~10[1]	~ 34[1]
Bottom entry w/aeration	83	95
Free fall	50	70
Free fall w/aeration	86	96
Free fall from sprayer	60-70	no data[2]
Free fall from venturi	-----[3]	-----[3]

(1) Slightly above removal expected from decay and volatilization without any treatment.
(2) Nozzle unable to operate at low flow rate.
(3) Water flow rates too low to obtain good venturi action.

Drago (1998) reported removals of 83 to 92 percent for a mechanical surface aeration system. The system had flow rates between 5,450 and 7,600 gpm and detention times of 288 to 408 minutes. Drago noted that mechanical surface aeration was only appropriate with a large existing clearwell.

Kinner et al. (1987) assessed the performance of free-fall aeration for radon removal. The researchers observed removals of 50 and 70 percent for detention times of 12 and 30 hours, respectively when water was allowed to free fall into a storage tank.

Dixon and Lee (1988) observed a decrease of approximately 18 percent in the levels of radon in water that was stored within a water supply distribution system. This decrease was attributed largely to volatilization of the gas caused by pumping and agitation of the water and by ventilation within the storage vessel. Decay of the radon accounted for only approximately 34 percent of the noted decrease in the radon concentration.

2.3 GRANULAR ACTIVATED CARBON (GAC)

In drinking water treatment the use of GAC in the United States has been limited primarily to applications for the control of synthetic organic chemicals and taste and odor compounds. However, since the detection of radon in drinking water supplies, a number of research and

pilot-scale studies have been undertaken to evaluate the effectiveness of GAC for controlling radon. Based upon the results of this research and pilot-scale work, GAC appears to be effective in removing radon from water.

2.3.1 Process Description

Radon is removed from water by adsorption using granular activated carbon (GAC). The adsorption process occurs when the radon molecules diffuse through the water to the surface of the GAC. Radon sorbs at the interface between the water and the carbon. Therefore, a high surface area is an important factor in the adsorption process. Although the outer surface of the carbon provides some available area for adsorption, the majority of the surface area is provided in the pores within the carbon particles.

Adsorption systems usually operate in a downflow mode where the contaminated water is introduced at the top of the carbon bed and flows through the bed to the bottom. As the water moves down through the bed, the radon is adsorbed to the carbon until all the available interfacial area is taken up. The radon moves with the water through the bed until there is available area for adsorption to take place. Contaminant removals are a function of the available interfacial area between water and carbon, and are a function of time.

The design of a GAC system needs to account for competitive adsorption from natural organic matter in the water that may compete with radon for adsorption sites and thus increase the amount of carbon needed to sufficiently remove radon (NRC, 1997). Adsorption can be limited by suspended solids accumulation in the carbon columns or beds, which can cause hydraulic short-circuiting (bypassing portions of the bed) and also by coating (blinding) the outer surface of the carbon. Adsorption of large molecules can also block the adsorption of other materials. The adsorption of oxides and carbonates, such as Fe, Mn, and Pb, can reduce the adsorption capacity of GAC for radon. However, the actual surface density of adsorbed decay daughter products does not

greatly affect the capacity for radon adsorption since the decay products tend to be at much lower concentrations than Fe and Mn in groundwater.

A minimum contact time is required to reduce the contaminant level to any particular concentration. This required residence time increases as the column or bed becomes partially exhausted (saturated with contaminants). The empty bed contact time (EBCT) is a nominal contact time that can be defined as the nominal volume of the contact vessel, divided by the design flow. The actual bed contact time is affected by other adsorbable materials in the water that can reduce the adsorption capacity for radon. At high radon levels, the bed/column size required for effective removals may become so large that GAC is impractical. The long EBCT required for the removal of radon from drinking water sources by GAC may not be feasible particularly when radon levels are far higher than the MCL levels.

GAC has a finite adsorption capacity that is determined by the type of GAC and the characteristics of the target contaminant. If VOCs are present during the GAC adsorption process, the VOC concentration in the water leaving the GAC will be similar to the influent VOC concentration when all available interfacial area has been exhausted. When the contaminant begins to appear in the effluent, breakthrough has occurred. Once the breakthrough concentration reaches a set level, the carbon must be regenerated or replaced. However, in the radon adsorption process (where VOCs are not present), an adsorbed radon atom decays, reducing the interfacial concentration of radon and restoring some adsorption capacity to allow new radon atoms to become adsorbed. Thus, the effective life of GAC is extended through the in-situ decay of the adsorbed radon (radon decays to ultimately become lead; 6.48 mg of radon are equivalent to 1 Curie and 1 Curie is 10^{12} picocuries).

Some of the major design considerations for GAC systems are:

- Adsorption/Decay Steady State

- Empty Bed Contact Time (EBCT)
- Contactor Configuration.

These major design factors are discussed below.

Additional design considerations include:

- Type of GAC - The adsorption capacity of GAC is partly determined by the type of GAC (as discussed in the adsorption section below), so this may influence system design. However, the selection of a particular type of GAC also often depends on the sources of GAC that are available nearby since major costs can be incurred for transporting GAC. Lowry and Lowry (1987) reported that the type of GAC used "has significant bearing upon the performance achieved." Rutherford, as cited in Hess et al. (1998), found that coconut charcoal works best for absorbing radon. NRC (1998) also noted that coconut-based GAC has been found to be the best for radon sorption. Since coconut-based GAC has a larger percentage of micropores than other types of GAC, it is thought that micropores may be the most effective for sorbing small molecules and atoms like radon (NRC, 1998).

- Temperature - Rutherford, as cited in Hess et al. (1998), also found that the cooler the GAC, the better the absorption of radon.

Adsorption/Decay Steady State—Carbon usage rates dictate the rate at which carbon will be exhausted and how often it needs to be replaced (AWWA and ASCE, 1998). In the classic application of granular activated carbon adsorption to the removal of organic compounds, adsorption isotherms have been found to be useful screening tools not only for determining preliminary carbon usage rates, but also for evaluating the effectiveness of different types of GAC. The Freundlich isotherm model provides a method of empirically evaluating the adsorption characteristics of GAC. The Freundlich equation for radon is:

$$X/M = K_r C^{1/n}$$

where:

X = radon adsorbed in pCi
M = mass of carbon in mg
C = equilibrium radon concentration in pCi/L
1/n, K_r = Freundlich isotherm constants.

A log-log plot of the experimental data generally yields a straight line whose slope is 1/n and intercept is K_r. The slope or 1/n provides an indication of adsorption intensity and the intercept or K_r provides an indication of adsorption capacity (Lowry and Brandow, 1985). **Table 2-11** lists the radon Freundlich constants for a number of different carbons. As indicated on this table, the adsorption capacity can vary greatly among different types of carbon.

Table 2-11. Freundlich Isotherm Data and Relative Ranking for Six Activated Carbons and Radon at 10°C

Carbon type	Mesh Size	1/n	K_r pCi Radon Adsorbed/mg Carbon
A	12×40	1.02	1.5600×10^{-3}
B	12×30	0.99	1.2300×10^{-3}
C	12×40	0.91	2.0600×10^{-3}
D	8×30	1.28	0.0044×10^{-3}
E	8×30	1.27	0.0046×10^{-3}
F	8×30	0.82	4.6500×10^{-3}

Source: Lowry and Brandlow (1985)

However, while adsorption isotherms may give an indication of the potential of a given carbon for radon removal, they do not yield sufficient data to develop design criteria for GAC treatment systems. This is due to the effect of decay and the adsorption/decay steady state relationship that dictates the performance of a carbon column/bed in continuous service (Lowry and Brandow, 1985).

Breakthrough is a key factor in the design of a GAC system and, as noted earlier, occurs when the effluent concentration of a contaminant after GAC treatment exceeds a maximum

acceptable criteria. When breakthrough occurs depends on the design of the carbon bed/column (e.g., type and depth of carbon) and the quality of the influent. Breakthrough curves are used to define the relationship between the physical and chemical factors of the GAC system (e.g., flow rate, bed/column size, carbon exhaustion rate), the number of beds/columns and their arrangement (i.e., in series or parallel), and treatment plant effluent requirements (AWWA and ASCE, 1998). For radon, the removal relationship shows an initial period where the adsorption is maximum and decay is minimum. A typical breakthrough curve for radon shows that the radon concentration in the treated water begins to increase gradually, and then over time it levels off at a steady state value. A steady state is established within the carbon bed when the adsorption rate equals the rate of decay.

Knowing the half life of radon (3.82 days), the decay constant of radon can be calculated as follows:

$$M(t) = M_o e^{-\lambda t}$$

where:

M = mass in mg at time t

t = time in days

M_o = initial mass in mg or concentration in mg/L or pCi/L

λ = decay constant in $days^{-1}$.

Knowing the half-life of radon (3.82 days), solving the above equation can be as follows:

$M(3.82) = M_o e^{-\lambda(3.82)}$

$M(3.82) = \frac{1}{2} M_o$, since 3.82 days is the half-life

so, $0.5 = e^{-\lambda(3.82)}$

$\ln 0.5 = -3.82\lambda$

and $\lambda = 0.18$/day.

Therefore, $M(t) = M_o e^{-0.18t}$

Researchers have found that the removal constant K_r varies by the type of GAC and by the source water quality. The different system constants reported by various studies are presented in **Table 2-12.** Early research showed a radon removal constant ranging between 1.25/hr and 3.2/hr in laboratory controlled studies and a radon removal constant ranging between 1.34/hr to 1.89/hr in field studies. As can be seen from **Table 2-13**, the K_r constant ranges from 1.35/hr to 5.8/hr. In more recent research, the K_r changed significantly between two different sites (and source waters) (AWWARF, et al, 1997). Iron, manganese, and TOC in source waters affect radon adsorption by GAC. One study reported a decrease in the rate constant from 4.57/hr to 2.76/hr when the source water iron concentration was increased from 0.09 to 3.9 mg/L (AWWARF, et al. 1997). Pretreatment to sequester/remove iron and manganese, or other pretreatment such as pH adjustment, can improve radon adsorption and extend carbon life. (Pretreatment is discussed further in Section 2.3.3.)

As the system rate constant (K_r) increases, the EBCT decreases. Since the system contact time is site specific, a treatability pilot study is required to determine the rate constant for a particular GAC type and source water. For small systems that cannot afford a treatability pilot study, a conservative K_r should be used.

Table 2-12. GAC K_r Constant by Carbon Type[1]

Carbon Type	K_{ss}(1/hr)[2]	
	Co = 50,600 Laboratory[3]	Co = 700,000 Field[4]
A	1.25	1.34
B	1.76	–
C	3.20	–
D	2.09	1.58
E	2.28	1.89
F	2.61[5]	–
G	1.24	–
H	1.97	–

Notes:
(1) Unpublished data. EPA Grant No. R-81-829-01-0 Office of Research and Development
(2) K_{ss} (K at steady state) calculated from Empty Bed Contact Time (EBCT)
(3) Continuous flow
(4) Full-scale household systems
(5) Data limited.

Table 2-13. GAC K_r Constant by Carbon Type as Reported From Different Sources

Rate Constant K in 1/hr or hr^{-1}	GAC Type	Source
4.57–5.15	Column 1 Barneby & Sutcliffe PE 12×30	AWWARF , 1997
4.76–5.31	Column 2 Barneby & Sutcliffe PE 12×30	
2.69–3.64	Column 3 Barneby & Sutcliffe PE 12×30	
3.17–4.52	Column 4 American Norit HD 3000	
1.81–3.67	Column 5 Calgon F300	
2.43 (2.99–2.28)	American Norit HD 3000	New Jersey site AWWARF , 1997
5.8	BC1002	Amherst site, EPA, 1990
3.3	BC1002	Mont Vernon site, EPA, 1990
1.35	American Norit Peat (8×20)	Lowry and Lowry, 1987
2.09	ICI Americas* HydroDarco 4000 (12×40)	Lowry and Lowry, 1987
1.53	Calgon F-400 (12×40)	Lowry and Lowry, 1987
3.02	Barneby Cheney 299 or 1002	Lowry and Lowry, 1987
1.48	American Norit HydroDarco 4000	Lowry et al., 1987
2.98 without cation exchange pretreatment 3.29 with cation exchange pretreatment	BC1002	Kinner, et al., 1993

* Now American Norit

Empty Bed Contact Time—The required empty bed contact time can be calculated, given a radon influent level, desired radon effluent level, and a carbon steady state system constant. The system is modeled by the following equation:

$$c_t = c_o e^{-K_{ss}t} \quad \text{or} \quad t = \frac{\ln\left(\frac{c_t}{c_0}\right)}{K_{ss}}$$

where:

C_0 = influent radon level (pCi/L)
C_t = desired effluent level (pCi/L)
t = EBCT (hours)
K_{ss} = steady state system constant (1/hr).

The empty bed contact time is a function of contactor volume and flow rate.

Calculations by AWWARF (1997) indicate that the EBCT can range from 7 minutes at a K_{ss} of 4.5/hr, an influent radon concentration of 500 pCi/L, an effluent radon concentration of 300 pCi/L, and a removal efficiency of 40 percent to 293 minutes at a K_{ss} of 1.5/hr, an influent radon concentration of 300,000 pCi/L, an effluent radon concentration of 200 pCi/L, and a removal efficiency of 99.9 percent. As with the system rate constants discussed above, EBCT can be assessed through treatability pilot studies.

Contactor Configuration—The three basic configurations for contactor operation are downflow fixed bed, upflow fixed (packed) or expanded (moving) bed, and pulsed bed. These configurations can have single adsorbers, or multiple adsorbers operated in series or parallel (AWWA and ASCE, 1998). Single-stage operation is applicable to radon removal in ground waters because of the relatively low carbon usage rates. A system of multiple contactors in series has the advantage of being able to capture first-stage breakthrough. Two or more fixed beds operated in parallel typically are used when a high flow rate would require a vessel diameter too large to be economical or feasible.

Downflow fixed bed contactors offer the simplest and most common contactor configuration for radon removal in ground water. The contactors can be operated either under pressure or by gravity. Pressure contactors may be more applicable to ground water systems because of the nature of these systems. The use of gravity contactors for most ground water systems would involve repumping the treated water to the distribution system. On the other hand, pressure contactors might be used without repumping, thus reducing both capital and operating costs. Downflow contractors are used when the unit is also being used to filter out suspended solids (AWWA and ASCE, 1998). The suspended solids are removed periodically by backwashing.

When suspended solids concentrations are high, solids accumulation and resulting head losses may be high if downflow contactors are used. In these situations, upflow beds used with subsequent filtration processes to remove suspended solids may be preferable. Upflow beds can also be used in waters with low suspended solids concentrations since the bed is not needed as a filter (AWWA and ASCE, 1998). Upflow beds have also been applied to situations where very long

contact times (greater than 120 minutes) are required. For pulsed bed adsorbers, the bed is occasionally pulsed to release some of the exhausted carbon from the bottom, while some fresh replacement carbon is added to the top of the bed (AWWA and ASCE, 1998).

Point of entry GAC units typically consist of a metal or fiberglass pressure vessel containing gravel and the activated carbon. Adequate volume is provided above the carbon bed for expansion during backwashing. Capacities are usually between 1.0 cubic feet to 3.0 cubic feet (28 to 85 L) of carbon. (Lowry et al., 1987)

2.3.2 Removal Efficiency

Several studies have documented the removal efficiency of GAC for radon. Typical removal efficiencies in the range of 80 to 99 percent have been recorded. These studies have involved household unit or Point-of-Entry (POE) devices, pilot studies, and full scale plants. Flows have ranged from 125 gpd to approximately 10,000 gpd with average influent radon levels between approximately 2,500 pCi/L to approximately 750,000 pCi/L.

However, to remove 99 percent of the influent water radon, a long EBCT is needed. Dyksen, Hiltebrand and Guena (1986), as reported in Dixon and Lee (1987), concluded that EBCT for the removal of 99 percent of radon is 130 minutes. Experiments conducted by Dixon and Lee indicated a 35-percent reduction in radon concentrations using GAC filters with EBCT of 10.5 minutes. Hiltebrand,Dyksen and Raman (1987) conducted pilot studies that showed approximately 70 percent reduction of radon levels using a GAC filter with an EBCT of 30 minutes. Their research also showed that pressure GAC filters with EBCT of 2 minutes and loading rates of about 1 gpm/ft^2 may reduce radon concentrations up to 10 percent of influent concentration. **Table 2-14** presents a summary of radon removal efficiencies reported by various sources.

2.3.3 Pretreatment

GAC systems may require some kind of pretreatment to prevent clogging of the carbon bed and to minimize the organic loading on the carbon. Clogging of the bed could be caused by suspended solids in the raw water and/or by precipitation of iron and manganese on the carbon. The

Table 2-14. Radon Removal Efficiencies by GAC

Source	Influent Radon Level (pCi/L	Effluent Radon Level (pCi/L)	% Removal	EBCT (minutes)	Flow	GAC Type	Source Water Quality	System Design Size and Other Design Parameters	Comments
Kinner, et al. (1987, 1988, 1989, 1990) Mt. Vernon, NH*	249,900 (Ph I); 68,900–210,491 (Ph II)	<138–2,530 (Ph I); 4,750–68,400 (Ph II)	81.1*	78.5 (Ph I) 53.3 (Ph II)	24 m^3/day (Ph I) 36 m^3/day (Ph II)	BC1002	atmospheric storage tank	20 ft^3 & 27 ft^3 for a total of 47 $ft.^3$	2 contactors in series Phase I - Initial operation Phase II - Long term
Lowry et al. (1984)	155,000	4,000–15,000 22,000	90.3–97.4 85.8	80 per each unit	6,500 gpd	NA	NA	48 ft^3 carbon	2 contactors in series After 2 months, leaks developed and were repaired. The bottom numbers for effluent and removal are for after repairs.
Kinner et al. (1993) Derry, NH	22,837–54,765	<400 (first 4 months) 3,000-6,000	99.7–79 without pretreatment 99.7–85 with pretreatment	6	270 gpd	BC1002	Pretreatment by pleated paper filter on both units cation exchange on 1unit	1.6 ft^3	POE unit
Lowry, et al. (1984, 1987)	53,600–74,900	130–7,800	85.4–99.8	36–215	12–150 gpd	AN HD4000	No pretreatment or backwashing	0.5–2.5 ft^3 (14.2–70.8 L)	Full-scale laboratory unit, operated at 5 different bed volumes
Lowry (1988)	2,619–758,760	59–6,859	83.2–99.7	NA	209–939 L/day	BC 299 and CF 400	NA	1.7–3.0 ft^3	10 household units
U.S. EPA (1990) Mont Vernon, NH	249,000–210,491	2,530–24653	90–99%	78.5	24 m^3/day	BC1002	NA	0.57 m^3 & 0.76 m^3 for a total 1.33 m^3	2 contactors in series
Amherst, NH	41,800–56,600	12,000–7,971	71–80%	20.6	59 m^3/day	NA	NA	0.85 m^3 GAC	Iron levels were 0.50 mg/l
AWWARF, et al. (1997) Atkinson, NH	14,830–17,110	NA	90% for Col. 1 & 2 40–60% for contactors 3A, 4A, &5A 90% for contactors 3B, 4B, & 5B	Column 1 = 52 Column 2 = 52 Column 3 = 104 Column 4 = 104 Column 5 = 104	0.1 gpm to each column	Columns 1, 2, & 3– BS PE 12×30; Column 4– HD 3000; Column 5– Calgon F300	Fe = 2.42 - 6.33 without pretreatment <0.16 with greensand filtration Greensand filtration and potassium permanganate	Column 1 = 0.70 ft^3 Column 2 = 0.70 ft^3 Column 3 = 1.40 ft^3 Column 4 = 1.40 ft^3 Column 5 = 1.40 ft^3	5 GAC columns, each with 2, 3, or 4 contactors: Columns 1 & 2 each consisted of 2 contactors in series and received pretreated water. Columns 3, 4, & 5 each consisted of four contactors in series and received raw water.
AWWARF, et al. (1997) Colorado	≤150–7,550	100–1,000	NA	34.2	0.20 gpm	AN HD 3000	No pretreatment Fe < 0.16	0.32 ft^3 each unit for total of 0.96 ft^3	3 contactors in series
AWWARF, 1997 Short Hills, NJ	2,170	<500	NA	43	0.19 gpm	AN HD 3000	No pretreatment Fe ≤ 0.05	0.27 ft^3 each unit for total of 1.08 ft^3	4 contactors in series

* Average

AN HD 4000 = American Norit HydroDarco 4000 BC 299 = Barneby Cheney 299 CF 400 = Cargon Filtrasorb 400 BS = Barneby & Sutcliffe

NA = Not Available/Not Provided BC 1002 = Barneby Cheny 1002

former is typical of surface water systems, while iron and manganese in the soluble form may be encountered in ground water systems. Clogging may also be caused by biological growths when the carbon bed life is long. The influent water may also contain competing organics. Competitive adsorption and the influence of high concentrations of background organics have been found to affect the removal of organics but their impact on radon removal is unknown. (McCreary and Snoeyink, 1980).

AWWARF (1997) found that iron (and possibly TOC) decreased the K_{ss} of GAC from 4.5 h^{-1} to 3.2 h^{-1}. NRC (1998) noted that the pattern and rate of accumulation of uranium, radium, and Pb-210 can vary greatly when iron is present. Cornwell et al., as cited in NRC (1998), reported that high levels or uranium, radium, and Pb-210 occurred with iron-rich backwash residuals from GAC units. In another study, iron, manganese, and turbidity at the levels shown in **Table 2-15** were not found to affect radon removal (U.S. EPA, 1990).

Table 2-15. Turbidity, Iron, and Manganese Levels

Parameter	Mont Vernon average influent level	Amherst average influent level
Turbidity, NTU	0.17 - Phase I 0.05 - Phase II	1.75 - Phase I 2.99 - Phase II
Iron, mg/L	0.06 - Phase I 0.06 - Phase II	0.50 - Phase I 0.78 - Phase II
Manganese, mg/L	0.02 - Phase I 0.02 - Phase II	0.09 - Phase I 0.10 - Phase II

Source: EPA, 1990

Fouling of the GAC by oxidized metals, organics, particulates, and/or microorganisms can be controlled by pretreatment and/or frequent backwashing. Periodic backwashing of the GAC units can remove some suspended solids which might otherwise clog the bed. Disinfection with chlorine prior to GAC adsorption creates chlorine by-products during the reduction of chlorine on GAC. Since some of the chlorine by-products are adsorbed by carbon, design of GAC systems needs to account for this competitive effect. Filtration ahead of the GAC system is a common solution to prevent clogging of the bed. For POE units a small sediment filter can be installed immediately

upstream of the GAC unit (Lowry, et al., 1987). Pretreatment can be provided to reduce the organic loading on the carbon, thereby decreasing the carbon usage rate. The need for pretreatment should, however, be justified on the basis of cost and performance. Examples of processes that may be used for pretreatment include conventional treatment and ozonation.

2.3.4 Post Treatment

The dynamic behavior of bacterial populations on GAC has been the subject of several studies. (Klotz et al., 1976, Cairo et al., 1979, McElhaney and McKeon, 1978, and Parson et al., 1980). While the results of these studies have not presented a consistent picture of the dynamics of bacterial growth on GAC and in effluent from GAC contactors, all found the average number of bacteria in the effluent from GAC systems to be significantly higher than influent levels. More recent GAC radon removal studies measured the bacterial population in the effluent and found that at both the Mont Vernon and Amherst sites, bacterial populations in the effluent were significantly greater than those in the influent. At Mont Vernon the effluent level was as high as 362,000 CFU/100 ml while at Amherst the effluent ranged from 20,000 to 40,000 CFU/100 ml (EPA, 1990). No incidents of waterborne disease outbreaks have been linked to GAC systems; however, these studies indicate a need to ensure adequate disinfection of GAC contactor effluents prior to distribution of the water and a need for careful monitoring of the disinfected water. If chlorination is used to disinfect, the formation of disinfection byproducts (DBPs) is unlikely to be a concern until the GAC is saturated since the natural organic matter (NOM) needed for DBP formation will sorb to the GAC (NRC, 1998). If the GAC becomes saturated, DBP formation after chlorination could be a concern.

In addition, well pumps may need to be modified or replaced to address the additional head loss in the pressurized treatment system (Kennedy/Jenks Consultants, 1991).

2.3.5 Operational Considerations

Gamma radiation exposure from process units and waste disposal issues related to the accumulation of radioactive lead-210 on the media are two concerns associated with using GAC for radon removal. The decay of radon within the GAC bed results in the growth of radon progeny.

Beta and gamma emissions are associated with daughters Bi-214 and Pb-214 which have short half lives. The radon adsorbed on the GAC decays into its radioactive daughter products, resulting in a buildup of radioactive lead-210. Pb-210 accumulates on the bed because of its long half-life (over 20 years), and its tendency to be adsorbed on the media.

2.3.5.1 Gamma Emissions

The accumulation of radon (and other radionuclides such as uranium and radium) on the activated carbon poses a potential health risk to full-time operators of the water treatment system, maintenance personnel, and handlers of the spent carbon. Radioactive air emissions could also necessitate an analysis of radiation exposure to the nearby community (persons living or working in the immediate vicinity or downwind).

According to research conducted on gamma emissions from a GAC, the level of radiation surrounding the bed depends on the influent radon level, radon effluent level, and distance from the bed. The exposure rate is significantly lower a few feet from the GAC bed compared to the maximum exposure rate found at the surface of the GAC vessel. Field monitoring studies indicate that gamma exposure rate dissipates with distance, and shielding with lead or water decreases exposure rates further (Lowry, 1988). Lowry (1988) reported that encasing a small POE GAC unit (1.7 to 3.0 cubic feet) in a tank of water can virtually eliminate the problem of gamma exposure surrounding the GAC bed.

The levels of gamma emissions recorded from GAC contactors by several field monitoring studies are listed in **Table 2-16**.

Table 2-16. Gamma Emissions from GAC Contactors

Gamma emissions	Influent Radon Level (pCi/L)	Site	Source
500 µrem/hr	14,830–17,110	Atkinson, New Hampshire	AWWARF (1997)
500 µrem/hr	150–7,500	Colorado	AWWARF (1997)
4–5 mrem/hr Max exposure at surface of 2.5 cu ft bed	53,600–74,900	Full-scale laboratory study	Lowry et al. (1987)
4.6–16 mrem/hr at surface of unit #1 1.1–1.8 mrem/hr at bottom of unit #2 40–100 mrem/hr for workers in direct contact with GAC bed during coring for 1–1.5 hours	191,113	Mont Vernon, NH	Kinner et al. (1988)

Lowry and Brandow (1985) showed that radiation at the surface of the household contactor vessel decreased to less than 1.0 mrem/hr at 3 feet from the tank surface.

Some studies using field observations and models have investigated the exposure due to gamma radiation from GAC beds. Based on data collected during a study of GAC household POE units, Lowry (1988) developed a relationship to predict the maximum gamma exposure rate based on the radon level in the raw water. Equations that model the relationship between acceptable distance and raw water radon level were developed. The maximum gamma exposure rate that can be expected can be predicted by the relationship that 1.0 mrem/hr is produced for each 10,360 pCi/L of radon in raw water and applies for GAC units that have reached a steady-state operation. (Lowry, 1988)

Analyses and conclusions/recommendations by researchers are listed below:

- A GAC unit located 3 feet from a living area would require no shielding up to an influent radon level of 21,000 pCi/L (Lowry, 1988).
- There is no increased gamma exposure if raw water is less than 5,000 pCi/L and GAC is adequately shielded.

- A GAC unit in a cellar needs no special precautions up to an influent radon level of 30,000 pCi/L.

Based on their analysis, researchers recommended an upper level of approximately 5,000 pCi/L for influent radon concentration to avoid hazard due to gamma radiation for a domestic water supply. The analysis took into consideration the standard promulgated by EPA which limits residential exposure to gamma radiation to 20 uR/h above the background exposure rate, or approximately 170 mrem/year; an exposure period of 8 hours per day; and a safe distance of a few feet from the surface of the GAC unit. It was estimated that the exposure from a unit that removes 95 percent of the influent radon concentration of 5,000 pCi/L at a flow rate of 300 gpd was less than 0.058 mR/hr (equivalent to 170 mR/yr) at a distance of approximately two feet from the GAC unit (Rydell, 1989).

Based on research studies, AWWARF (1997) verified the following equation (developed by Lowry and Brandlow, 1985) to provide an estimate of the gamma emissions for any given radon influent concentration.

$$\Upsilon_{max} = \frac{Rn}{17.8 \frac{pCi/L}{\mu rem/hr}}$$

where:

Υ_{max} = maximum gamma emission (μrem/hr)

Rn = influent radioactivity (pCi/L).

A computer program called CARBDOSE models radon removal by a domestic style GAC filter (Rydell et al., 1989). The program can estimate the exposure dose from a GAC unit at a specified distance from the unit. It also models the accumulation of Pb-210 on the media as a function of years of operation, and estimates the Pb-210 activity per gram of wet carbon. Martins (1992) developed graphs that depict the exposure rate versus the radon influent concentrations for various system configurations and sizes.

The gamma radiation exposure rate to operators in the work area depends on several factors including radon concentration, distance between the work area and the GAC units, time spent in the work area, and the extent of shielding. The exposure rate can be reduced by shielding with materials such as lead or water, and engineering controls that maximize the distance between the beds and workers, and minimize the time spent by workers near the GAC units. Possible measures to reduce radon exposure by workers include:

- Automate the treatment system
- Install remote instrumentation and a remote control center
- Implement a radiation protection program that establishes operator exposure time management and measures radiation exposure (time logs, dosimetric badges, periodic Geiger-Mueller counter tests)
- Add vessel shielding, such as lead liners or water jackets around the GAC system
- Provide physical barriers such as caging around the contactors at one meter distances to prevent casual contact and therefore limit unnecessary body exposure
- Change site configuration to maximize distances between vessels or parallel trains
- Add a storage silo for offline storage of spent carbon (option for waste treatment)
- Improve ventilation/dispersion (Martins, 1992).

2.3.5.2 Spent GAC Disposal

A GAC bed used for radon removal can last for many years with little decrease in efficiency, assuming no limiting water quality conditions exist. Radionuclides (Pb-210 from the decay of radon and from the source water, and uranium and radium from the source water) accumulate at the GAC media. The presence of iron increases the ability of radium and uranium to adsorb to the media since iron is reactive with these compounds (AWWARF, 1997). Depending on the contaminants and the extent of accumulation, the disposal of the spent carbon containing Pb-210 and/or other contaminants could pose problems.

Currently there are no Federal regulations governing the disposal of radioactive wastes generated by water treatment facilities. The US Nuclear Regulatory Commission's (USNRC) definition of low level radioactive wastes is not based on the level of radioactivity but on how the material was generated. That agency does not regulate naturally occurring radioactive material (NORM). EPA's *Suggested Guidelines for Disposal for Drinking Water Treatment Wastes Containing Radioactivity* (U.S. EPA, 1994) and *Management of Water Treatment Plant Residuals* (U.S. EPA, 1996a) review disposal options and recommend disposal criteria. EPA's guidelines are summarized in **Table 2-17.**

Table 2-17. EPA Guidelines for Disposal of Radioactive Water Treatment Plant Residuals

Radionuclide level (pCi/g)		Recommended Disposal
Radium	Uranium 238	
<3	<30	Landfill – waste should be dewatered and mixed with other wastes.
3 to 50	30 to 75	Covered landfill to prevent release of radon to air. Dewatered and disposed in RCRA hazardous waste facility.
50 to 2,000	75 to 750	Handle on a case-by-case basis. RCRA hazardous waste facility. Low level radioactive waste facility.
>2,000	>750	As permitted by State regulations. Low level radioactive waste facility.

Source: "Assessment of GAC Adsorption for Radon Removal," (AWWARF, 1997).

AWWARF (1997) notes that most States deal with the disposal of radioactive water treatment plant residuals on a case-by-case basis. The States have no specific regulations or guidelines for these radioactive residuals but would apply existing solid waste or hazardous waste disposal requirements. New Hampshire requires that wastes containing radium at 0.444 pCi/g or uranium 238 at greater than 58.4 pCi/g be disposed of in a low level radioactive waste facility. Illinois licenses water treatment facilities and landfills receiving radium bearing sludges as radiation installations. Sludges containing less than 5 pCi/g total radiation can be disposed of in a permitted landfill. Sludges with radioactivity levels between 5 and 50 pCi/g can also be disposed of in a permitted landfill but under more stringent requirements. Sludges with radioactivity levels greater

than 50 pCi/g are handled on a case-by-case basis by the Illinois EPA and the Illinois Department of Nuclear Safety. (AWWARF, 1997)

AWWARF (1997) provides a method for predicting the accumulation of Pb-210 on the GAC using the following simplified equation:

$$\text{Pb-210 radioactivity/g of carbon after year 1} = \frac{(-2.57\times10^{-1})\ C_r K_{ss}}{(d)\ln\left(\frac{C_t}{C_o}\right)}$$

where:

C_r = radon removal (pCi/L)

K_{ss} = rate constant for a given GAC (1/hr)

d = density of GAC (lb/ft^3)

C_o = influent radon concentration (pCi/L)

C_t = effluent radon concentration (pCi/L).

As indicated in the AWWARF report (1997), this equation can be used as a general indication of Pb-210 buildup. The AWWARF (1997) report shows a set of Pb-210 buildup curves for different K_{ss} values. The above constant of 2.57×10^{-1} is believed to be the result of multiplication of a unit conversion factor of 546.92 and a curve slope value of 0.47×10^{-3} for a K_{ss} value of 4.5/hr.

Hess, et al. (1999) studied the effects of washing GAC in acid reagents and bases to determine whether they could be used to regenerate carbon. The GAC filters were used to remove radon from well waters with up to 100,000 pCi/L. Carbon used as radon filters was washed with either hydrochloric acid, nitric acid, acetic acid, EDTA, sodium hydroxide, potassium hydroxide, or distilled water. This series of washes was found to remove many of the radionuclides that had built up in the GAC as a result of the decay of radon that had adsorbed during use as a filter to

remove radon from drinking water. Pb-210 was reduced by factors ranging up to 65%, but in some cases also increased by as much as a factor of 2 due to a reduction in the mass and density of the sample. Thus, washing GAC in certain acids and bases may reduce the levels of Pb-210 and other radionuclides in spent GAC to levels not requiring special waste disposal. The researchers did not indicate whether spent acids and bases would require special waste disposal arrangements. (Hess, et al., 1998)

2.3.6 Case Studies

Full-scale studies to date using GAC for removing radon have involved central treatment systems and point-of-entry (POE) treatment devices. The majority have been on POE.

Mt. Vernon, New Hampshire—A GAC system for radon removal was installed in Mt. Vernon, New Hampshire by Dr. Jerry Lowry. The water supply consisted of two wells which supplied approximately 6,500 gallons per day to 40 mobile homes. The concentration of radon in the water averaged 155,000 pCi/L (Lowry, et. al., 1984)

The treatment system consisted of two GAC contactors connected in series. The contactors contained a total of 48 cubic feet of carbon which provided an empty bed contact time for each unit of 80 minutes. After achieving steady state operations in 10 to 15 days, the levels of radon in the treated water ranged from 4,000 to 15,000 pCi/L. This corresponds to a removal efficiency of 90.3 to 97.4 percent. Following 2 months of operation, major leaks developed in the distribution system that resulted in the wells being pumped dry several times. Following repairs, the levels of radon in the treated water rose to 22,000 pCi/L which corresponds to an 85.8 percent removal efficiency. The reasons for the decreased removal efficiency were unknown. However, one possibility was that sediments containing radium may have been deposited in the contactors.

Derry, New Hampshire—Kinner et al. (1990) conducted a pilot scale study at Derry, NH using two different GAC systems applied at the point of entry (POE). The first system consisted of a sediment filter with pleated paper for pretreatment and a GAC unit with 0.047m^3 of Barneby Cheney 1002 coconut-based carbon. The second system consisted of a sediment filter with pleated

paper, an ion exchange unit with 0.042m^3 of strong cationic resin and a GAC unit with 0.0465m^3 of 1002 carbon. Pretreatment and/or backwashing was applied to prevent fouling. The first system (with cation exchange pretreatment) achieved removals ranging between 85 and 99.7 percent, while the second system (without cation exchange pretreatment) achieved removals ranging between 79 and 99.7 percent. The systems were operated at a flow rate of 270 gpd at six 18-min intervals and a 30-min interval each day.

Mont Vernon, New Hampshire—Kinner et al. (1988), performed a full-scale study using a GAC system designed by Lowry Engineers. The system consisted of two filters operating in series. The first filter (30" diameter) contained 20 ft^3 of Barneby Cheney 1002 coconut-based carbon. The second filter (36" diameter) contained 27 ft^3 of carbon. The system achieved removals ranging between 74 and 88 percent. This decreased efficiency was attributed to clogging possibly from iron, manganese, bacteria or organics. The system was operated at an average flow of about 40,700 gpd with influent radon levels of about 191,000 pCi/L. Backwash was provided at 10 gpm. Spent carbon was shipped to an approved low level radioactive waste landfill in the western United States.

Leed, Maine—Lowry et al. (1990) performed a full scale GAC adsorption study in Leed, Maine. Influent radon levels were 1,124,000 pCi/L and the average flow was 886 L/day retained over 22 months. A standard GAC setup was used for the study. During adsorption, 99.5 percent radon removals were achieved while all progeny, Po-218, Pb-214, Bi-214 and Pb-210, were retained on the bed. Desorption occurred only when Rn-free (< 1 pCi/L) water with pH < 3.0 was applied to the bed. One hundred percent of the progeny was retained in the bed at pH > 3.0. It was concluded that optimal elution occurs when pH is between 2.0 and 3.0.

Hodsdon (1993) conducted a field survey of radon treatment facilities using GAC. The facilities surveyed included very small to medium sized water systems. A summary of the findings are presented in **Table 2-18**.

Point-of-Entry Units—Lowry et al. (1989) summarized data obtained from various full-scale point of entry (POE) GAC studies conducted between 1984 and 1989. The total number of selected units was 121 distributed in several states as shown in **Table 2-19**. Typical GAC systems were used for the studies. These systems included pump/hydropneumatic pressure systems, sediment filters, manual control valves, bottom injection flow inlets, and pressurized GAC treatment units with 6 inches of support gravel and 36 inches of GAC depth. However, different sizes of GAC units were used as shown in **Table 2-20**.

Table 2-18. Summary of Hodsdon's 1993 Survey of GAC Treatment Facilities

Influent Radon Level (pCi/L)	Location	System Design, Size, and Other Design Parameters	Removal Efficiency	Comments
7,367	Golden, Jefferson County, CO	Granular Activated Carbon – supply capacity 5 gpm – 1 contactor w/2 cu ft of carbon	20.4% (effluent = 5,866 pCi/L)	Avg daily use 1,000gpd – max capacity 7,200 gpd Sodium hypochlorite GAC followed by ion exchange pretreatment for iron and min removal by a cartridge filter
7,000–10,000	Friendship, ME	Granular Activated Carbon 2 wells – supply capacity 70 gpm each – 2 contactors	99+% (effluent = 50–70 pCi/L)	Avg daily use 3,000 gpd – max capacity 100,800 gpd Sodium hypochlorite Radon removal system is part of new groundwater supply
4,244	Readfield, ME	Granular Activated Carbon – supply capacity 30 gpm (2 wells @ 15 gpm each) – 2 contactors	96% (effluent = 174 pCi/L)	Avg daily use 2,000 gpd – max capacity 43,200 gpd Radon removal system is part of new groundwater supply
3,900	Conifer, CO	Granular Activated Carbon – supply capacity 3 gpm -1 contactor w/2 cu ft of carbon	42% (effluent = 2,260 pCi/L)	Avg daily use 3,000–4,000gpd Sodium hypochlorite Pretreatment – ion exchange unit
2,000 avg (1,470–2,280)	Woodbridge, VA	Granular Activated Carbon – supply capacity 180–200 gpm – 2 contactors in series w/EBCT of 20 mins each	initial – 90% in 1 yr – 60% >2 yrs – 0% 200–800 pCi/L	Avg daily use 280,000 gpd Chlorine GAC contractors initially installed for PCE removal

Table 2-19. Categorization of POE GAC Units by State

Categorization of POE GAC Units by State			
State	**Number**	**State**	**Number**
Maine	61	Colorado	3
New Hampshire	20	Rhode Island	3
New Jersey	12	Connecticut	6
Kentucky	1	New York	1
Pennsylvania	6	North Carolina	1
Massachusetts	5	Vermont	1

Table 2-20. Relative Use of Different Sized GAC Units

GAC Model	GAC (cu ft)	Vessel Size	Number Installed
Not designated	2.0/3.0	12" × 48"	12/3
GAC10	1.0	10" × 35"	15
GAC17	1.7	10" × 54"	72
GAC30	3.0	14" × 47"	16

Note: Barneby Cheney Type 299 coconut-based carbon was used in Models 10, 17, and 30. Calgon F-400 was used in 11 of the 12 (2.0 cu ft) not designated units. Norit was used in 1 of the not designated 2.0 cu ft units and in the 3.9 cu ft not designated units.

From the 121 selected installations, 64 percent achieved removals greater than 95 percent, 30 percent achieved removals between 80 and 90 percent, and 6 percent experienced premature failure that is believed to be water quality related. Based on these results, it was concluded that in order to meet maximum contaminant levels (MCLs), the POE GAC application should be limited to well supplies with Rn ≤ 5,000 pCi/L.

In addition, a more specific evaluation of selected full-scale units was conducted. Eleven locations were selected from the 121 based on the following criteria:

1. All installations had a long period of service.
2. One or more had several performance checks.
3. One or more had particularly water quality problem other than Rn.
4. One or more showed a progressive premature failure.

The removals ranged between 90 and 99 percent except for one installation where the removal ranged between 30 and 60 percent.

Best Management Practices

3.0 INTRODUCTION TO BEST MANAGEMENT PRACTICES

Best management practices (BMPs) are combinations of activities or modifications to treatment processes that under certain conditions will prevent the use of water sources high in radon levels and achieve acceptable water quality.

3.1 DESCRIPTION OF PRACTICES

3.1.1 Geologic Controls (Siting)/Alternate Sources

Development of alternative water sources located within a reasonable distance of a community which do not exceed the MCL for radon may provide a satisfactory solution to a community water quality problem. Although surface water sources may be free of radon, they may require treatment, such as clarification and disinfection, which may be as expensive as removing radon from the original source water. However, the radon contaminant in the original source may be peculiar to a localized geological formation and developing wells of different depths and at different locations should not be precluded.

Many communities may have existing facilities that can be utilized in the development of an alternative source. For example, systems with filtration or chlorination processes may adapt those processes to treatment of a new water source. Different combinations of new and existing processes relative to the size of the system and quality of water source impact significantly on cost and complexity.

3.1.2 Regionalization

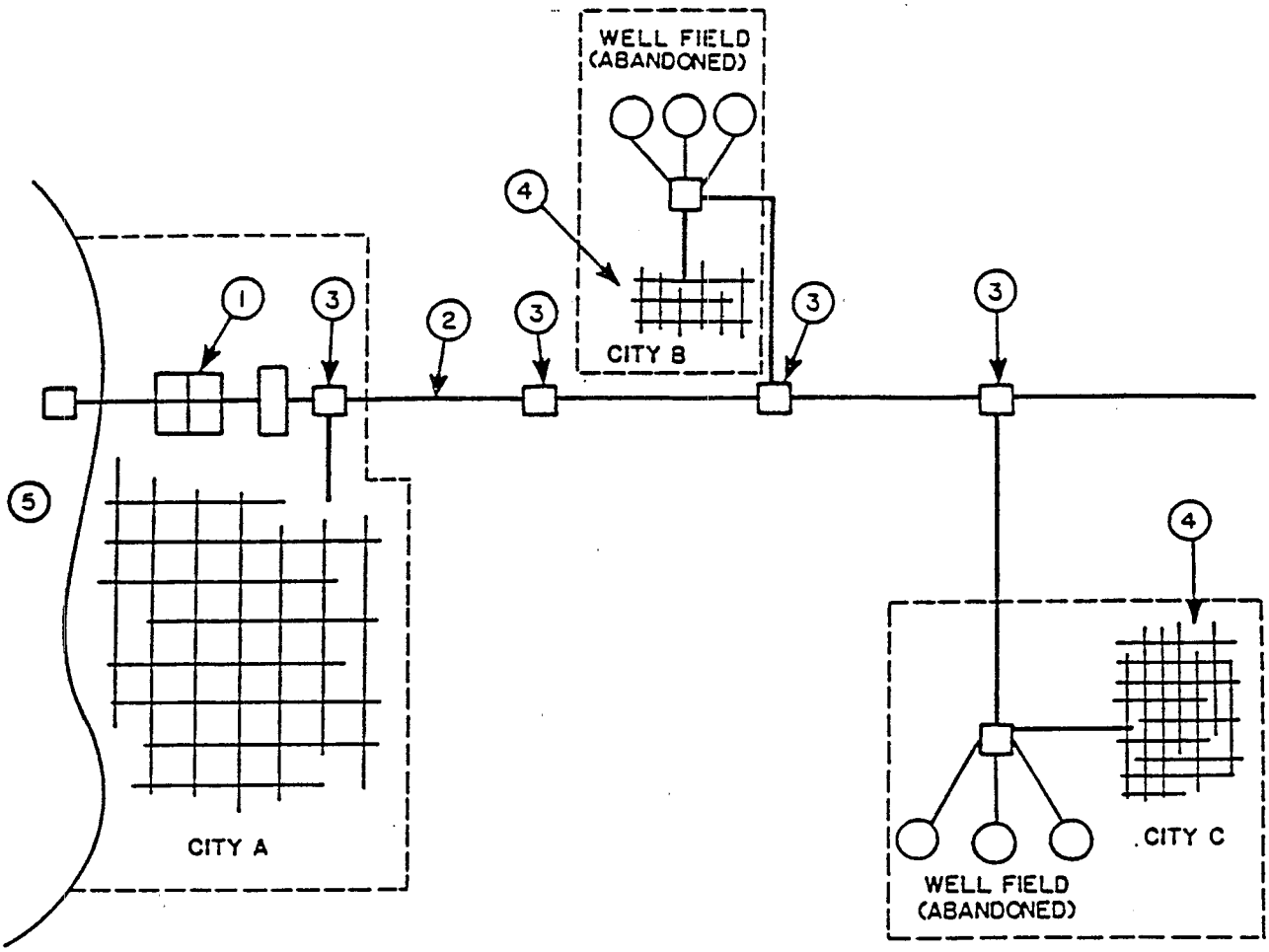
A feasible option, especially for small water systems that are out of compliance with the radon MCL requirements, is to join with other small or large systems that do comply with MCL requirements to form a regional water supply system. A schematic of such a system is shown as

Figure 3-1. This differs from alternate source development in that the basic water source has already been developed by the host community.

Generally it is the smaller communities or systems that may encounter radon concentrations in excess of the MCL because these systems tend to use ground water sources. Ground water sources are used by 91 percent of the systems serving under 500 people and 74 percent of the systems serving 501-3,300 people (NRC, 1997). Small systems also tend to have more operational reliability problems than do the larger systems (U.S. EPA, 1987). The cost of treating poor quality ground water and the technical difficulties that many small systems face make regionalization an appealing idea. With centralized treatment, treatment costs (capital and O&M) are frequently much lower than decentralized treatment. Regionalization can also provide other cost savings through shared maintenance service and/or central billing, which show economies of scale.

The cost of regionalization is independent of the particular contaminant being considered since regionalization involves supplanting the contaminated water supply with water from a (presumably larger) host community. A community may arrange for more than one host community to supply it with water. However, if multiple transmission pipelines are involved, this may increase costs. Since regionalization is one community arranging with a neighboring community to supply it with potable water, the distance between communities has shown to be the most sensitive factor affecting regionalization costs in this analysis. Piping treated water may prove prohibitive in sparsely populated regions. Regionalization requires a feasibility and economic study, preferably one that includes value engineering. A regionalization plan should include alternative solutions with cost comparisons such as pipe laying costs above ground versus below ground (where feasible), the use of one large pumping station versus several smaller pumping stations, and the use of multiple elevated reservoirs versus one large ground reservoir.

Figure 3-1. Regionalization



LEGEND

1. TREATMENT PLANT
2. TRANSMISSION LINE, NEW
3. PUMPING STATIONS, NEW
4. DISTRIBUTION
5. LAKE

Griffin (1989) noted the advantages of regionalization as follows:

- Cheaper treated water due to economics of scale
- Dependability of supply
- Longer life expectancy of pipelines than water treatment plants
- Long term economic benefits because of better quality, steady water supply, and less spending on water treatment.

Griffin (1989) also lists problems associated with regionalization:

- Requires the cooperation of individuals and groups with different mentalities, needs, and economic capacities
- May mean the abandonment of existing treatment facilities
- Challenges in places where water rights are an issue and water is scarce.

3.1.3 Extended Atmospheric Storage

Extended storage allows sufficient time for some radon reduction to occur through decay and losses to the atmosphere. During extended storage, the radon-contaminated water can be exposed to the atmosphere so that the contaminant may be naturally transferred to the atmosphere. Storage may be provided by reservoirs or water tanks, though water tanks would be easier to monitor for percent removals. Removals can be increased in the tanks by providing ventilation through the tanks to minimize the buildup of radon, which decreases removal efficiencies by hindering the natural diffusion process. The dimensions of the tanks also affect removal efficiencies, though more studies will be required to determine the removal efficiencies and costs of shallower tanks with large surface areas for greater contact with the atmosphere versus deeper tanks with the same storage capacity.

Advantages of storage can be summarized as follows:

- Provides radon treatment with and without ventilation or aeration because of natural decay
- Provides continuous water supply when key treatment units are out of service and during emergencies
- May provide savings on energy consumption by treating and storing water during off-peak energy rates.

Disadvantages associated with storage are included below in Section 3.1.5.

3.1.4 Blending

Many systems rely on ground water and surface water sources. In many cases, ground water is used during peak seasons or during dry years. For system with access to surface water, blending might be a viable option for reducing radon levels in drinking water, particularly for small systems. Since radon concentrations in surface water are typically very low, blending surface water with ground water will decrease, often significantly, the concentration of radon in the water supply. In addition, blending a low radon ground water source with the source high in radon is an option.

3.1.5 Limitations of BMPs

Although the above best management practices (BMPs) achieve some degree of removal, the following barriers limit their implementation in full-scale treatment:

- Existing storage tanks may not provide adequate headroom and ventilation to prevent the accumulation of a gaseous layer of radon, which can re-enter the aerated water. Storage must be carefully managed to avoid water stagnation. Deterioration of water quality can be dramatic otherwise, especially in the summer.
- Modifications to storage facilities may interrupt service.
- These systems will probably not achieve removals that are sufficient to attain desired water qualities, if influent levels are extremely high.
- Removals will not be consistent, depending on seasonal usage patterns and radon occurrence levels.

- The capacity of existing storage tanks will probably be insufficient to provide the necessary detention time to reduce radon concentrations to acceptable levels if high influent levels are present.

- The use of other sources, such as blending a surface water source with an existing ground water source, may reduce radon levels but may introduce other contaminants that require the addition of other treatment. Additional monitoring may be necessary to track source water quality, thus increasing costs.

- Additional transmission pipelines or pumps may be needed (e.g., storage systems may operate at atmospheric pressure, requiring either elevated tanks or repumping).

- Water quality may be less consistent (e.g., if storage times fluctuate greatly based on demand or if the quality of a blended source is not as reliable).

- Disinfection may be needed (e.g., if water is exposed to the atmosphere or blended with a surface water source).

3.2 REMOVAL EFFICIENCY

Limited data are available on removal efficiencies for the BMPs described above. These data are shown in **Table 3-1.**

Table 3-1. Removal Efficiencies for BMPs

Best Management Practice	Effect on Radon Level
Atmospheric Storage	7–13% removal – 9-hr detention time 33–36% removal – 30-hr detention time
Blending (6.34 MG of well water with 18.34 MG surface water)	79% reduction

3.3 DESIGN CRITERIA

The half-life of radon is 3.82 days. Therefore, to achieve a minimum of 50 percent removal of radon, a 4-day storage capacity is needed (if radon removal occurs by decay alone). While this might seem to be cumbersome for large systems with available sources of ground water, large and small systems with intermittent flows and fluctuating demands may find storage to be the best technology.

3.4 TREATABILITY/CASE STUDIES

Storage: Kinner et al. (1987) performed a laboratory study at the University of New Hampshire to monitor radon removal from a still pool of water to determine the effect of storage. A plastic storage tank with a capacity of 30 gallons was filled with water containing radon to a depth of 27 inches. The radon concentration was monitored for 5 to 6 days during four test runs. The results of this bench study are presented in **Table 3-2.**

Table 3-2. Bench Studies

Detention Time (hr)	Percent Decay[1]	Percent Removal
9	7	7–13
30	20	33–36

(1) The values for percent removal due to decay were calculated assuming first order decay and a radon half-life of 3.82 days.

The results of the study were used to develop design criteria for storage tanks. Although it is difficult to scale-up the removals cited above, the study determined low level radon removal may be attainable through the installation of storage tanks.

Blending: Based on volumetric dilution, Dixon and Lee (1987) blended 6.34 MG of well water with an average radon concentration of 1079 pCi/L and 18.34 MG of surface water with no radon. The average radon concentration in the blended water was 226 pCi/L.

Treatment Cost Analysis for Radon Removal Technologies

4.0 INTRODUCTION

This chapter presents capital and operation and maintenance (O&M) costs for treating radon in drinking water. Costs are presented for aeration technologies, granular activated carbon (GAC), pre-engineered centralized treatment devices, and regionalization. The cost equations and point estimates of costs presented in this chapter are developed to be used in the regulatory impact analysis process to estimate regulatory compliance costs for the prospective Radon Rule. Section 4.1 describes the cost estimating approach. Section 4.2 presents capital and O&M costs (in the form of summary cost tables) for aeration and GAC. Section 4.3 presents costs for inter-connecting small public water supplies (regionalization) as an alternative to installing treatment devices. Section 4.4 presents equations for estimating capital and O&M costs for pre-engineered centralized treatment devices for systems with very small flows (less than 10,000 gpd). Section 4.5 presents a comparative analysis of the aeration and GAC costs using case studies and other cost-estimating models. Section 4.6 presents the best-fit equations for aeration and GAC developed in Sections 4.2 through 4.4 in a summary form.

4.1 DESCRIPTION OF COST ESTIMATING APPROACH

For aeration and GAC, point estimates of capital and O&M costs for a series of plant sizes ranging from 10,000 gallons per day (gpd) to 100 million gallons per day (mgd)[9] were developed using cost estimating software. Costs were also estimated for aeration technologies for small plant sizes (0.1 to 2 mgd) using current cost estimating literature and according to generally recommended engineering practices. Since Radon's compliance costs could be borne primarily by small systems, the alternative costs using this approach provide another resource for analysts for estimating regulatory compliance costs. In addition to the basic technology costs for aeration and GAC, costs

[9] System sizes and flow ranges used in this costing exercise apply primarily to community water systems (CWS).

were also developed for indirect cost elements using various cost-estimating tools. Indirect elements include costs for structures, land, permitting, disinfection, and pretreatment.

Cost estimates for treatment units for capacities less than 10,000 gpd were obtained from the published literature on point-of-entry (POE) systems.[10] For centralized treatment of radon using POE devices, capital and O&M costs were estimated using the report entitled "Cost Evaluation of Small System Compliance Options: Point-of-Use and Point-of-Entry Treatment Units. EPA. Draft. April 20, 1998." Costs for regionalization were based on best professional judgment and using published unit cost data.

The following sections provide more detailed descriptions of the cost approach, cost estimating models, model inputs (design parameters and cost factors) and assumptions used for estimating capital and O&M costs.

4.1.1 Description of the Approach Used for Estimating and Validating PTA and GAC Costs

Specifically, the following approach is used for estimating PTA, DBA and GAC costs for plant sizes greater than 10,000 gpd:

- Available design and cost estimating models for PTA and GAC were modified and adapted for estimating radon treatment costs.
- Point estimates of capital and O&M costs were generated for 11 plant sizes ranging from 10,000 gpd to 100 mgd. The plant sizes were selected to provide representation across small and large water treatment plants.
- Indirect capital costs for permitting, structures, piloting, land, pretreatment, and post-treatment were also developed.
- In addition to model-based costs for PTA, costs were estimated for small systems using an alternative approach.

[10] POE technologies can be used by very small community water systems (CWS) or transient and non-transient non-community water supply systems (TNCWS and NTNCWS).

- Best-fit curves were fitted to the data points and cost equations (flow versus capital and O&M costs) were generated.

- Costs were compared to costs developed using other models and to case studies.

4.1.2 Description of the Cost Estimating Models For PTA and GAC

Two models, the PTA-COST and the GAC-COST, were used to estimate centralized capital and O&M costs for PTA and GAC, respectively[11]. Both models were developed by EPA but were modified by SAIC for estimating Radon treatment costs. Costs from other models, historically used by EPA for generating unit treatment costs, were also used but only for comparison with PTA-COST and GAC-COST estimates.

4.1.2.1 The PTA-COST Model

The PTA-COST Model was developed by EPA in the early 1980s for generating cost-optimized designs for counter-current packed tower aeration systems for removing volatile organic compounds (VOCs) from water. The PTA-COST Model was designed to generate process designs and costs for small to large PTA configurations. The PTA-COST Model has been modified several times over the past decade and was used most recently in 1992 for estimating radon treatment costs.

The PTA-COST Model (the 1992 version), written in an old version of the Hewlett Packard Basic language, was translated to a spreadsheet-based program and its design routines were modified to produce realistic PTA designs. These modifications include constraining the program to base costs on realistic tower dimensions (the 1992 version generated unrealistic tower dimensions) and simplifying the way the model checks for flooding conditions.

Significant changes were not made to the cost estimating routines. Data are not available to reliably change the equations in the model that describe the base capital and O&M costs. Therefore,

[11] Note that in this report, the PTA costs are assumed to also represent costs for technologies that are similar in performance and costs to PTA. These technologies include multi-staged bubble aeration (MSBA) and shallow tray aeration (STA). Costs for Diffused Bubble Aeration (DBA) were estimated separately.

the PTA-COST Model's estimated costs are validated by comparing them with costs from case studies and outputs from other models. While changes were not made to the underlying cost-estimating routines in the PTA-COST Model, cost indices and the labor rate were changed to update model costs to December 1997. The indices and labor rates used are discussed later in this section.

The design generated by the PTA-COST Model (1998 version) is for a system with a steel tower and internals, plastic packing, an air blower, influent pumping, clearwell (whose size can be adjusted based on detention time), piping, instrumentation, and electrical and air duct. The PTA-COST Model design does not consider a building (for housing pumps and other support equipment) or a chemical wash system. Costs for additional items are estimated separately. (see Section 4.2).

O&M costs generated by the PTA-COST Model include labor (mainly for taking readings), administrative costs, and power for pumps and the blowers. Appendix A-0 presents a conceptualized diagram of the assumed configuration.

4.1.2.2 The GAC-COST Model

EPA developed the original GAC-COST Model written in FORTRAN computer language in the late 1980s. EPA's application of this model is documented in a report entitled "EPA's Drinking Water and Groundwater Remediation Cost Evaluation: Granular Activated Carbon." The original GAC-COST Model was updated, converted to a spreadsheet, and additional automation added to simplify use. The current model performs GAC design calculations (e.g., it calculates empty bed contact time, contactor volume, and quantity of GAC) based on user supplied design criteria (e.g., design and average flow rate, percent radon removal, number of contactors, and loading). It then estimates capital and O&M costs for these designs.

For small systems, the model assumes that systems will use preengineered (package) treatment units. For larger systems, the model automatically selects the lowest cost of either a steel pressure contactor design or a concrete gravity contactor design. For these systems, capital costs include construction costs, backwash pumping, and the initial GAC load. Further details of the

elements included in construction costs are not provided in the original model documentation. However, given the similarity in capital cost found between the GAC-COST Model and other models (see Section 4.2), the GAC-COST Model is believed to include the same basic capital cost elements associated with "standard" GAC units. O&M costs in the model include labor, power, maintenance, process and GAC transport , GAC replacement, and spent carbon transport and disposal.

Construction costs generated by the model can be updated using cost indices. Cost factors (e.g., engineering, construction), used for estimating total capital costs, can also be adjusted by the user. O&M costs can be updated using the Producer Price Index, Bureau of Labor Statistics (BLS) labor rates, and water and energy unit costs.

4.1.2.3 Other EPA Models

EPA has traditionally used three models for estimating drinking water treatment technology costs. They are the Very Small Systems Model (VSS), the WATER Model, and the Water/ Wastewater (W/W) Cost Model. These models are capable of estimating capital and O&M costs for aeration and GAC as well as numerous other technologies. Use of a particular model is predicated on the size of the treatment system being costed.

These models are used only for making comparisons with the PTA-COST and GAC-COST Model outputs. Although they offer breadth in terms of the number technologies they cover, they have several limitations. First, the models cannot generate designs. Designs have to be generated separately by hand or by using another model. Second, the input design parameters for these models have to be within the original design constraints on which these models' cost equations are based. Thus, costs cannot be linked directly to a removal efficiency. Finally, these models are several years older than the unmodified PTA-COST Model and the GAC-COST Model. Despite these limitations, these models, provided they are used with care, are still good indicators of generalized *technology* costs and are generally sufficient for regulatory-type cost analysis or as a comparative tool.

The main features of the VSS, Water, and W/W Costs Models are described below.

The VSS Model

The VSS is a spreadsheet containing tables for 18 water treatment technologies. The spreadsheet was developed by SAIC using cost equations presented in an EPA Manual entitled "Very Small Systems Best Available Technology Cost Document, September 1993." Each table in the VSS spreadsheet corresponds to a treatment technology. Users input a public water system's design and operating flow, an escalation factor (e.g., average CCI increase), and the treatment plant's design and average flows . Capital and O&M costs are generated by the spreadsheet using the underlying cost equations. The VSS Model is applicable for treatment plants with design flows from 10,000 gpd to about 270,000 gpd.

The WATER Model

The WATER Model is also a spreadsheet program based on cost estimating equations presented in the EPA Report entitled "Estimation of Small System Water Treatment Costs 1984." The WATER Model can estimate capital and O&M costs based on user supplied design criteria and cost indices for 45 unit processes. Costs can be generated for a single process or a combination of processes (a treatment train). The costs in the WATER Model are applicable for plant sizes from 15,000 gpd to 1 mgd.

Construction cost data in the WATER Model are based on unit equipment cost data supplied by manufacturers, cost data from actual plant construction, unit takeoffs from actual and conceptual designs, and published data. Operation and maintenance requirements are based on operating data at existing plants, BPJ, and information from equipment manufacturers.

Construction costs generated by the WATER Model can be updated using cost indices. Engineering cost factors, used for estimating total capital costs, can also be adjusted by the user. O&M costs can be updated using labor indices, labor rates, and chemical costs.

The W/W Costs Model

The W/W Costs Model is a computerized DOS-based model and is applicable to large plants (1 to 200 mgd) but is also capable of estimating costs for package plants for some technologies (e.g., GAC). Version 2.0 of the W/W Costs Model was developed in 1994 by Culp/Wesner/Culp, an engineering consulting firm, based on various information sources including an EPA Report titled "Estimating Water Treatment Costs. Cost Curves Applicable to 1 to 200 mgd Treatment Plants, Volume 2, August 1979." This report provides conceptual designs and cost curves for 99 unit processes.

The W/W Costs Model allows the user to select from among 149 individual unit processes. About 90 unit processes are solely applicable to drinking water treatment. Similar to the WATER Model, the W/W Costs Model can be used to estimate costs for a single unit process or a combination of unit processes. Key inputs include construction cost indices (e.g., *Engineering News Record* indices), engineering cost factors, labor rates, and chemical costs.

4.1.3 Case Studies

Costs reported in case studies from several different sources and costs from other models were used to validate the costs generated by the PTA-Model and GAC Model. These case studies encompass projects for small to medium water treatment plants that have implemented aeration to treat radon and other VOCs. A brief description of each of the sources and general information vis-a-vis each case study is presented below.

A.E. Hodsdon Engineers Report: This document is an unpublished report entitled "Field Verification of Radon Treatment Costs for Very Very Small to Medium Sized Water Systems" prepared by A.E. Hodsdon Consulting Engineers for the AWWA. The study collected costs incurred by utilities to install various types of radon treatment systems including PTA, STA, DBA, and GAC. Data was collected via a questionnaire which requested a breakdown of costs. Only the raw data from this document was used for comparative analysis.

Operating Experiences at VOC Treatment Facilities: This report was prepared by Malcolm Pirnie, Inc. and presents process performance and costs for air stripping and GAC at facilities treating volatile organic compounds (VOCs). Since the same types of technologies that remove VOCs are applicable for Radon, the costs presented in this report were used.

Evaluation of Full-Scale Treatment Technologies at Small Drinking Water Systems, Summary of Available Cost and Performance Data: This document is a recently developed (1998) reference tool that contains cost and performance data for treatment technologies applicable to small drinking water systems.

MSBA Information from Lowry Engineers: Information was also obtained from memoranda from Lowry Engineers on the performance and costs of multi-staged bubble aeration (MSBA). Lowry Engineers have extensive experience in implementing aeration technologies for Radon removal.

Wright-Pierce Engineering Case Studies: Cost data for installed multi-stage bubble aeration was provided via personal communication to EPA by Wright-Pierce Engineers.

Assessment of GAC Adsorption for Radon Removal: This report was prepared by the American Water Works Association Research Foundation (AWWARF) and is a research effort aimed at determining radon removal efficiency of different types of GAC. Cost data are also provided for hypothetical treatment plants.

American Water Works Service Company: This report entitled "Pennsylvania-American Water Company, Eastern Region, Comprehensive Planning Study, 1990" details the costs of upgrading a ground water treatment facility in Frackville, Pennsylvania. Costs are included for various upgrades including a PTA system for VOC removal.

AWWARF: This report "Critical Assessment of Radon Removal Systems for Drinking Water Supplies, 1998" The report critically compares old EPA cost estimates with AWWA cost estimates and provides cost estimates from case studies.

4.1.4 Costing of PTA and DBA Units Using Direct Engineering Costing Methods

Since small systems may be impacted the most by the Radon regulation, a separate cost estimate for PTA was developed for small plants using best professional judgment and the cost estimating literature such as R.S. Means publications. Also, this cost estimate is based on using alternative materials of construction to those dictated by existing configurations. Costs were also estimated for DBA. Diffused bubble aeration is a technology that can be retrofitted into existing water treatment plants. It offers another alternative to installing a full-fledged PTA or similar unit and can provide a facility with a low-cost yet effective Radon control technology.

4.1.5 Assumptions for Engineering Cost Factors and Other Costing Inputs

In November of 1997, EPA convened the Technology Design Panel (TDP) at an EPA-sponsored workshop in Denver. The TDP was comprised of experts from the drinking water field. They provided recommendations on a host of issues vis-a-vis EPA's regulatory cost analysis process. Among the issues discussed was the need to bring better consistency in assumptions for estimating costs. Therefore, the assumptions for cost-related items in this report are based largely on the discussions among these experts which are embodied in two documents. These documents are: "Discussion Summary: EPA Technology Design Workshop." November 6 to 7, 1997 Denver, Colorado and the "Technology Design Information Package." November 1997.[12] Each of the cost elements is discussed below.

Engineering Cost Factors

[12] In many cases, the TDP did not provide specific recommendations. They provided ranges of expected values for various cost items. In cases where ranges were provided or in areas where they disagreed, the costing assumptions were based on an interpretation of the TDP's intent.

Based on an EPA Manual entitled "Innovative and Alternative Technology Assessment Manual," total capital costs are comprised of construction and other non-construction costs. Construction costs include the installed cost of components, miscellaneous structures, piping, instrumentation and site preparation. Non-construction costs include engineering design fees, overhead and profit, and contingencies. Non-construction costs are estimated based on assumed percentages. These percentages are known as engineering cost factors. For example, engineering design fees, which are based on the complexity and scale of a project, range from 4 to 15 percent of construction costs.

In the past, engineering cost factors in EPA's Technology and Cost (T and C) documents were based on best professional judgment and the literature. To promote better consistency in the application of engineering cost factors, the TDP made some recommendations (see **Table 4-1**).

As **Table 4-1** shows, the TDP left some leeway for interpretation of their guidelines and this is appropriate because the complexity of the technology under consideration and other factors will permit analysts some flexibility when developing treatment technology costs for T&C documents. At the same time, the lumping of many capital cost elements into three categories allows analysts to prepare cost estimates more quickly. The approach by the TDP is suited for regulatory cost analysis and where applicable their guidelines were integrated into the PTA and GAC Cost Models and applied to the VSS, WATER, and W/W Costs Model as well.

Small Systems	
Installed Process Equipment	40%
Engineering Design	20%
Construction [Indirect]	40%
Total Capital Costs	100%

Large Systems	
Process Equipment	22–29%
Engineering Design	25%
Construction [Indirect]	25–50%
Total Capital Costs	100%

Source: Discussion Summary: EPA Technology Design Workshop. November 6 and 7, 1997. EPA.
Note: Construction costs include miscellaneous indirect items like sitework, profit, and contingencies.

Table 4-1. Summary of Percentages Recommended by the TDP

However, a review of cost estimating literature and case studies indicate that the percentages recommended by the TDP are conservative. For example engineering design fees are reported in cost estimating literature to vary from 4 to 15 percent of total construction costs (Humphreys, 1993), with the higher percent being more applicable for complex chemical processing plants or small projects. Economies-of-scale results in indirect construction costs like engineering to become a relatively small component of the total capital costs.

An evaluation of case studies on PTA places mean engineering and indirect construction costs at 17 percent and 17 percent of total capital costs, respectively [**Figure 4-1**]. The percentages in Figure 4-1 are based on data for small drinking water plants with flows ranging from 9 to 1,400 gallons per minute (gpm). The 17 percent for engineering is high based on best professional judgment and the published literature but still below the TDP-recommendations (Table 4-1). However, for very small plants, engineering design can represent a large portion of total capital costs.

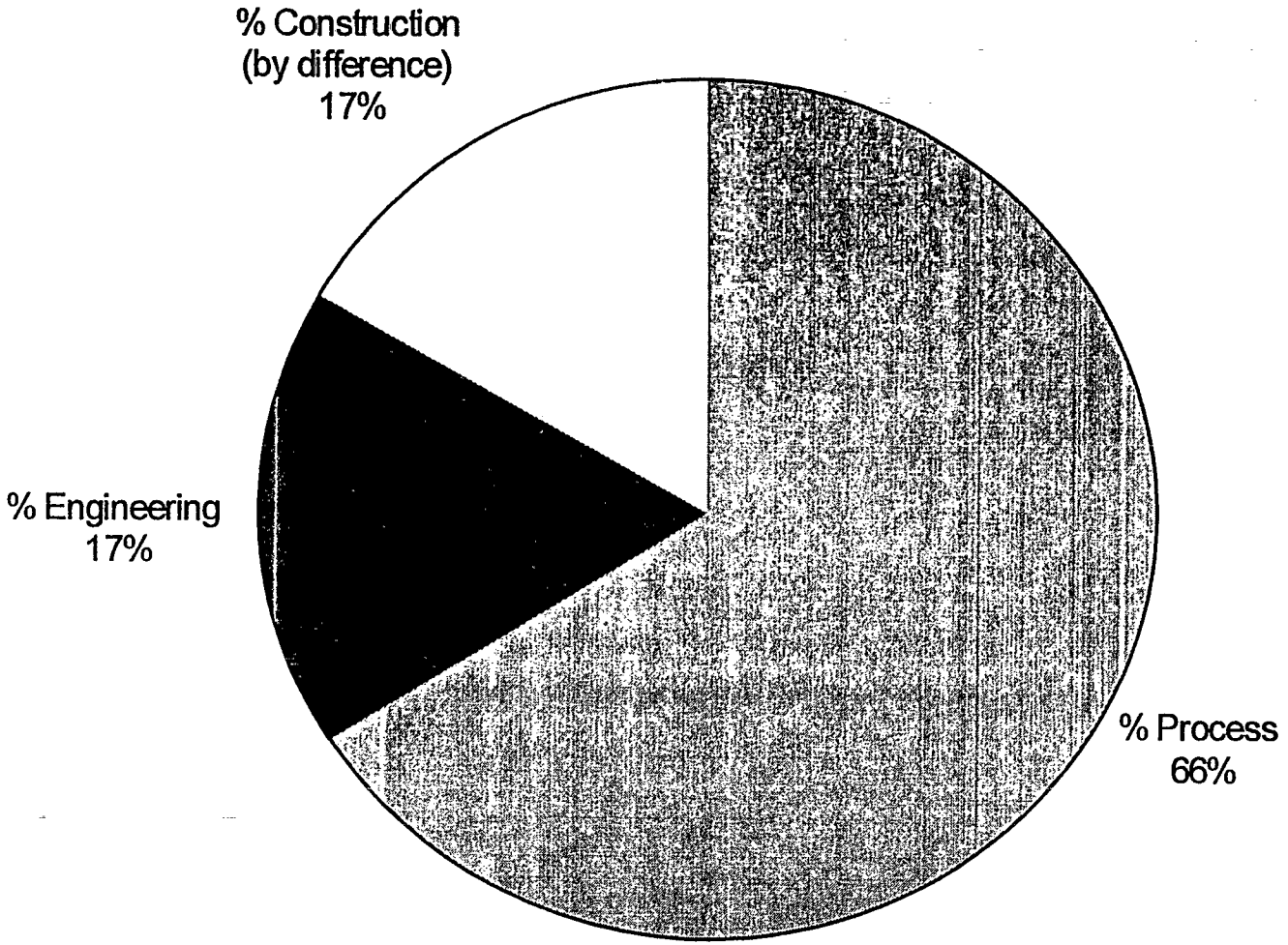


Figure 4-1. Percent Breakdown of Capital Costs for PTA, STA, and MSBA Case Studies

The case study data showed that engineering comprised only 8 percent of the capital costs for the 1,400 gpm plant, which is in line with expectations.

Figure 4-1 shows construction costs only account for 17 percent of total capital costs. This is much lower than the percentages recommended by the TDP, however, five of the 11 case studies had construction costs ranging from 3 to 10 percent of total capital costs. These may be low because some of the case studies were retrofits using innovative installation techniques rather than full-fledged installations. Without these data points, construction costs account for 25 percent of the total capital costs. This is in line with the TDP recommendations for small systems but at the lower range of the values for large systems.

Only four case studies were available for GAC, but the data shows that process equipment costs and installation account for two thirds of the total capital costs (**Figure 4-2**).

The implication of the TDP assumptions of process equipment costs can be seen by the following example.

Case 1 (Using TDP-recommended percentages)

Model-generated process equipment costs = $100 or 40 percent of total capital costs
Engineering costs = $50 or 20 percent of total capital costs (imputed by setting process = 40 percent of total capital costs)
Construction costs = $100 or 40 percent of total capital costs (imputed by setting process = 40 percent of total capital costs)

Total Capital Costs = $100 (process) + $50 (engineering) + $100 (construction) = $250

Case 2 (Using Case Study data where process equipment is a greater percentage of total capital costs)

Process Equipment Costs = $100 or 66 percent of total capital costs
Engineering costs = $25.75 or 17 percent of total capital costs
Construction costs = $25.75 or 17 percent of total

Total Capital Costs = $100 (process) + $25.75 (engineering) + $25.75 (construction) = $151.52

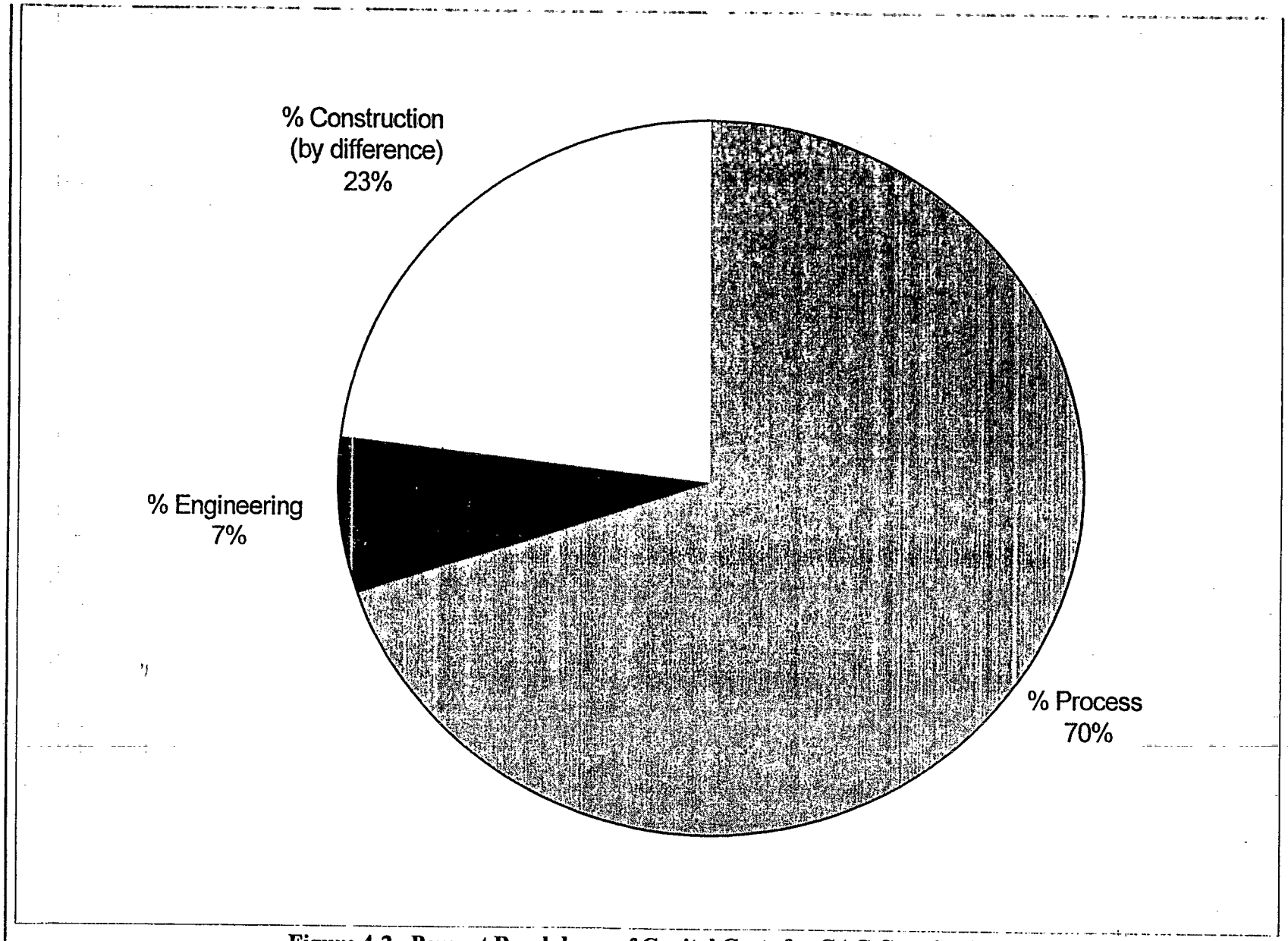


Figure 4-2. Percent Breakdown of Capital Costs for GAC Case Studies

The difference between the case study data and setting model-based estimates of process costs at 40 percent of total capital costs are 65 percent. This suggests that using the TDP-based approach, which assumes that equipment costs account for no more than 50 percent of the total capital costs may result in conservative estimates.

Because of the relatively high degree of conservatism introduced into the PTA and GAC Model Cost estimates if the TDP recommendations were adopted, costs estimates for alternative designs for PTA and DBA were based on applying percentages for individual elements based on the literature and best professional judgment.[13] This "two-pronged" approach for generating costs was designed to acknowledge the recommendations of the TDP while providing an alternative source for comparative analysis of the results. **Table 4-2** lists the percentages for engineering and construction costs used for PTA and GAC Models. The percentages used for the direct engineering approach are presented in Table 4-7.

Table 4-2. Percentages Used in the PTA-COST and GAC-COST Models[1]

Cost Component	Treatment Plant Size[2]					
	Small		Medium		Large	
	PTA	GAC	PTA	GAC	PTA	GAC
Installed Process Components[2]	50%	40.0%	40.0%	35.0%	30.0%	30.0%
Engineering	15%[2]	20.0%	22.5%	25.0%	30.0%	30.0%
Indirect Construction Costs[3]	35.0%	40.0%	37.5%	40.0%	40.0%	40.0%
Total Capital Costs	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

[1] Based on TDP guidelines.
[2] The TDP did not define small and large systems by flow. For this report small plants are 1 mgd; medium 1 to 10 mgd; and large plants are greater than 10 mgd.
[3] Includes miscellaneous indirect items like sitework, interest during construction, administrative and legal costs, and contingencies.

[13] Note that the TDP also provided recommendations that allows flexibility in making assumptions for engineering cost factors. Their recommended ranges for individual elements of indirect costs agree well with values reported in the literature and best professional judgment.

Labor Rates

Another issue discussed during the TDP workshop in Denver were operator labor rates used to estimate O&M costs. Old T&C documents show that analysts assumed labor rates for water treatment professionals to be about $15 dollars per hour. The TDP suggested that loaded labor rates should be used and that labor rates should account for system size. The TDP Panel recommended loaded labor rates ranging from $28 to $75, with the higher labor rates for highly trained water treatment professionals. They recommended checking labor rates from the Bureau of Labor Statistics (BLS) or from State operator surveys.

An evaluation of the labor rates (unloaded) from the BLS "1998-1999 Occupational Outlook Handbook- Water and Wastewater Treatment Plant Operators" reported unloaded weekly labor rates ranging from $335 to $1,034 with a mean of $668 which translates to $16.70 for a 40 hour workweek. Based on the BLS data, the maximum value of $1,034 translates to $25.85 per hour. Based on this data, the following loaded labor rates were selected.

Small Systems (< 1 mgd)	–	$28
Medium (1 to 10 mgd)	–	$40
Large (>10 mgd)	–	$52

Note: Above rates reflect a loading of 70–100 percent of base salary for fringe and other benefits

The above rates incorporate the TDP's recommendations for using loaded rates and acknowledge that labor rates increase as a function of system size.

Redundancies

Prudent design practices generally allow for redundancies. These may include an extra pump to allow for uninterrupted service. However, drinking water treatment plants typically have storage, which would allow for some down-time of equipment for repair. In the TDP workshop, the experts agreed that redundancy is not a major concern for small systems, particularly those with storage capacity. Most members of the TDP agreed that it was prudent to include redundancy for pumps and

chemical feeders. Accordingly, an extra pump and blower was assumed to be required for PTA and DBA.

Permits

In almost all cases, new construction will require the need for permits. Permits are required for construction and for discharge to air, water, or land. The TDP members suggested that permits be included as part of design costs or a value of 3 percent of total construction costs be assumed with a minimum floor of $2,500. Note that the TDP has already recommended relatively high percentages for design and including permitting costs at 3 percent of the construction costs may overinflate permitting relative to other costs. Permitting was not broken out separately for the available case studies that reported differentiated cost data (about 20 studies). Only one out of the 20 case studies reported permitting as a separate line item. The permitting costs for this facility were about seven percent of the total capital costs. **Figure 4-3** shows a breakdown of the mean percent for permitting and other "extra" line items. It is inferred from these case studies that permitting is typically not a cost driver and may already be rolled into items like engineering design. Thus, assuming an additional 3 percent of capital costs for permitting adds a level of conservatism that may not be necessary, particularly when the assumed engineering cost factors are already conservative. Since percentages for engineering are already believed to be conservative, permitting is not included as part of the basic technology installation costs but the final decision to use the 3 percent suggested by TDP or to assume it as part of the design is better made during the RIA process. Accordingly, permitting costs are presented in this document as a separate line item.

Land

Treatment plants typically have land available to install a new unit process. Neither PTA, nor GAC are particularly land-intensive technologies but some systems may need to purchase land to install these systems. The TDP members discussed the fact that land could be an important item driving costs, particularly for scenarios where treatment plants are located in dense urban areas such as Los Angeles county. However, the TDP members did not provide specifics on valuing land but generally agreed that regulatory analysis costs should acknowledge that treatment plants may have

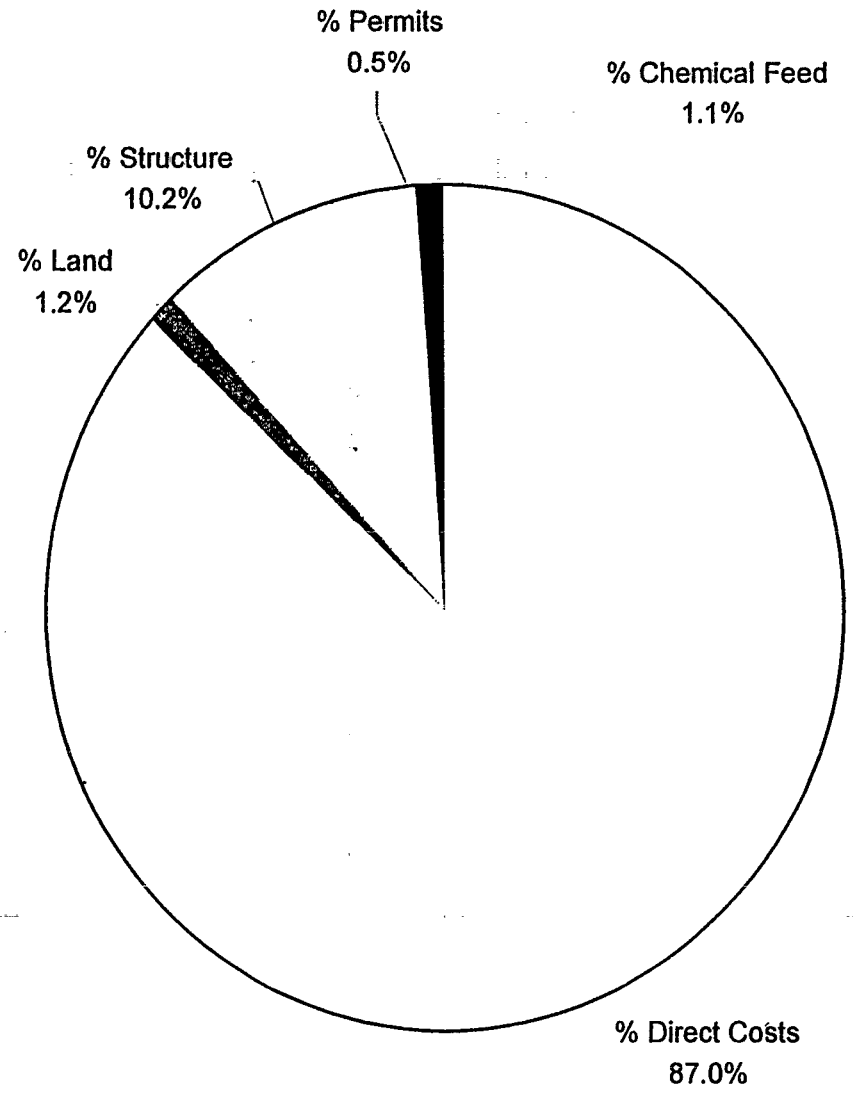


Figure 4-3. Mean Percent Breakdown of Various Indirect Cost Compounds

to purchase land and that the value of this land would vary based on whether it was located in a rural, suburban, or an urban area.

For the purposes of this document, the TDP's recommendations for land were addressed by assigning land values based on system size. The following land values were used.

Small Systems (< 1 mgd)	–	$1,000 per acre
Medium (1 to 10 mgd)	–	$10,000 per acre

The cost per acre for small systems is based on the assumption that small systems will typically be located in rural areas or in areas where land is not expensive. Larger systems would be located in small towns or metropolitan areas where land prices are higher. Note that of the 20 case studies with disaggregated costs for aeration, only two reported land acquisition. Land accounted for about 15 percent and 3 percent of the total capital costs for these two case studies. Across all case studies, land accounts for about one percent of total costs. This suggests that it may not be a significant cost driver.

Pre-and Post-Treatment Costs

As noted previously, the installation of PTA or GAC could trigger the need for other technologies. Disinfection of previously undisinfected groundwater water or post-treatment may be necessary because the water passing through the packing or the GAC system could become microbiologically contaminated. Also, PTA or GAC systems can be fouled if the raw water contains too much iron and/or manganese. In this case, the water would need to be pre-treated prior to the PTA or GAC unit.

Costs for disinfectionare included in this document for estimating disinfection costs for those systems requiring disinfection. Costs for disinfection are based on the document "Evaluation of Central Treatment Options As Small System Treatment Technologies." Note that about half of the ground water PWS universe already disinfects. Thus, a limited subset of potentially impacted facilities would need to install disinfection.

While some utilities are expected to require pre-treatment to improve the raw water quality for PTA and GAC, the number is expected to be small. First, it is presumed that water supplies with high iron and manganese problems are already treating these pollutants for aesthetic reasons. Second, an evaluation of co-occurrence data (**Table 4-3**) indicates that only a small fraction of systems have iron or manganese at levels greater than the secondary MCLs (0.3 mg/l for Fe and 0.05 mg/l for Mn). Third, for the case of PTA (or other types of aeration), chemical wash systems can be purchased at a small fraction of the costs for installing full-blown iron and manganese treatment units. For those utilities (believed to be limited) requiring pre-treatment, generalized capital and O&M cost curves were taken from the same document as that for pre-treatment.

Table 4-3. Co-Occurrence Data for Iron and Manganese Versus Radon

Radon (pCi/L)	Diss. Fe (mg/L)					
	ND	**< 0.3**	**0.3–1.5**	**1.5–2.5**	**>2.5**	**Totals**
ND	0.67%	0.36%	0.21%	0.02%	0.31%	1.57%
<100	2.17%	1.72%	0.53%	0.12%	0.48%	5.02%
100–300	7.55%	10.20%	2.67%	1.34%	1.74%	23.50%
300–1,000	18.89%	22.61%	3.08%	0.57%	1.31%	46.46%
1,000–3,000	6.42%	9.05%	0.74%	0.10%	0.62%	16.93%
>3,000	**2.10%**	**3.82%**	**0.31%**	**0.02%**	**0.26%**	**6.51%**
Totals	**37.80%**	**47.76%**	**7.54%**	**2.17%**	**4.72%**	**100.00%**

Radon (pCi/L)	Diss. Mn (gm/L)				
	ND	**< 0.02**	**0.02–0.05**	**> .050**	**Totals**
ND	0.69%	0.26%	0.05%	0.57%	1.57%
>100	2.67%	0.84%	0.36%	1.15%	5.02%
100–300	8.00%	5.97%	2.20%	7.33%	23.50%
300–1,000	21.99%	11.84%	3.17%	9.48%	46.48%
1,000–3,000	6.45%	5.90%	1.24%	3.34%	16.93%
> 3,000	1.43%	3.39%	0.53%	1.17%	6.52%
Totals	**41.23%**	**28.20%**	**7.55%**	**23.04%**	**100.00%**

Source: EPA, 1999.

Housing

Housing can also be required to enclose the entire process or components of the process. PTA systems do not require housing except for components like pumps, blowers, and control instrumentation but an entire GAC unit can be enclosed in a building (although many GAC units are also found outdoors). For the purposes of this document, housing requirements for PTA and GAC are based on best professional judgment. A review of engineering literature reports that building costs can account for up to 20 percent of the process equipment costs (AWWA/ASCE, 1990). For the 20 case studies, eight facilities reported requiring structures. These eight facilities' costs for structures were about 19 percent of the total costs, which corroborates the literature. The mean across all case studies was 10 percent (Figure 4-3).

For PTA, it is assumed that building costs account for 10 percent of the process equipment costs because housing requirements need only address pumps, blowers, and instrumentation. For GAC, it is assumed that housing costs are 20 percent of the process equipment costs.

4.1.6 Summary of Design and Cost Assumptions Used for Each Model

The key design inputs for the PTA-COST Model are the design and average plant flows, Henry's law co-efficient for Radon, the desired removal efficiency, air-to-water ratios, cost indices, and a labor rate. Other variables are "internal" and can only be manually altered. These variables include size ratios for the clearwell, physical constants, and cost/design relationships developed by the original authors of the program. These design factors were also used for sizing PTA units costed using the direct engineering costing approach.

The basic input parameters for GAC design are the design and average flows of the system and the rate constant (K_{ss}). The higher the K_{ss} value, the more the contaminant adsorbs to the carbon. Higher K_{ss} values result in lower empty bed contact times (EBCT), the time the water needs to be in contact with the carbon to achieve the desired performance goal (AWWARF, 1997). This translates into smaller process units and lower costs. In a study conducted by AWWARF, K_{ss} values used for conceptual design scenarios for treating radon ranged from 1.5 to 4.5. Costs in this report are based on a K_{ss} of 3.0, the mid-point of the AWWARF scenario values.

The key design and cost input variables for PTA and GAC are presented in **Tables 4-4** and **4-5** for the models used. **Table 4-6** presents a summary of input cost factors and cost indices used in the models.

4.1.7 Summary of Assumptions Used for Alternative PTA

As noted earlier, PTA costs were estimated using an alternative approach, which entailed considering different materials of construction and a potentially less expensive configuration. This approach was used only for a series of small plants, ranging in size from 0.05 to 2.9 mgd. This method was used because radon compliance costs are expected to be incurred by small systems and having an alternative to the model-based costs for PTA would provide analysts with more flexibility during the RIA.

For this approach, PTA designs were based on standard design equations available in engineering literature. **Table 4-7** presents the design and cost estimating assumptions used. The key difference from the PTA Cost Model's conceptual configuration and the direct engineered design is the fact that the tower rests on a slab and that the clearwell is at grade. These differences are expected to result in a more cost-effective design (excavation and concrete work are minimized) and may be more realistic for small systems dealing strictly with a Radon problem. Appendix A-0 presents a conceptualized diagram of the design.

4.1.8 Summary of Assumptions Used for Alternative DBA

Diffused bubble aeration has also been demonstrated to be effective for Radon removal. Cost estimates for DBA were developed by selecting and costing components that are common with PTA (primarily the blower). Specifically, costs for the tower and installation, internals, packing material were "backed out" of the cost estimates for the direct-engineered PTA treatment unit. The same number of plants as the direct engineered PTA were used. The air blower was sized using the same equations and assumptions as the direct engineered PTA using a water height of 3 feet. This "back-of-the-envelope" cost estimate for DBA yields conservative estimates of capital and O&M cost estimates. The design assumptions for this configuration are presented in **Table 4-8**.

Table 4-4. Summary of Design Inputs for Estimating PTA Costs

Model	Design Inputs
PTA-COST	Flow: Range of flows to cover plant sizes from 0.01 to 100 mgd Loading Rate: 30 gpm/ft2 (flooding considerations) Air-to-Water Ratio: 15 (This can vary from 2 to 50 based on flooding checks) Tower Dimensions: Column diameter: Between 0.5 and 10 feet Packing height: Between 1 and 20 times the diameter but less than 40 feet Removal Efficiencies: 80 and 99 percent. Clearwell: Generated by the model based on detention time. (5- and 10-minute detention times were considered.)
VSS*	Flow: Range of flows to cover plant sizes from 0.015 to 0.270 mgd (the model's flow domain) Costs based on designs generated by PTA-COST Model
Water*	Flow: Range of flows to cover plant sizes from 0.015 to 1 mgd (the model's flow domain) Costs based on design generated by PTA-COST Model
W/W Cost*	Flow: Range of flows to cover plant sizes from 1 to 100 mgd Costs based on design generated by PTA-COST Model
* These models cannot perform process design. The PTA-COST Model was used to generate the process design for use in these models. Outputs from these models are used for comparison with PTA-COST Model results only.	

Table 4-5. Summary Design Inputs for Estimating GAC Costs

Model	Design Inputs
GAC-COST	Flow: Range of flows from 0.01 to 100 mgd K_{ss}: 3.0 (Mean of the values reported in AWWARF's Radon Report)[1] Removal Efficiency: 50, 80, and 99 percent. GAC replacement frequency: 555 days[1] Density of carbon: 26 lbs/ft^3 Transportation and disposal of GAC as a non-radioactive waste costs are included (see Appendix A).
VSS*[1]	Flow: Range of flows to cover plant sizes from 0.015 to 0.270 mgd (the model's flow domain) Costs based on designs generated by GAC-COST Model
Water*[1]	Flow: Range of flows to cover plant sizes from 0.015 to 1 mgd (the model's flow domain Costs based on design generated by GAC-COST Model
W/W Cost*[1]	Flow: Costs based on design generated by GAC-COST Model
[1] Assessment of GAC Adsorption for Radon Removal. Revised Final. November, 1997. AWWARF. Denver, CO. GAC replacement frequency is based on length of study in the AWWARF Report. * These models cannot perform process design. The GAC-COST Model was used to generate process designs. Outputs from these models are used for comparison with GAC-COST Model results only.	

Table 4-6. Cost Indices and Other Factors for Models

Cost Index/Parameter	Index/Factor Value
Engineering and Design (percent of total capital costs) [1]	See Section 4.1.5
Construction (percent of total capital costs) [1]	See Section 4.1.5
Land Cost ($/Acre) [2]	$1,000 for rural (< 1 mgd) $10,000 for urban (> 1 mgd)
Electricity Cost ($/kwh) [3]	0.090
Labor ($/hr) [4]	$28 per hour for systems < 1 mgd) $40 per hour for systems between 1 and 10 mgd $52 per hour for systems > 10 mgd
Diesel Fuel ($/gal) [3]	0.979
Natural Gas ($/ft^2) [3]	0.0085
Building Energy (kwh/ft^2/yr) [5]	19.5
ENR Skilled Labor (1967 base) (1913 base)	 531 (for WATER Model) 5,294 (for W/W Costs Model)
ENR Building Costs (1967 base) (1913 base)	 499.1 (for WATER Model) 3,370 (for W/W Costs Model)
ENR Construction Cost Index (1983 base) Average CCI Increase	 542 (for PTA-Cost Model) 3.2 (for W/W Costs Model)
PPI for Finished Goods	367.9 (for WATER Model)
BLS Commodity Code No. 114	441.9 (for WATER Model)
BLS Commodity Code No. 132	447.9 (for WATER Model)
BLS Commodity Code No. 1017	405.6 (for WATER Model)
BLS Commodity Code No. 1149	517.8 (for WATER Model)
BLS Commodity Code No. 117	281.9 (for WATER Model)

[1] Engineering and construction cost percentages are based on evaluation of constructed projects and from recommendations from experts (seeSection 4.1.3).
[2] Land costs are based on "Technology Design Conference Information Package. USEPA. Nov. 1997" and best professional judgment.
[3] Bureau of Labor Statistics.
[4] Labor costs are based on range of labor values presented in TDP Report. Rates are loaded values.
[5] WATER Model Document.

Table 4-7. Design and Cost Assumptions for Alternative PTA Configuration

Process Item or Parameter	Value
Plant Sizes	Five plants sizes: 0.1 to 2.2 mgd design flows.
Performance	80 and 99 percent removal
Tower Height	Restrained to 20 ft by varying diameter within a 1 to 5 foot range to maintain low profile. Tower height is three feet greater than packing height.
Tower Diameter	Between 1 and 5 feet.
Tower Construction	Fiberglass Unit with steel internals mounted on 10' × 15' 8" concrete slab.
Pumps	Dual centrifugal pumps at the inlet. Designed to deliver water to top of the tower. 20 percent allowance for suction head and another 20 percent for frictional losses. Pumps and blowers are housed in sheds.
Clearwell	At grade ready-made tank
Blower	Standard air blower
Piping and valving	Pipe diameter based on 6 ft/s delivery. Three butterfly valves to regulate and distribute flow (see conceptual diagram)
Packing	Plastic packing
Air-to-Water Ratio	15–25 to keep tower height at 20 feet
Overall mass transfer coefficient	0.015 per second (see Appendix for other physical constants used)
O&M labor	15 minutes per shift to take readings. Two shifts for plants under 1 mgd, three shifts for plants greater than 1 mgd. Labor rate of $28 per hour for plants under 1 mgd; $40 per hour for plants greater than 1 mgd.
Maintenance	Two days per year
Packing reconditioning	Once every year
Other Factors	Engineering Design – 15 Percent Other Indirect Costs – 12 Percent (Profit); 15 Percent (Contingencies)

4.2 CAPITAL AND O&M COSTS AND EQUATIONS

Point estimates of capital and O&M costs for aeration and GAC were first generated based on the approach(es) described in Section 4.1. Cost curves were then generated using the trendline function in Microsoft Excel, which generates best-fit equations for the flow and cost relationship. Polynomial equations were used to provide the best possible fit.

Table 4-8. Design and Cost Assumptions for Direct Engineered DBA

Process Item or Parameter	Value
Plant Sizes	Plants sizes: 0.05 to 2.9 mgd design flows.
Performance	80 and 99 percent removal
Water Height	Restrained to 3 ft.
Tank size	Based on 5 minutes retention time. At grade ready-made tank
Tank	Fiberglass Unit with steel internals mounted on 10' × 15' 8" concrete slab.
Pumps	Dual centrifugal pumps at the outlet. Designed to boost water delivery to the next treatment step.. With 20 percent allowance for suction head and another 20 percent for frictional losses. Pumps and blowers are housed in sheds.
Blower	Standard air blower
Piping and valving	Pipe diameter based on 6 ft/s delivery. Three butterfly valves to regulate and distribute flow
O&M labor	15 minutes per shift to take readings. Two shifts for plants under 1 mgd, three shifts for plants greater than 1 mgd. Labor rates of $28 per hour for plants under 1 mgd and $40 per hour for plants greater than 1 mgd.
Maintenance	Two days per year
Other Factors	Engineering Design – 15 Percent Other Indirect Costs – 12 Percent (Profit); 15 Percent (Contingencies)

4.2.1 Capital and O&M Costs for PTA and DBA

Table 4-9a presents a summary of capital and O&M costs from the PTA-COST Model for all of the scenarios considered for PTA. **Table 4-9b** presents costs for other indirect items potentially associated with the base aeration technology. **Table 4-9c** presents capital and O&M costs for direct-engineered PTA. **Table 4-9d** presents capital and O&M costs for DBA. Equations based on the costs shown in Tables 4-9a through 4-9d are presented at the end of this chapter.

Appendices A-1 and A-2 present more detailed breakdowns of estimated costs, cost curves and resulting best fit equations.

Table 4-9a. Capital and O&M Costs for Packed Tower Aeration (PTA)

CAPITAL COST					O&M COSTS				
Design Flow (mgd)	5 Minute 99% (1)	5 Minute 80% (1)	10 Minute 99% (1)	10 Minute 80% (1)	Average Flow	5 Minute 99% (1)	5 Minute 80% (1)	10 Minute 99% (1)	10 Minute 80% (1)
	Base	Base	Base	Base	(mgd)	Base	Base	Base	Base
0.01	27,979	21,505	29,945	23,471	0.002	1,470	1,338	1,470	1,338
0.03	41,661	33,109	44,919	36,367	0.007	1,674	1,495	1,675	1,496
0.07	63,501	52,001	68,425	56,927	0.017	2,059	1,801	2,062	1,804
0.11	77,308	62,832	83,500	69,024	0.028	2,316	1,970	2,321	1,975
0.31	117,716	92,852	128,424	103,560	0.091	3,456	2,726	3,479	2,749
0.75	180,340	140,076	197,882	157,618	0.240	5,771	4,306	5,847	4,381
2.20	415,326	314,198	456,938	355,816	0.820	14,128	10,122	14,453	10,447
7.80	1,057,889	695,559	1,154,142	791,812	3.300	54,432	35,774	55,960	37,302
23.00	3,452,713	2,063,633	3,745,140	2,356,060	11.000	173,419	108,668	178,691	113,940
81.00	10,199,394	5,881,980	11,153,507	6,836,090	44.000	662,207	423,862	678,558	440,213
100.00	12,256,307	6,994,577	13,352,424	8,090,694	56.000	843,648	542,329	865,957	564,637

Note: Base costs do not include indirect items (permitting, land, pre-treatment, post-treatment)
Redundancies are factored into the base technology costs above.
(1) Clearwell detention time.

Table 4-9b. Costs for Indirect Items Potentially Associated with Aeration

Design Flow (mgd)	Average Flow (mgd)	Clearwell Costs*		Permitting				Land		Housing				Pre-treatment Capital	Pre-treatment O&M	Post-treatment Capital	Post-treatment O&M
		80 and 99 Percent**		80 Percent **		99 Percent**		80 and 99 Percent**		80 Percent **		99 Percent**					
		5 Min***	10 Min***	5 Min***	10 Min***	5 Min***	10 Min***	5 Min***	10 Min***	5 Min***	10 Min***	5 Min***	10 Min***				
0.01	0.002	$6,118	$7,101	$2,500	$2,500	$2,500	$2,500	$270	$272	$1,075	$1,174	$1,399	$1,497	$7,851	$2,680	$8,062	$2,680
0.03	0.0069	$7,836	$9,465	$2,500	$2,500	$2,500	$2,500	$276	$277	$1,655	$1,818	$2,083	$2,246	$19,712	$2,701	$8,062	$2,701
0.07	0.01745	$9,909	$12,371	$2,500	$2,500	$2,500	$2,500	$278	$285	$2,600	$2,846	$3,175	$3,421	$40,096	$2,748	$8,062	$2,748
0.11	0.028	$11,419	$14,514	$2,500	$2,500	$2,500	$2,505	$282	$288	$3,142	$3,451	$3,865	$4,175	$58,559	$2,795	$9,773	$2,795
0.31	0.091	$16,549	$21,903	$2,786	$3,107	$3,531	$3,853	$292	$300	$4,643	$5,178	$5,886	$6,421	$183,206	$3,086	$37,155	$3,086
0.75	0.24	$23,980	$32,751	$4,202	$4,729	$5,410	$5,936	$307	$320	$7,004	$7,881	$9,017	$9,894	$390,289	$5,761	$37,155	$5,761
2.2	0.82	$41,403	$57,691	$9,426	$10,674	$12,460	$13,708	$3,337	$3,526	$12,568	$14,233	$16,613	$18,278	$980,500	$13,109	$45,229	$13,109
7.8	3.3	$89,864	$128,365	$20,867	$23,754	$31,737	$34,624	$4,055	$4,405	$27,822	$31,672	$42,316	$46,166	$2,897,122	$15,774	$82,905	$15,774
23	11	$203,089	$290,817	$61,909	$70,682	$103,581	$112,354	$5,228	$5,896	$61,909	$70,682	$103,581	$112,354	$7,310,933	$17,561	$172,516	$17,561
81	44	$530,824	$817,058	$176,459	$205,083	$305,982	$334,605	$7,954	$9,767	$176,459	$205,083	$305,982	$334,605	$21,478,154	$45,314	$462,668	$45,314
100	56	$604,533	$933,368	$209,837	$242,721	$367,689	$400,573	$8,421	$10,494	$209,837	$242,721	$367,689	$400,573	$25,723,720	$56,378	$521,555	$56,378

*Costs are the same for the 80 and 99 percent removal scenario (i.e., costs differ only as a function of clearwell detention time selected)
** Removal efficiency
***Clearwell detention times.

Table 4-9c. Capital and O&M Costs for Direct-Engineered PTA

Flows (mgd)		Capital Costs		O&M Costs	
Design	Average	80% Removal	99% Removal	80% Removal	99% Removal
0.0432	0.0216	$27,300	$29,000	$8,700	$8,700
0.072	0.036	$28,600	$30,700	$8,700	$8,800
0.1296	0.0648	$28,700	$31,000	$8,800	$8,900
0.36	0.18	$36,600	$41,800	$9,900	$10,600
0.72	0.36	$50,400	$57,200	$10,600	$11,900
1.08	0.54	$57,800	$69,000	$12,200	$15,700
1.44	0.72	$59,900	$70,100	$12,200	$15,700
2.88	1.44	$82,000	$99,400	$12,800	$17,500

Table 4-9d. Capital and O&M Costs for DBA

Design Flow (mgd)	Average Flow (mgd)	Capital Cost	O&M Cost
0.0432	0.0216	$19,100	$8,600
0.072	0.036	$20,300	$8,600
0.1296	0.0648	$20,000	$8,600
0.36	0.18	$22,300	$9,200
0.72	0.36	$34,700	$9,200
1.08	0.54	$37,800	$10,300
1.44	0.72	$40,900	$10,300
2.88	1.44	$56,900	$10,300
Note: Costs are the same for 80 and 99 percent removals.			

4.2.2 Capital and O&M Costs for GAC

Table 4-10a presents a summary of Capital and O&M costs for GAC for all of the performance scenarios considered. **Table 4-10b** presents costs for other indirect items potentially associated with the base GAC costs in Table 4-10a. Appendix A-3 present the breakdown of estimated costs and charts.

Table 4-10a. Capital and O&M Costs for GAC

Design Flow (mgd)	Average Flow (mgd)	Capital Costs			O&M Costs		
		Removal Efficiencies			Removal Efficiencies		
		50%	80%	99%	50%	80%	99%
0.01	0.002	$200,178	$257,071	$374,096	$12,971	$13,100	$13,457
0.03	0.0069	$293,233	$394,296	$602,176	$14,907	$15,269	$16,309
0.07	0.01745	$411,868	$569,282	$971,159	$16,974	$17,779	$20,229
0.11	0.028	$500,405	$699,796	$1,208,840	$18,355	$19,605	$23,365
0.31	0.091	$795,474	$1,236,400	$2,401,522	$23,586	$27,256	$37,347
0.75	0.24	$1,313,660	$2,187,442	$4,791,942	$31,712	$39,980	$76,408
2.2	0.82	$3,080,503	$5,705,503	$11,673,936	$63,266	$92,278	$175,475
7.8	3.3	$7,581,376	$13,249,687	$28,217,632	$165,512	$267,143	$588,849
23	11	$19,269,087	$34,665,414	$75,844,735	$421,489	$747,899	$1,762,002
81	44	$49,865,101	$91,797,355	$205,781,817	$1,449,685	$2,628,487	$6,249,214
100	56	$58,500,325	$108,181,943	$243,878,375	$1,784,407	$3,243,189	$7,809,316

Table 4-10b. Costs for Indirect Items Potentially Associated with GAC

Design Flow (mgd)	Average Flow (mgd)	Permitting			Housing			Land			Pre-treatment Capital	Pre-treatment O&M	Post-treatment Capital	Post-treatment O&M
		50%	80%	99%	50%	80%	99%	50%	80%	99%				
0.01	0.002	$6,005	$7,712	$11,223	$12,787	$17,339	$29,928	$26,508	$26,795	$27,378	$179,209	$19,113	$8,062	$2,680
0.03	0.0069	$394,296	$602,176	$18,065	$15,269	$16,309	$48,174	$26,911	$27,412	$28,436	$198,870	$19,265	$8,062	$2,701
0.07	0.01745	$569,282	$971,159	$29,135	$17,779	$20,229	$77,693	$27,417	$28,192	$29,786	$234,008	$19,590	$8,062	$2,748
0.11	0.028	$699,796	$1,208,840	$36,265	$19,605	$23,365	$96,707	$27,792	$28,772	$30,797	$264,024	$19,913	$9,773	$2,795
0.31	0.091	$1,236,400	$2,401,522	$72,046	$27,256	$37,347	$192,122	$29,069	$30,760	$34,313	$356,555	$21,807	$37,155	$3,086
0.75	0.24	$2,187,442	$4,791,942	$143,758	$39,980	$76,408	$383,355	$30,870	$33,600	$39,453	$497,077	$26,068	$37,155	$5,761
2.2	0.82	$5,705,503	$11,673,936	$350,218	$92,278	$175,475	$817,176	$34,626	$39,642	$50,782	$1,106,166	$37,495	$45,229	$13,109
7.8	3.3	$13,249,687	$28,217,632	$846,529	$267,143	$588,849	$1,975,234	$43,308	$54,116	$79,552	$2,728,856	$185,447	$82,905	$15,774
23	11	$34,665,414	$75,844,735	$2,275,342	$747,899	$1,762,002	$4,550,684	$58,466	$80,602	$135,990	$5,645,460	$567,802	$172,516	$17,561
81	44	$91,797,355	$205,781,817	$6,173,455	$2,628,487	$6,249,214	$12,346,909	$97,662	$153,296	$303,368	$19,881,836	$1,999,649	$462,668	$45,314
100	56	$108,181,943	$243,878,375	$7,316,351	$3,243,189	$7,809,316	$14,632,702	$108,457	$173,998	$352,936	$24,545,476	$2,468,702	$521,555	$56,378

4.3 INTERCONNECTION (REGIONALIZATION) COSTS

An alternative option for a utility to achieve compliance is through regionalization, which entails linking up with other water systems that can cost-effectively provide water that meets the regulatory requirement. It is well known from many studies (Castillo et al., 1997) that small water systems have historically (pre-regulation periods included) had problems delivering a safe and affordable level of water service to its customers.

Interconnection and consolidation of services is one way to achieve economies of scale for compliance. Associated costs may include studies, legal fees, and interconnection costs (i.e., costs for pipes and appurtenances).

Cost data for estimating interconnection costs were not readily available. A "back-of-the-envelope" estimate was assumed by taking the cost of installed cast iron pipe at $44 per linear foot (an average cost for several pipe diameters) from the R.S. Means Plumbing Cost Data (1998) and applying 20 percent for fittings, excavation, and other expenses resulting in a cost of $53 per linear foot or $279,840 per mile. This cost, even if halved, indicates that interconnection costs could be as high as treatment using aeration.

4.4 CENTRALIZED TREATMENT FOR SYSTEMS WITH LESS THAN 10,000 GPD

Point-of-entry (POE) costs were taken directly from the document entitled *Cost Evaluation of Small System Compliance Options: Point-of-Use and Point-of-Entry Treatment Units*. Draft. April 20, 1998.

The equations for POE treatment of Radon to 300 pCi/l are as follows:

$$GAC: \quad y = 11.47x^{-0.04}$$

$$Aeration: \quad y = 12.24x^{-0.07}$$

where y = *$ per thousand gallons;* x = *number of households*

Note that unlike previous equations, the independent variable is x or the number of households served.

4.5 COMPARISON OF PTA CAPITAL COSTS WITH CASE STUDIES

Figure 4-4 presents the PTA Cost Model and the direct engineered 99-percent capital cost curves and the case study data described previously in Section 4.1.[14] The case study data costs, from different years, were escalated to 1997 dollars assuming an annual inflation rate of three percent. A power fit for the case study data was also generated using the trendline function in Microsoft Excel.

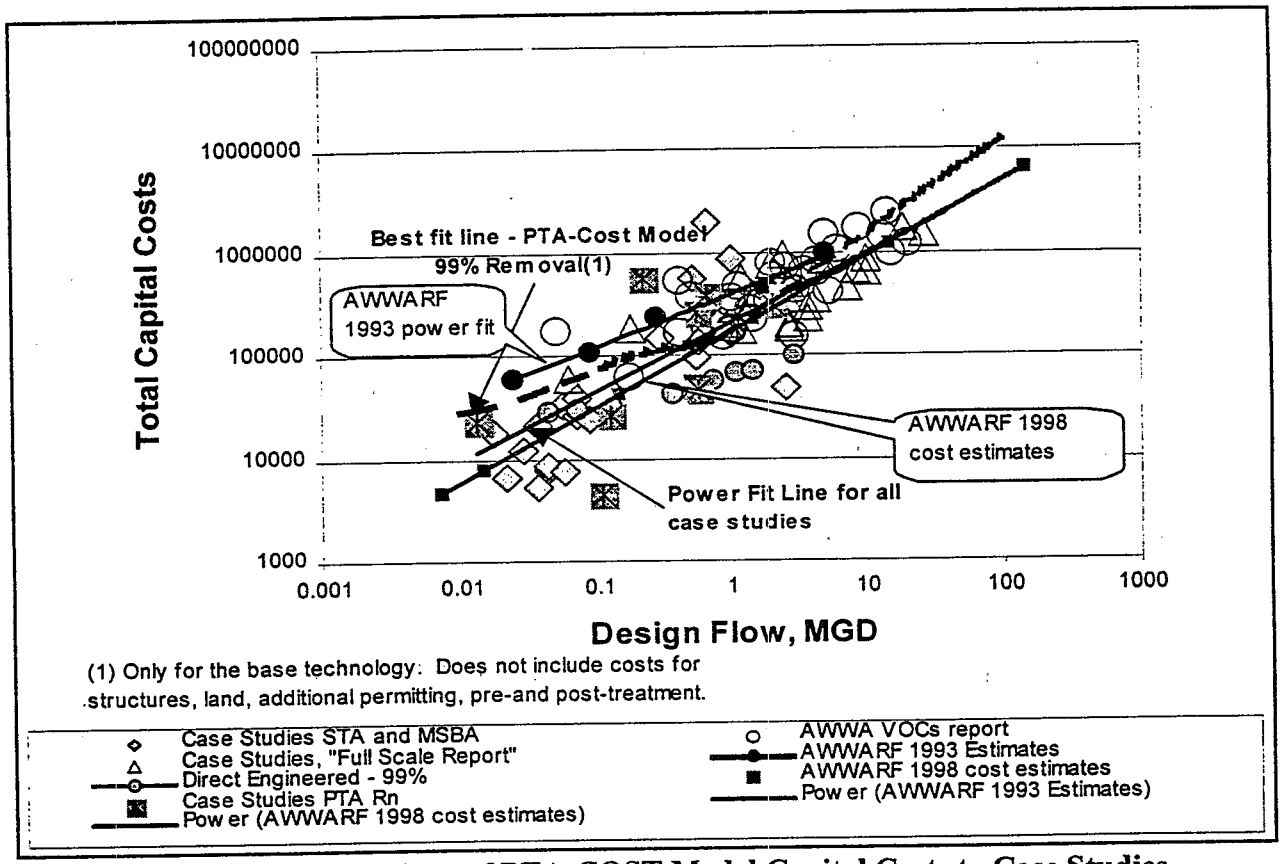


Figure 4-4. Comparison of PTA-COST Model Capital Costs to Case Studies

The case study data in Figure 4-4 demonstrate scatter across the range of plant sizes. The scatter stems from several reasons. For example, some of the case studies reported in the A.E.

[14] On a log scale, the 80-percent cost curves are almost identical to the 99-percent cost curves. To minimize clutter, the 80 percent cost curves are not shown in Figure 4-4.

Hodsdon Report were implemented using volunteer labor. These projects, at the lower-end of the flow scale, are below the PTA Cost Model's and the direct engineering capital cost curve in Figure 4-4. This is logical because if standard construction methods were used, the cost of these projects would probably be closer to the PTA. However, data from other case studies, which were constructed using conventional means agree well with the PTA Cost Model's estimates.

Scatter also stems from the fact that some projects include some components that are not necessarily associated with the base technology. These might include relocation of existing pumps or other equipment, re-configuration of the piping, and installation of ancillary items not directly related to the specific technology but implemented as part of the overall project. Other reasons for the scatter include the variability in labor rates (costs can vary by geographical region), the year the project was implemented, and soil conditions.

Thus, one can conclude that utilities across the United States will encounter different costs when implementing a given technology for their system and that a single utility's experience is not necessarily a good indicator of costs that other utility's will incur in complying with the same regulation. Thus, if modeled costs lie within the boundaries of a range of case studies, then the modeled costs can be taken as a reasonable indicator of potential compliance costs for the purposes of an RIA, which attempts to model costs at the national level.

As Figure 4-4 shows, the PTA Cost Model's costs are remarkably close to a power fit generated from the case study data for the larger systems. Note also that the PTA Cost Model Cost curve is just for the basic PTA Cost technology. Separate cost curves are presented in the appendices for instances when utilities will require disinfection, buildings, land, and permitting. Including these costs would push the PTA technology cost curve towards the higher end of the case study scatter.

In Figure 4-4, the direct engineering cost curve has a flatter slope than the PTA Cost Model curve. The costs generated based on the direct engineering approach are also less than the PTA Cost

Model's curve. The lower costs developed using the direct engineering approach are the result of using a fiberglass tower and an above grade clearwell. But the capital costs using the direct engineering approach are still greater than the costs reported in some case studies because certain fixed costs result in a flat curve at the lower end of the flow range.

In addition, capital cost estimates (escalated to 1997 dollars) presented by AWWARF, 1995, for six plants in its report "Estimating the Cost of Compliance With Drinking Water Standards: A User's Guide." The report noted that the costs for the six plants addresses issues related to very small systems and the AWWARF capital costs for aeration were shown to be two to three times greater than EPA's capital cost estimates for PTA prepared at that time. In addition, the report also concluded that EPA's capital costs tended to fall in the lower ranges of actual constructed projects and that the EPA costs tended to produce "minimum" cost requirements. A 1998 AWWARF report "Critical Assessment of Radon Removal Systems for Drinking Water Supplies" also notes that actual bid costs were well above EPA's capital cost curve for PTA.

Figure 4-4 shows that the capital cost curve from the revised version of the PTA Cost Model is a better fit to the case study data, some of which are the same ones used in the AWWARF reports noted above. As can be seen from the AWWAF's 1998 reports (Figure 8.5) , the "best fit"is well-below the "PTA Cost" for small systems.

What is reassuring is that EPA's traditional models, also appear to agree with independent model costs (**Figure 4-5**) and with the case studies. This provides further support to the PTA-Cost Model as a good tool for estimating conceptual-level cost estimates for treating Radon.

4.5.1 Comparison of O&M Costs With All Case Studies

Figure 4-6 presents a comparison of the case study O&M data with the PTA-COST Model and the direct engineered data. The PTA-COST Model's estimates for O&M are greater than those reported in the case studies for plants less than 1 mgd. This trend is reversed as the plant size increases but the PTA-COST Model is still within the lower end of the scatter. Also, note that the O&M costs display more scatter than the capital costs. Estimates of O&M costs are greater using

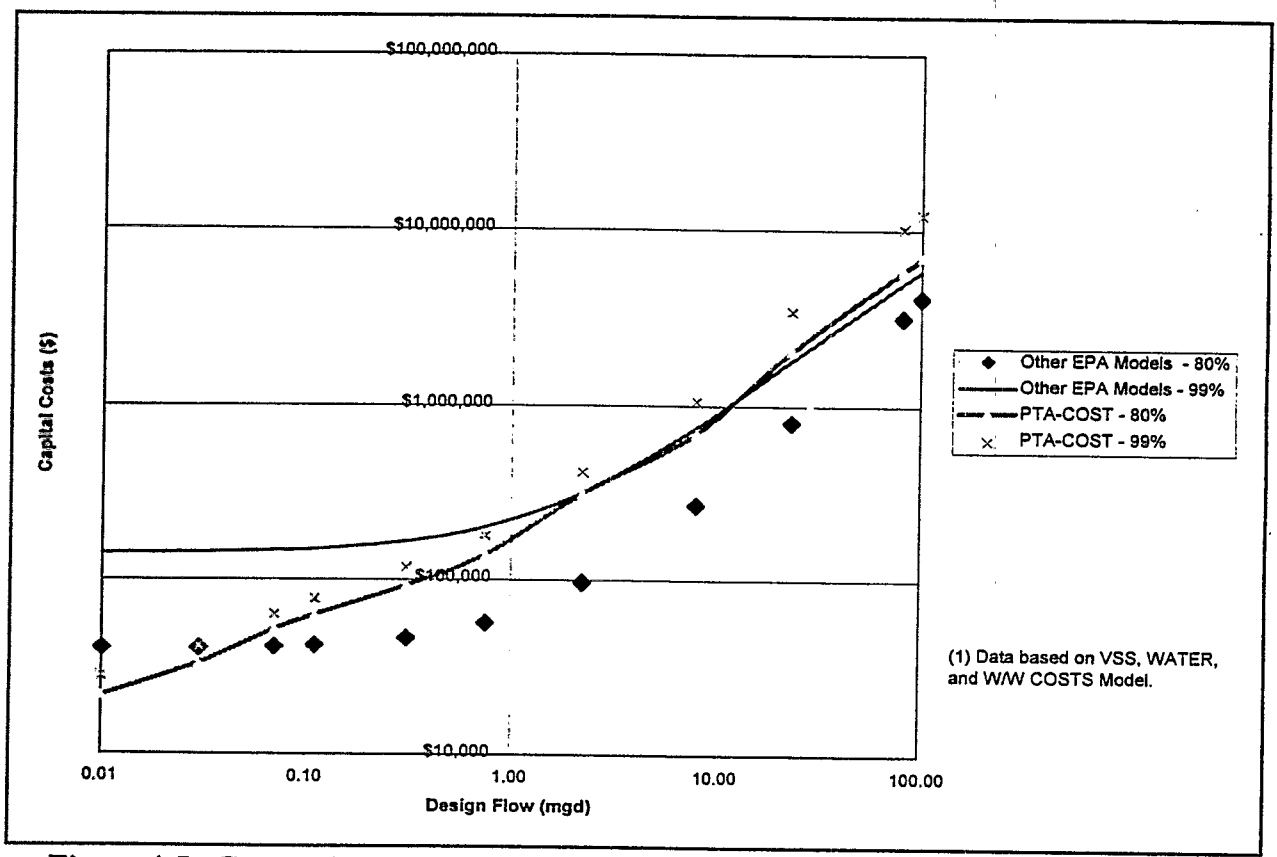


Figure 4-5. Comparison of PTA-COST Model Capital Costs with Other EPA Models

the direct engineering approach than the PTA-COST Model approach. However, the direct engineering O&M cost estimates changes with flow (cost slope) is flatter than that of- the PTA-COST Model slope. This is reasonable because labor costs increase in discrete steps. For example, labor requirements for a 0.75-mgd plant and a 1-mgd plant are probably the same, particularly for PTA technology because the only difference might be a change in the tower height or diameter. For compliance estimates, the RIA analysts can choose between the PTA-COST or the direct engineering O&M cost equations.

A comparative analysis of the GAC costs were not performed because the case study information for this technology is limited. However, GAC costs (Table 4-10a) and PTA costs (4-9a) differ by an order of magnitude. PTA is a cheaper alternative for Radon removal and perhaps more practical (disposal of spent GAC is an issue) than GAC based on the modeled results.

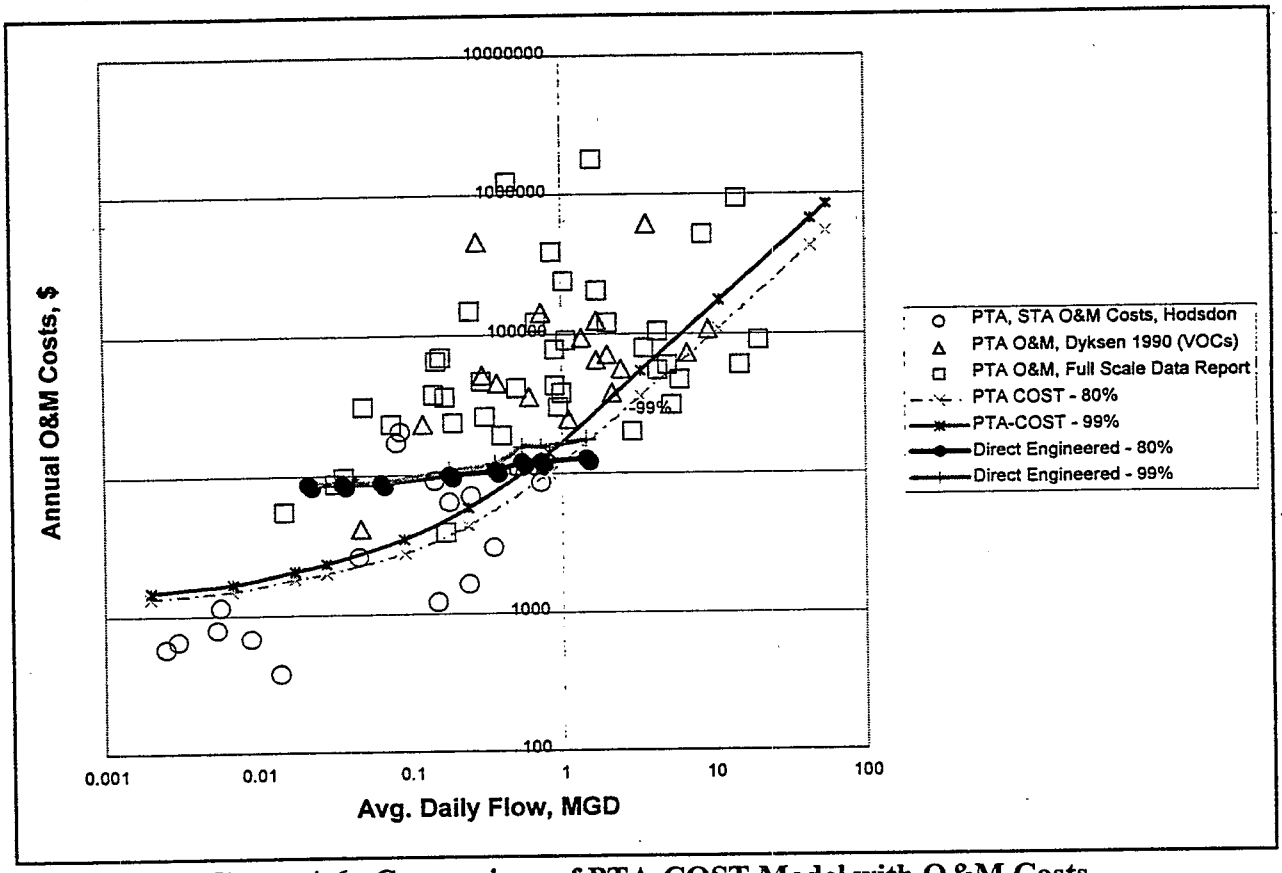


Figure 4-6. Comparison of PTA-COST Model with O&M Costs with Case Studies and Other Models

4.6 SUMMARY OF EQUATIONS FOR AERATION AND GAC TECHNOLOGIES

Table 4-11 lists all of the cost equations developed for aeration and GAC.

Table 4-11. Summary Table of Cost Equations for Radon Removal Technologies

Note: y = Capital or O&M Cost in $
x = Design Flow for Capital Costs and Average Flow for O&M Costs in mgd
PTA = Packed Tower Aeration
DBA = Diffuse Bubble Aeration
GAC = Granular Activated Carbon

Technology/Cost Item	Capital Cost Equation	O&M Cost Equation
PTA (99-percent removal, 5-minute detention): Non-Engineered	y = 6E+06x^3 - 3E+06x^2 + 836,934x + 19,816 0.01<=x<=0.31 mgd y = -260.6x^2 + 147,424x + 63,719 0.31<x<=100 mgd	y = 7E+06x^3 - 1E+06x^2 + 58919x + 1306.3 0.003<=x<=0.091mgd y = 0.4487x^3 - 42.909x^2 + 16030x + 1720.1 0.091<x<=56 mgd
PTA (80-percent removal, 5-minute detention): Non-Engineered	y = 6E+06x^3 - 3E+06x^2 + 738360x + 14224 0.01<=x<=0.31mgd y = 1.2483x^3 - 364.69x^2 + 93243x + 65640 0.31<x<=100mgd	y = 7E+06x^3 - 963314x^2 + 49305x + 1198.5 0.003<x<=0.091mgd y = 0.1896x^3 - 13:891x^2 + 9833.2x + 1944.8 0.091<x<=56mgd
PTA (99-percent removal, 10-minute detention): Non-Engineered	y = 6E+06x^3 - 4E+06x^2 + 90,7713x + 21,139 0.01<=x<=0.31mgd y = -287x^2 + 161095x + 66723 0.31<x<=100mgd	y = 7E+06x^3 - 1E+06x^2 + 59164x + 1305.6 0.003<=x<=0.091mgd y = 0.5695x^3 - 52.841x^2 + 16608x + 1609.4 0.091<x<=56mgd
PTA (80-percent removal, 10-minute detention): Non-Engineered	y = 6E+06x^3 - 4E+06x^2 + 809237x + 15546 0.01<=x<=0.31mgd y = 0.8242x^3 - 330.21x^2 + 104903x + 74847 0.31<x<=100mgd	y = 7E+06x^3 - 965596x^2 + 49550x + 1197.9 0.003<=x<=0.091mgd y = 0.3359x^3 - 26.071x^2 + 10453x + 2069.2 0.091<x<=56mgd
Clearwell (5-minute detention)	y = 24214x^3 - 75137x^2 + 89312x + 12860 0.01<=x<=2.2 mgd y = 50835x^0.8022 2.2<x<=100mgd	NA

Table 4-11. Summary Table of Cost Equations for Radon Removal Technologies (Continued)

Technology/Cost Item	Capital Cost Equation	O&M Cost Equation
PTA (99-percent removal, 5-minute detention): Non-Engineered	y = 6E+06x^3 - 3E+06x^2 + 836,934x + 19,816 0.01<=x<=0.31 mgd y = -260.6x^2 + 147,424x + 63,719 0.31<x<=100 mgd	y = 7E+06x^3 - 1E+06x^2 + 58919x + 1306.3 0.003<=x<=0.091mgd y = 0.4487x^3 - 42.909x^2 + 16030x + 1720.1 0.091<x<=56 mgd
PTA (80-percent removal, 5-minute detention): Non-Engineered	y = 6E+06x^3 - 3E+06x^2 + 738360x + 14224 0.01<=x<=0.31mgd y = 1.2483x^3 - 364.69x^2 + 93243x + 65640 0.31<x<=100mgd	y = 7E+06x^3 - 963314x^2 + 49305x + 1198.5 0.003<x<=0.091mgd y = 0.1896x^3 - 13.891x^2 + 9833.2x + 1944.8 0.091<x<=56mgd
PTA (99-percent removal, 10-minute detention): Non-Engineered	y = 6E+06x^3 - 4E+06x^2 + 90,7713x + 21,139 0.01<=x<=0.31mgd y = -287x^2 + 161095x + 66723 0.31<x<=100mgd	y = 7E+06x^3 - 1E+06x^2 + 59164x + 1305.6 0.003<=x<=0.091mgd y = 0.5695x^3 - 52.841x^2 + 16608x + 1609.4 0.091<x<=56mgd
PTA (80-percent removal, 10-minute detention): Non-Engineered	y = 6E+06x^3 - 4E+06x^2 + 809237x + 15546 0.01<=x<=0.31mgd y = 0.8242x^3 - 330.21x^2 + 104903x + 74847 0.31<x<=100mgd	y = 7E+06x^3 - 965596x^2 + 49550x + 1197.9 0.003<=x<=0.091mgd y = 0.3359x^3 - 26.071x^2 + 10453x + 2069.2 0.091<x<=56mgd
Clearwell (5-minute detention)	y = 24214x^3 - 75137x^2 + 89312x + 12860 0.01<=x<=2.2 mgd y = 50835x^0.8022 2.2<x<=100mgd	NA
Clearwell (10-minute detention)	y = 33104x^3 - 103388x^2 + 125982x + 14982 0.01<=x<=2.2mgd y = 68618x^0.8298 2.2<x<=100mgd	NA

Table 4-11. Summary Table of Cost Equations for Radon Removal Technologies (Continued)

Technology/Cost Item	Capital Cost Equation	O&M Cost Equation
Land (80-percent removal)	y = 515.87x^3 - 595.99x^2 + 209.55x + 267.42 0.01<=x<=2.2mgd y = 0.0029x^3 - 0.8614x^2 + 109.94x + 3157.5 2.2<x<=100mgd	NA
Land (99-percent removal)	y = 552.19x^3 - 654.27x^2 + 246.86x + 269.67 0.01<=x<2.2mgd y = 0.0025x^3 - 0.8654x^2 + 133.03x + 3308 2.2<x<=100mgd	NA
Housing (80-percent removal, 5-minute detention)	y = 58662x^3 - 71361x^2 + 28749x + 834.48 0.01<=x<=0.75mgd y = 7519x^0.7041 0.75<x<=100mgd	NA
Housing (80-percent removal, 10-minute detention)	y = 62515x^3 - 76365x^2 + 31399x + 914.07 0.01<=x<=0.75 mgd y = 8465.3x^0.7102 0.75<x<=100mgd	NA
Housing (99-percent removal, 5-minute detention)	y = 13972x + 1800.6 0.01<=x<=0.75mgd y = -0.0031x^4 + 0.6952x^3 - 54.625x^2 + 5216.6x + 4866 0.75<x<=100mgd	NA
Housing (99-percent removal, 10-minute detention)	y = 15349x + 1925.1 0.01<=x<=0.75mgd y = -0.0039x^4 + 0.8598x^3 - 64.162x^2 + 5719.7x + 5347.4 0.75<x<=100mgd	NA

Table 4-11. Summary Table of Cost Equations for Radon Removal Technologies (Continued)

Technology/Cost Item	Capital Cost Equation	O&M Cost Equation
Pre-treatment	y = -775153x^3 + 682813x^2 + 437962x + 4759.8 0.01<=x<=0.75mgd y = 5.9266x^3 - 1451.8x^2 + 341048x + 216032 0.75<x<=100mgd	y = 2746.4exp(1.9885x) 0.003<=x<=0.82mgd y = -0.1373x^3 + 17.551x^2 + 209.99x + 13723 0.82<x<=56mgd
Post-treatment	y = 6419.8exp(5.3948x) 0.01<=x<=0.31mgd y = -0.113x^3 - 1.4464x^2 + 6155.8x + 33526 0.31<x<=100mgd	y = 2746.4exp(1.9885x) 0.003<=x<=0.82mgd y = -0.1373x^3 + 17.551x^2 + 209.99x + 13723 0.82<x<=56mgd
PTA (80-percent removal): Direct Engineered	y = -0.0002x^3 + 0.1911x^2 + 1.5247x + 27449 30<=x<=500gpm y = 4E-05x^3 - 0.1224x^2 + 140.41x + 6360 500<x<=2000gpm	y = -0.0007x^3 + 0.2278x^2 - 8.232x + 8774.6 15<=x<=125gpm y = 3E-06x^3 - 0.0117x^2 + 13.203x + 8329 125<x<=1000gpm
PTA (99-percent removal): Direct Engineered	y = -7E-05x^3 + 0.0716x^2 + 41.084x + 27751 30<=x<=750gpm y = 0.0199x^2 - 30.46x + 80640 750<x<=2000gpm	y = 0.0002x^3 - 0.1173x^2 + 29.14x + 8120.9 15<=x<=375gpm y = 0.0058x^2 - 5.04x + 16780 375<x<=1000gpm
DBA (80 and 99-percent removals): Direct Engineered	y = -1.125x^2 + 150x + 15613 30<=x<=90gpm y = 0.0859x^2 - 14.836x + 20639 90<x<=500gpm y = 2E-06x^3 - 0.0043x^2 + 15.52x + 27780 500<x<=2000gpm	y = 8600 15<=x<=45gpm y = -0.0366x^2 + 13.72x + 8056.7 45<x<=250gpm y = 8.8x + 7000 250<x<=375gpm y = 10300 375<x<=1000gpm

Table 4-11. Summary Table of Cost Equations for Radon Removal Technologies (Continued)

Technology/Cost Item	Capital Cost Equation	O&M Cost Equation
GAC (50-percent removal)	y = 1E+07x^3 - 1E+07x^2 + 1E+07x + 298885 0.01<=x=<0.75 mgd y = 80.787x^3 - 19730x^2 + 4E+06x + 3E+06 0.75<x<=100 mgd	y = -109383x^3 + 11128x^2 + 260630x + 14589 0.002<=x<=0.82 mgd y = 5.9326x^3 - 787.46x^2 + 164106x + 47197 0.82<x<=56 mgd
GAC (80-percent removal)	y = 7E+06x^3 - 9E+06x^2 + 5E+06x + 221221 0.01<=x<=0.75 mgd y = 39.689x^3 - 9739.2x^2 + 2E+06x + 1E+06 0.75<x<=100 mgd	y = 383612x^3 - 428770x^2 + 189279x + 13864 0.002<=x<=0.82 mgd y = 0.7882x^3 - 212.47x^2 + 66583x + 42636 0.82<x<=56 mgd
GAC (99-percent removal)	y = 6E+06x^3 - 8E+06x^2 + 4E+06x + 172842 0.01<=x<=0.75 mgd y = 24.306x^3 - 5912.5x^2 + 925097x + 808365 0.75<x<=100 mgd	y = 329892x^3 - 373677x^2 + 144903x + 13815 0.002<=x<=0.82 mgd y = 0.3736x^3 - 110.49x^2 + 36184x + 39188 0.82<x<=56 mgd

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Appendix A-0

Conceptualized Diagram for PTA Configurations Assumed in the PTA-Cost Model and the Direct Engineered Approach

Figure A-0-1

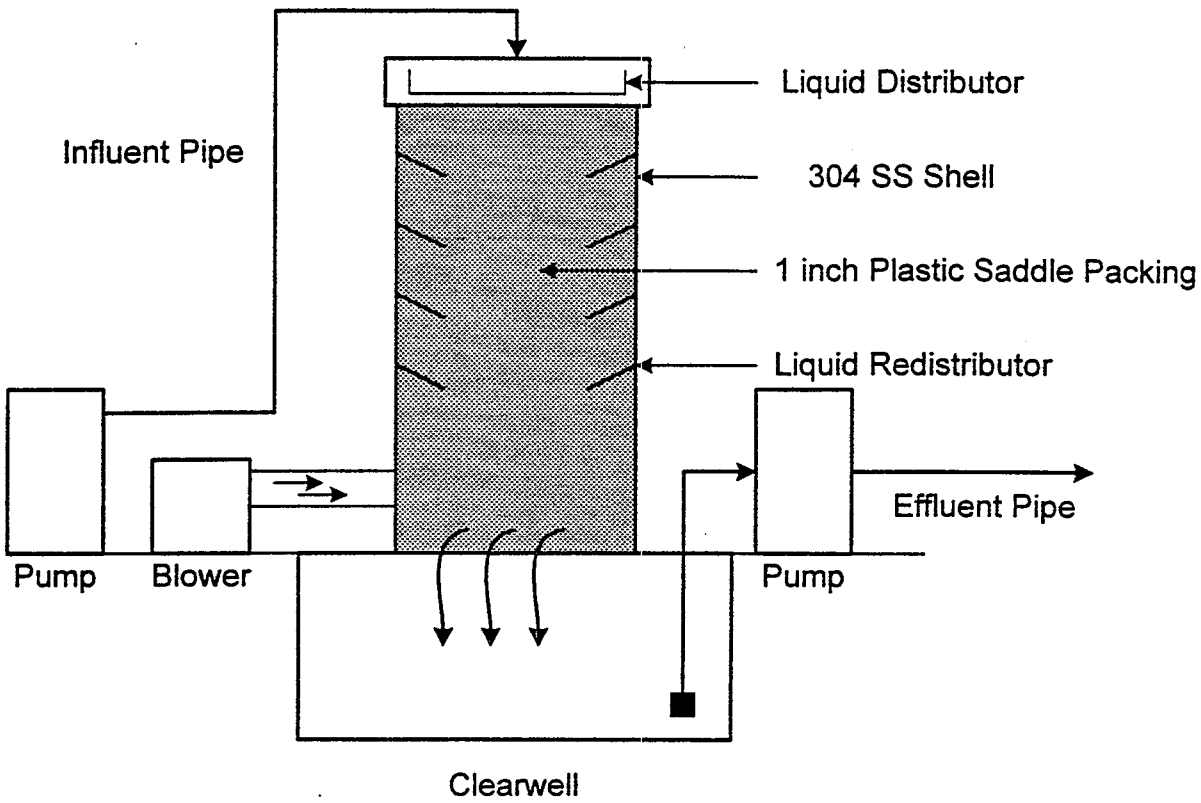
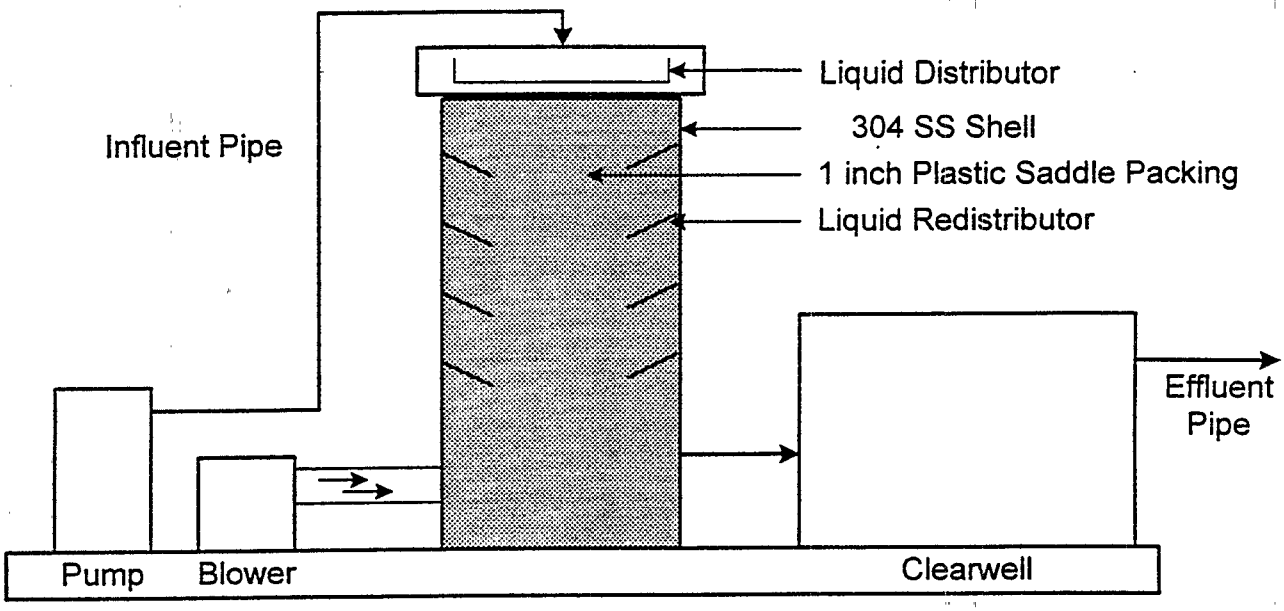

Liquid Distributor
Influent Pipe
304 SS Shell
1 inch Plastic Saddle Packing
Liquid Redistributor
Effluent Pipe
Pump
Blower
Pump
Clearwell

Figure A-0-2


Liquid Distributor
304 SS Shell
1 inch Plastic Saddle Packing
Liquid Redistributor
Influent Pipe
Effluent Pipe
Pump
Blower
Clearwell

Appendix A-1
Detailed Breakdown of Estimated Costs for PTA and Cost Curves Based on PTA-Cost Model

APPENDIX A.1

Table A.1.1 Detailed Breakdown of Cost Components for PTA
5 Minute Detention Time, 80 Percent Removal

Design Flow (mgd)	Avg Flow (mgd)	Initial Process	Num_Col	Pump & Blower	Effluent Pumping	Clearwell Vol. (m3)	Clearwell Depth (m)	Clearwell Area (m2)	Revised Process	Engg.	Construction	Tot. Aeration Capital	Aeration O&M	Clearwell	Permitting	Land (ft2)	Land ($)	Housing ($)	Pre-Tmt. Capital	Post-Tmt. Capital	Pre-Tmt. O&M	Post-Tmt O&M
0.01	0.002	$9,492	1	$420	$840	0.625	2.5	0.25	$10,752	$3,226	$7,527	$21,505	$1,338	$12,236	$2,500	11741.09	$270	$1,075	$7,851	$8,062	$4,975	$2,680
0.03	0.0069	$13,447	1	$1,255	$1,852	2	3	0.67	$16,554	$4,966	$11,588	$33,109	$1,495	$15,672	$2,500	12018.31	$276	$1,655	$19,712	$8,062	$11,675	$2,701
0.07	0.01745	$19,557	1	$3,036	$3,408	2.3814	2.95	0.81	$26,001	$7,800	$18,200	$52,001	$1,801	$19,818	$2,500	12090.65	$278	$2,600	$40,096	$8,062	$19,372	$2,748
0.11	0.028	$23,127	1	$3,572	$4,717	3.751	3.1	1.21	$31,416	$9,425	$21,991	$62,832	$1,970	$22,838	$2,500	12269.38	$282	$3,142	$58,559	$9,773	$24,978	$2,795
0.31	0.091	$34,977	1	$5,148	$6,301	8.704	3.4	2.56	$46,426	$13,928	$32,498	$92,852	$2,726	$33,098	$2,786	12718.5	$292	$4,643	$183,206	$37,155	$43,956	$3,086
0.75	0.24	$52,818	1	$7,807	$9,413	19.573	3.7	5.29	$70,038	$21,011	$49,027	$140,076	$4,306	$47,960	$4,202	13360.83	$307	$7,004	$390,289	$37,155	$70,563	$5,761
2.2	0.82	$94,278	1	$16,053	$15,348	56.316	3.9	14.44	$125,679	$70,695	$117,824	$314,198	$10,122	$103,508	$9,426	14535.2	$3,337	$12,568	$980,500	$45,229	$125,111	$13,109
7.8	3.3	$227,514	2	$23,434	$27,276	196.599	3.9	50.41	$278,224	$156,501	$260,835	$695,559	$35,774	$224,660	$20,867	17664.12	$4,055	$27,822	$2,897,122	$82,905	$244,905	$15,774
23	11	$542,585	4	$31,926	$44,579	584.288	3.8	153.76	$619,090	$619,090	$825,453	$2,063,633	$108,668	$676,963	$61,909	22774.61	$5,228	$61,909	$7,310,933	$172,516	$434,512	$17,561
81	44	$1,652,033	13	$33,580	$78,981	1971.36	4	492.84	$1,764,594	$1,764,594	$2,352,792	$5,881,980	$423,862	$1,769,413	$176,459	34645.71	$7,954	$176,459	$21,478,154	$462,668	$846,874	$45,314
100	56	$1,977,805	16	$33,653	$86,915	2359.098	4.2	561.69	$2,098,373	$2,098,373	$2,797,831	$6,994,577	$542,329	$2,015,110	$209,837	36681.66	$8,421	$209,837	$25,723,720	$521,555	$946,944	$56,378

Table A.1.2 Detailed Breakdown of Cost Components for PTA
5 Minute Detention Time, 99 Percent Removal

Design Flow (mgd)	Avg Flow (mgd)	Initial Process	Num_Col	Pump & Blower	Effluent Pumping	Clearwell Vol. (m3)	Clearwell Depth (m)	Clearwell Area (m2)	Revised Process	Engg.	Construction	Tot. Aeration Capital	Aeration O&M	Clearwell	Permitting	Land (ft2)	Land ($)	Housing ($)	Pre-Tmt. Capital	Post-Tmt. Capital	Pre-Tmt. O&M	Post-Tmt O&M
0.01	0.002	$12,729	1	$420	$840	0.625	2.5	0.25	$13,989	$4,197	$9,793	$27,979	$1,470	$12,236	$2,500	11741.09	$270	$1,399	$7,851	$8,062	$4,975	$2,680
0.03	0.0069	$17,723	1	$1,255	$1,852	2	3	0.67	$20,830	$6,249	$14,581	$41,661	$1,674	$15,672	$2,500	12018.31	$276	$2,083	$19,712	$8,062	$11,675	$2,701
0.07	0.01745	$25,307	1	$3,036	$3,408	2.3814	2.95	0.81	$31,751	$9,525	$22,225	$63,501	$2,059	$19,818	$2,500	12090.65	$278	$3,175	$40,096	$8,062	$19,372	$2,748
0.11	0.028	$30,365	1	$3,572	$4,717	3.751	3.1	1.21	$38,654	$11,596	$27,058	$77,308	$2,316	$22,838	$2,500	12269.38	$282	$3,865	$58,559	$9,773	$24,978	$2,795
0.31	0.091	$47,409	1	$5,148	$6,301	8.704	3.4	2.56	$58,858	$17,657	$41,201	$117,716	$3,456	$33,098	$3,531	12718.5	$292	$5,886	$183,206	$37,155	$43,956	$3,086
0.75	0.24	$72,950	1	$7,807	$9,413	19.573	3.7	5.29	$90,170	$27,051	$63,119	$180,340	$5,771	$47,960	$5,410	13360.83	$307	$9,017	$390,289	$37,155	$70,563	$5,761
2.2	0.82	$134,729	1	$16,053	$15,348	56.316	3.9	14.44	$166,130	$93,448	$155,747	$415,326	$14,128	$103,508	$12,460	14535.2	$3,337	$16,613	$980,500	$45,229	$125,111	$13,109
7.8	3.3	$372,446	2	$23,434	$27,276	196.599	3.9	50.41	$423,156	$238,025	$396,708	$1,057,889	$54,432	$224,660	$31,737	17664.12	$4,055	$42,316	$2,897,122	$82,905	$244,905	$15,774
23	11	$959,309	4	$31,926	$44,579	584.288	3.8	153.76	$1,035,814	$1,035,814	$1,381,085	$3,452,713	$173,419	$676,963	$103,581	22774.61	$5,228	$103,581	$7,310,933	$172,516	$434,512	$17,561
81	44	$2,947,257	13	$33,580	$78,981	1971.36	4	492.84	$3,059,818	$3,059,818	$4,079,757	$10,199,394	$662,207	$1,769,413	$305,982	34645.71	$7,954	$305,982	$21,478,154	$462,668	$846,874	$45,314
100	56	$3,556,324	16	$33,653	$86,915	2359.098	4.2	561.69	$3,676,892	$3,676,892	$4,902,523	$12,256,307	$843,648	$2,015,110	$367,689	36681.66	$8,421	$367,689	$25,723,720	$521,555	$946,944	$56,378

Table A.1.3 Detailed Breakdown of Cost Components for PTA
10 Minute Detention Time, 80 Percent Removal

Design Flow (mgd)	Avg Flow (mgd)	Initial Process	Num_Col	Pump & Blower	Effluent Pumping	Clearwell Vol. (m3)	Clearwell Depth (m)	Clearwell Area (m2)	Revised Process	Engg.	Construction	Tot. Aeration Capital	Aeration O&M	Clearwell	Permitting	Land (ft2)	Land ($)	Housing ($)	Pre-Tmt. Capital	Post-Tmt. Capital	Pre-Tmt. O&M	Post-Tmt O&M
0.01	0.002	$10,475	1	$420	$840	0.936	2.5	0.38	$11,735	$3,521	$8,215	$23,471	$1,338	$14,202	$2,500	11838.72	$272	$1,174	$7,851	$8,062	$4,975	$2,680
0.03	0.0069	$15,076	1	$1,255	$1,852	2.349	3	0.79	$18,183	$5,455	$12,728	$36,367	$1,496	$18,930	$2,500	12078.63	$277	$1,818	$19,712	$8,062	$11,675	$2,701
0.07	0.01745	$22,020	1	$3,036	$3,408	4.608	2.95	1.57	$28,464	$8,539	$19,925	$56,927	$1,804	$24,742	$2,500	12403.1	$285	$2,846	$40,096	$8,062	$19,372	$2,748
0.11	0.028	$26,223	1	$3,572	$4,717	6.664	3.4	1.96	$34,512	$10,354	$24,158	$69,024	$1,975	$29,028	$2,500	12537.89	$288	$3,451	$58,559	$9,773	$24,978	$2,795
0.31	0.091	$40,331	1	$5,148	$6,301	15.2	3.8	4	$51,780	$15,534	$36,246	$103,560	$2,749	$43,806	$3,107	13083.61	$300	$5,178	$183,206	$37,155	$43,956	$3,086
0.75	0.24	$61,589	1	$7,807	$9,413	35.322	4.2	8.41	$78,809	$23,643	$55,166	$157,618	$4,381	$65,502	$4,729	13924	$320	$7,881	$390,289	$37,155	$70,563	$5,761
2.2	0.82	$110,925	1	$16,053	$15,348	99.405	4.5	22.09	$142,328	$80,059	$133,431	$355,816	$10,447	$144,228	$10,674	15358.32	$3,526	$14,233	$980,500	$45,229	$125,111	$13,109
7.8	3.3	$266,015	2	$23,434	$27,276	340.216	4.6	73.96	$316,725	$178,158	$296,929	$791,812	$37,302	$320,913	$23,754	19187.11	$4,405	$31,672	$2,897,122	$82,905	$244,905	$15,774
23	11	$630,313	4	$31,926	$44,579	1012.5	4.5	225	$706,818	$706,818	$942,424	$2,356,060	$113,940	$969,390	$70,682	25682.28	$5,896	$70,682	$7,310,933	$172,516	$434,512	$17,561
81	44	$1,938,266	13	$33,580	$78,981	3555.064	4.6	772.84	$2,050,827	$2,050,827	$2,734,436	$6,836,090	$440,213	$2,723,527	$205,083	42543.14	$9,767	$205,083	$21,478,154	$462,668	$846,874	$45,314
100	56	$2,306,640	16	$33,653	$86,915	4291.248	4.8	894.01	$2,427,208	$2,427,208	$3,236,278	$8,090,694	$564,637	$3,111,227	$242,721	45713.53	$10,494	$242,721	$25,723,720	$521,555	$946,944	$56,378

Table A.1.4 Detailed Breakdown of Cost Components for PTA
10 Minute Detention Time, 99 Percent Removal

Flow (mgd)	Avg Flow (mgd)	Initial Process	Num_Col	Pump & Blower	Effluent Pumping	Clearwell Vol. (m3)	Clearwell Depth (m)	Clearwell Area (m2)	Revised Process	Engg.	Construction	Tot. Aeration Capital	Aeration O&M	Clearwell	Clearwell	Permitting	Land (ft2)	Land ($)	Housing ($)	Pre-Tmt. Capital	Post-Tmt. Capital	Pre-Tmt. O&M	Post-Tmt. O&M
0.01	0.002	$13,712	1	$420	$840	0.936	2.5	0.38	$14,972	$4,492	$10,481	$29,945	$1,470	$7,101	$14,202	$2,500	11838.72	$272	$1,497	$7,851	$8,062	$4,975	$2,680
0.03	0.0069	$19,352	1	$1,255	$1,852	2.349	3	0.78	$22,459	$6,738	$15,722	$44,919	$1,675	$9,465	$18,930	$2,500	12078.63	$277	$2,246	$19,712	$8,062	$11,675	$2,701
0.07	0.01745	$27,769	1	$3,036	$3,408	4.608	2.95	1.57	$34,213	$10,264	$23,949	$68,425	$2,062	$12,371	$24,742	$2,500	12403.1	$285	$3,421	$40,096	$8,062	$19,372	$2,748
0.11	0.028	$33,461	1	$3,572	$4,717	6.664	3.4	1.96	$41,750	$12,525	$29,225	$83,500	$2,321	$14,514	$29,028	$2,505	12537.89	$288	$4,175	$58,559	$9,773	$24,978	$2,795
0.31	0.091	$52,783	1	$5,148	$6,301	15.2	3.8	4	$64,212	$19,264	$44,949	$128,424	$3,479	$21,803	$43,606	$3,853	13083.61	$300	$6,421	$183,206	$37,155	$43,956	$3,088
0.75	0.24	$81,721	1	$7,807	$9,413	35.322	4.2	8.41	$98,941	$29,682	$69,259	$197,882	$5,847	$32,751	$65,502	$5,936	13924	$320	$9,894	$390,289	$37,155	$70,563	$5,781
2.2	0.82	$151,374	1	$16,053	$15,348	99.405	4.5	22.09	$182,775	$102,811	$171,352	$456,938	$14,453	$57,691	$144,228	$13,708	15358.32	$3,526	$18,278	$980,500	$45,229	$125,111	$13,109
7.8	3.3	$410,947	2	$23,434	$27,276	340.216	4.6	73.96	$461,657	$259,682	$432,803	$1,154,142	$55,960	$128,365	$320,913	$34,624	19187.11	$4,405	$46,166	$2,897,122	$82,905	$244,905	$15,774
23	11	$1,047,037	4	$31,926	$44,579	1012.5	4.5	225	$1,123,542	$1,123,542	$1,498,056	$3,745,140	$178,691	$290,817	$969,390	$112,354	25682.28	$5,896	$112,354	$7,310,933	$172,516	$434,512	$17,561
81	44	$3,233,491	13	$33,580	$76,981	3555.064	4.6	772.84	$3,348,052	$3,348,052	$4,461,403	$11,153,507	$678,558	$817,058	$2,723,527	$334,605	42543.14	$9,767	$334,605	$21,478,154	$462,688	$846,874	$45,314
100	56	$3,685,159	16	$33,653	$86,915	4291.248	4.8	894.01	$4,005,727	$4,005,727	$5,340,970	$13,352,424	$865,957	$933,368	$3,111,227	$400,573	45713.53	$10,494	$400,573	$25,723,720	$521,555	$946,944	$56,378

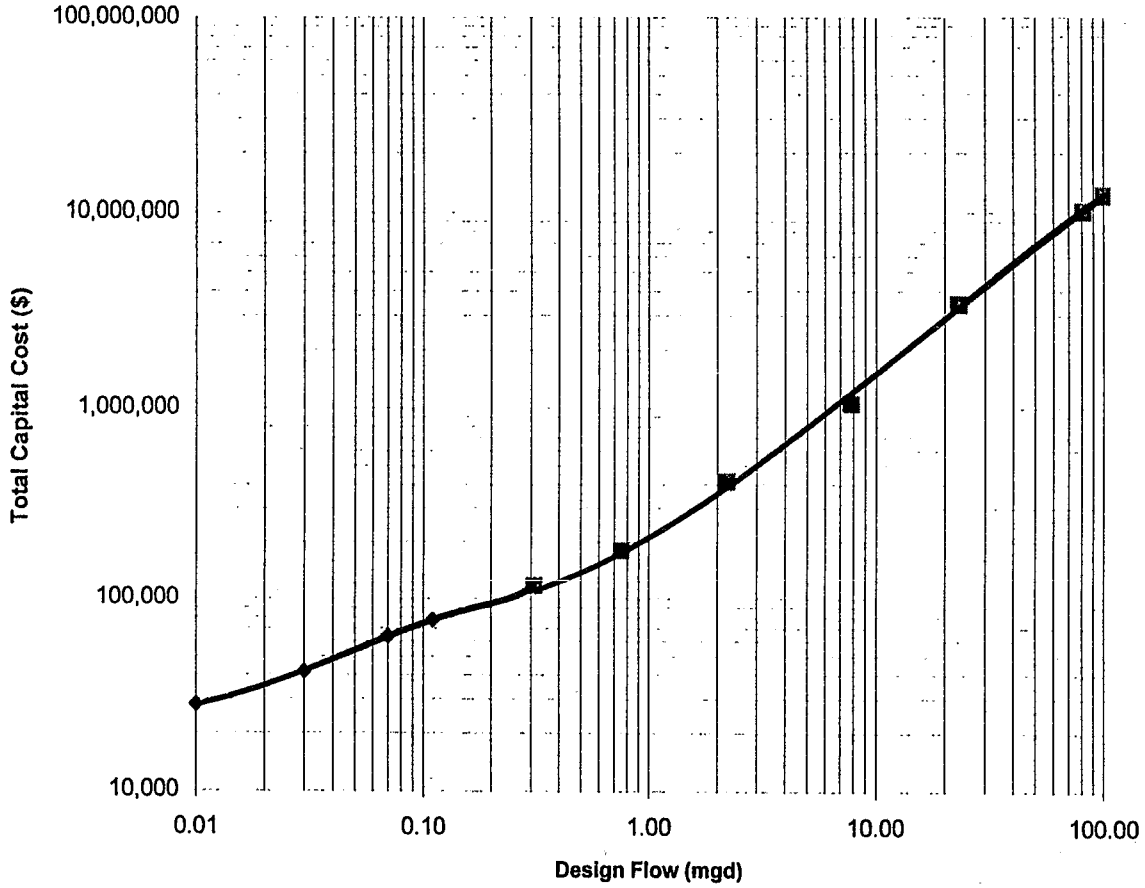
Key for Tables A.1.1-A.1.4

Item	Assumption/Rationale
Design Flow	The selected design flow for cost analysis (11 plant sizes).
Average Flow	The average flow for the selected design flow (11 plant sizes).
Initial Process	Process equipment cost calculated by PTA-Cost Model. Includes steel support column shells, internals, 2" plastic packing, blower, pump and motor, clearwell, pipng, instrumentation, air duct, and electrical.
Pump and Blower	The cost of a redundant pump and blower to allow continued operation in case of failure at a single point. Estimated from PTA Cost Model output as [$Pump + $Blower]/Number of columns.
Effluent pumping	When clearwell is added, a pump is necessary to pump from clearwell to distribution system. Pump costs estimated by regression of pump cost versus plant size from RS Means data.
Clearwell volume	Estimated by the PTA Cost Model
Clearwell depth	Estimated by the PTA Cost Model
Clearwell area	Clearwell volume divided by clearwell depth (used for estimating land requirement).
Revised process	The sum of initial process, pump and blower, and effluent pumping costs. This estimate accounts for redundancies.
Engineering	*Small systems (<1 mgd):* 30 percent of Revised Process (15 percent of total capital costs) based on average of case study data for small systems. *Large systems (>10 mgd):* 40 percent of revised process (20 percent of total capital costs) based on TDP recommendations. *Medium systems (1 to 10 mgd):* 35 percent of process (17.5 percent of total capital costs). Average of small and large system percentages.
Construction	*Small systems (<1 mgd):* 70 percent of process costs (35 percent of total capital costs) based on average of case study data for small systems. *Large Systems (>10 mgd):* 100 percent of process (40 percent of total capital costs) based on TDP recommendations. *Medium systems (1 to 10 mgd):* 85 percent of process (37.5 percent of total capital costs). Average value of small and large system percentages.
Total Aeration Capital	The sum of Revised Process, Engineering, and Construction.
Aeration O&M	O&M costs (including labor, administration, and power) for aeration estimated by the PTA Cost Model.
Clearwell	The cost of a clearwell is included in the PTA Cost Model output (i.e., initial process). However, the cost of the clearwell may need to be "backed off" for RIA scenarios.
Permitting	The greater of 3 percent of Total Aeration Capital or $2,500 based on TDP recommendations.

Key for Tables A.1.1-A.1.4 (Continued)

Item	Assumption/Rationale
Land (sq. ft.)	Land area is based on process footprint (clearwell area with allowance for access) plus a sixty foot buffer zone between tower and adjacent land.
Land ($)	The utility can purchase land for $ 1,000 per acre in rural areas (< 1 mgd), or $ 10,000 per acre in urban areas (> 1 mgd).
Housing	20% of Revised Process Cost.
Pre-treatment Capital	Generalized capital cost equations for iron and manganese removal.
Post-treatment Capital	Generalized capital costs for disinfection following aeration.
Pre-treatment O&M	Pre-treatment O&M costs based on generalized O&M equations.
Post-treatment O&M	O&M costs based on generalized O&M equations.

Figure A.1-1 Total Capital Costs for 99% Removal of Radon Using PTA (5 minute detention)



Cost Equation

$y = 6E+06x^3 - 3E+06x^2 + 836,934x + 19,816$
$0.01 <= x <= 0.31$

$y = -260.6x^2 + 147,424x + 63,719$
$0.31 < x < 100$

y = Capital Costs ($)
x = Design Flow (mgd)

Figure A.1-2 O&M Costs for 99% Removal of Radon Using PTA (5 minute detention)

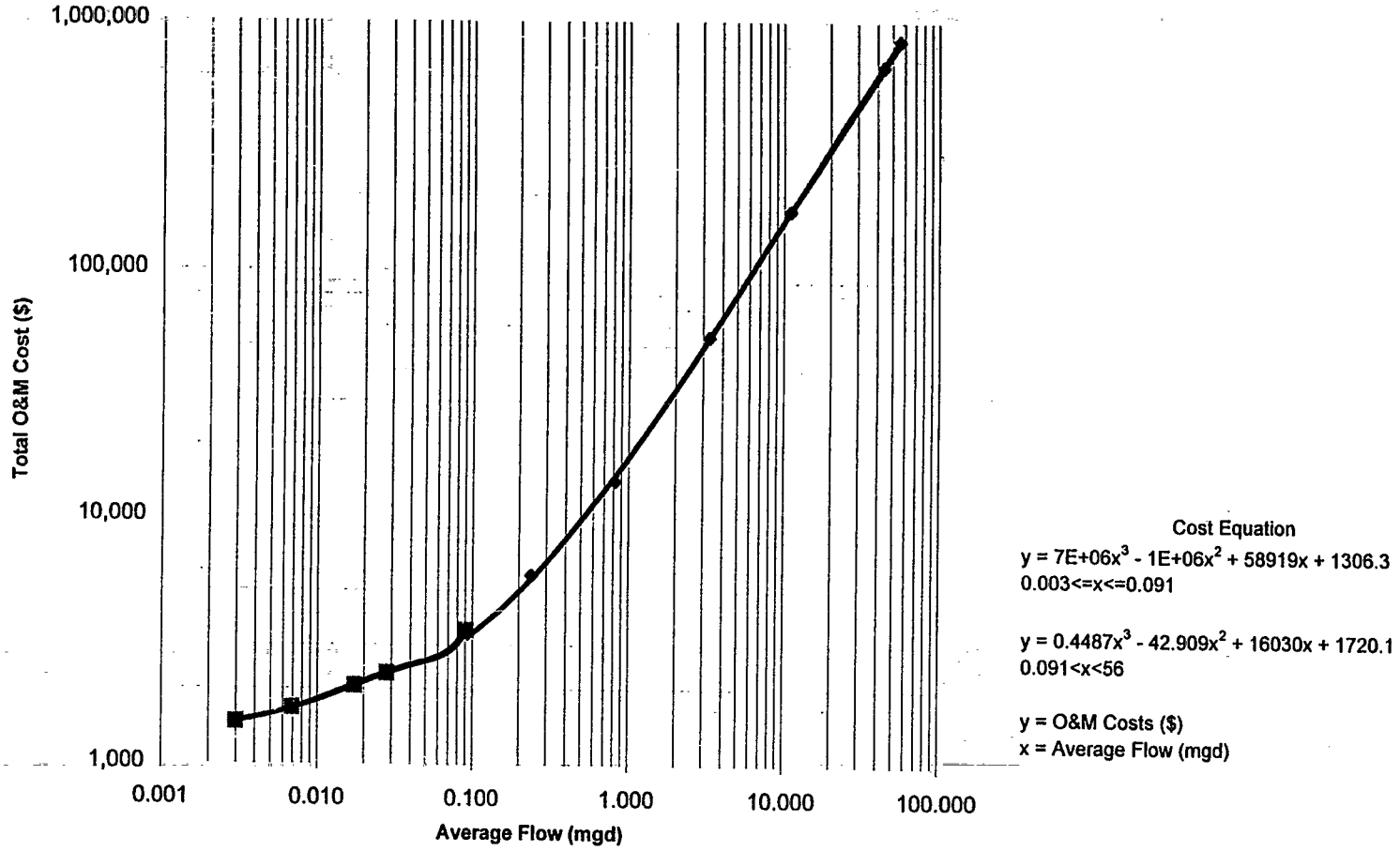
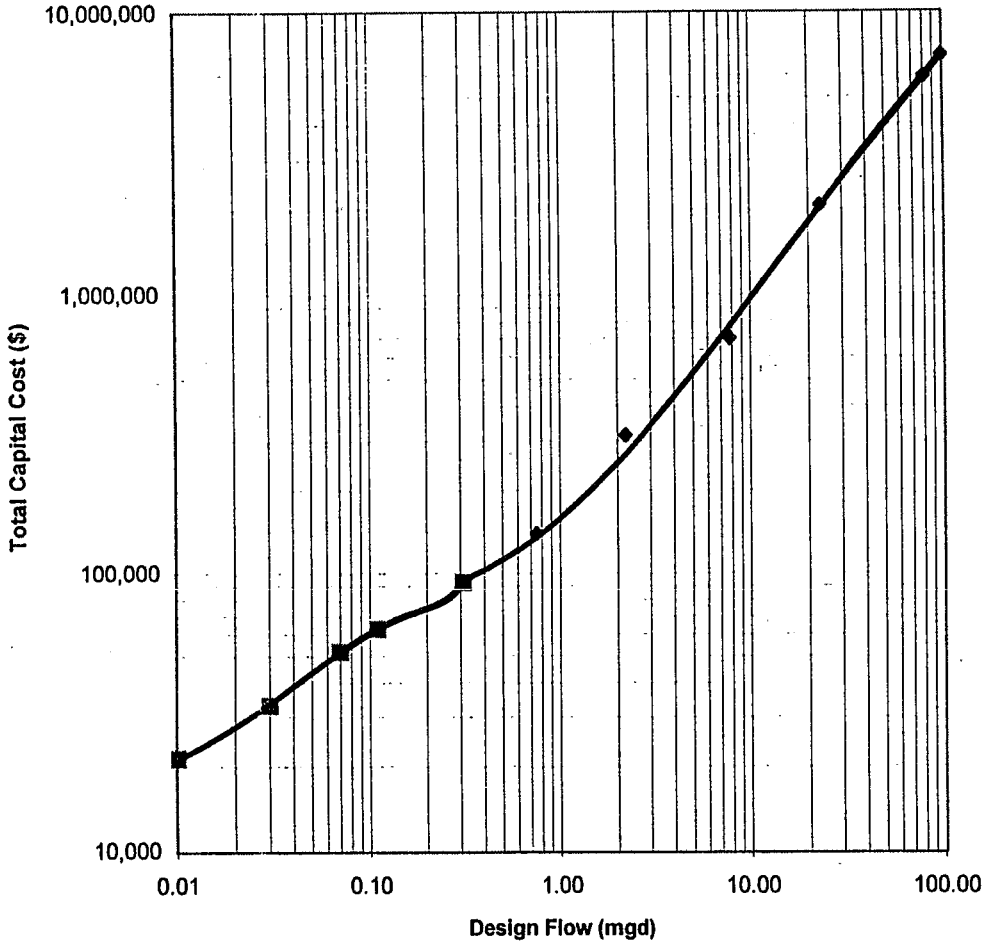


Figure A.1-3 Capital Costs for 80% Removal of Radon Using PTA (5 minute detention)



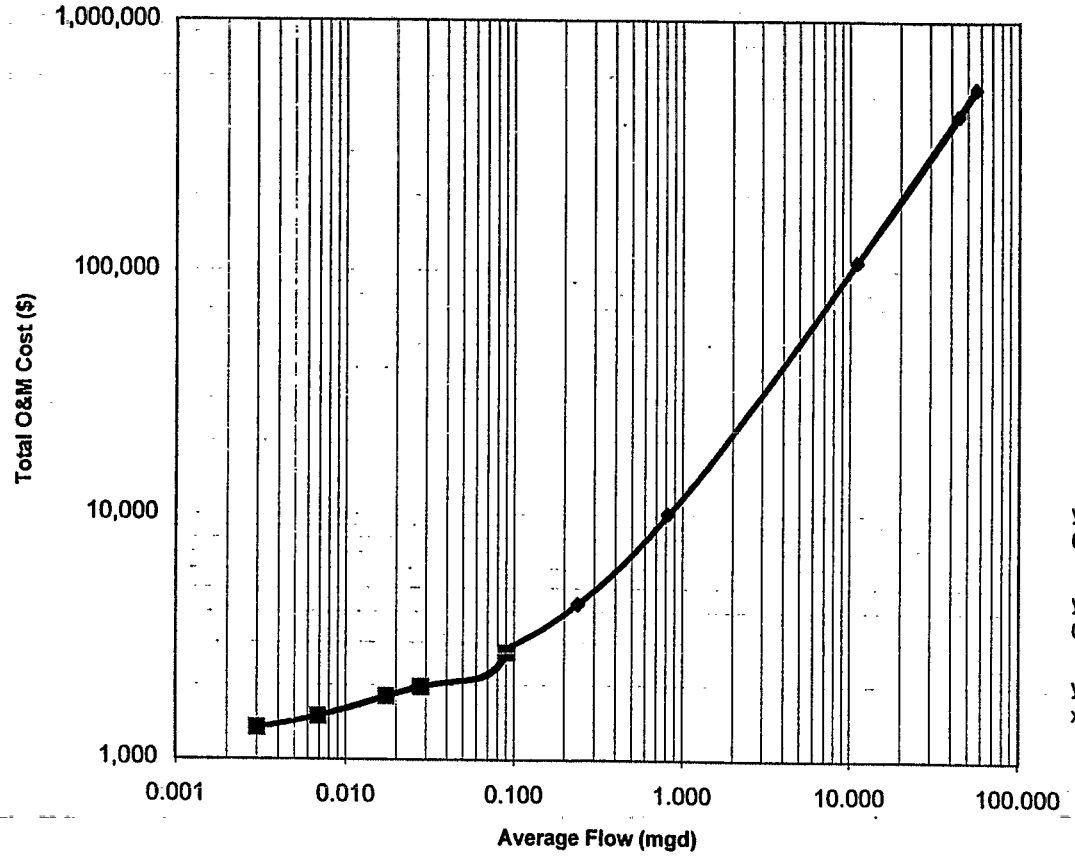
Cost Equation

$y = 6E+06x^3 - 3E+06x^2 + 738360x + 14224$
$0.01 <= x <= 0.31$ mgd

$y = 1.2483x^3 - 364.69x^2 + 93243x + 65640$
$0.31 < x < 100$ mgd

y = Capital Costs ($)
x = Design Flow (mgd)

Figure A.1-4 O&M Costs for 80% Removal of Radon Using PTA
(5 minute detention)



Cost Equation

$y = 7E+06x^3 - 963314x^2 + 49305x + 1198.5$
$0.003 < x <= 0.091$ mgd

$y = 0.1896x^3 - 13.891x^2 + 9833.2x + 1944.8$
$0.091 < x < 56$ mgd

y = O&M Costs ($)
x = Average Flow (mgd)

Figure A.1-5 Capital Costs for 99% Removal of Radon Using PTA (10 minute detention)

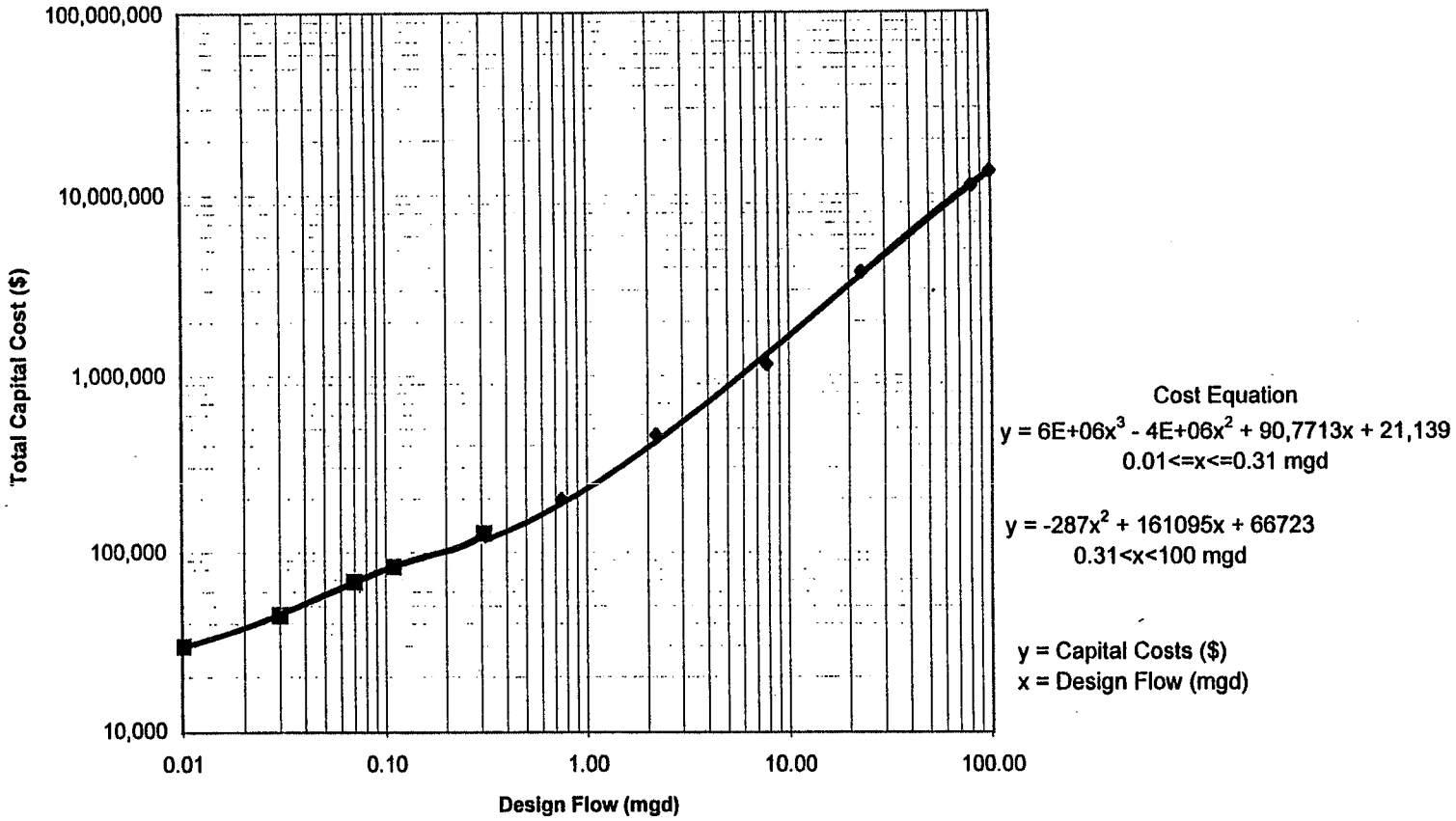
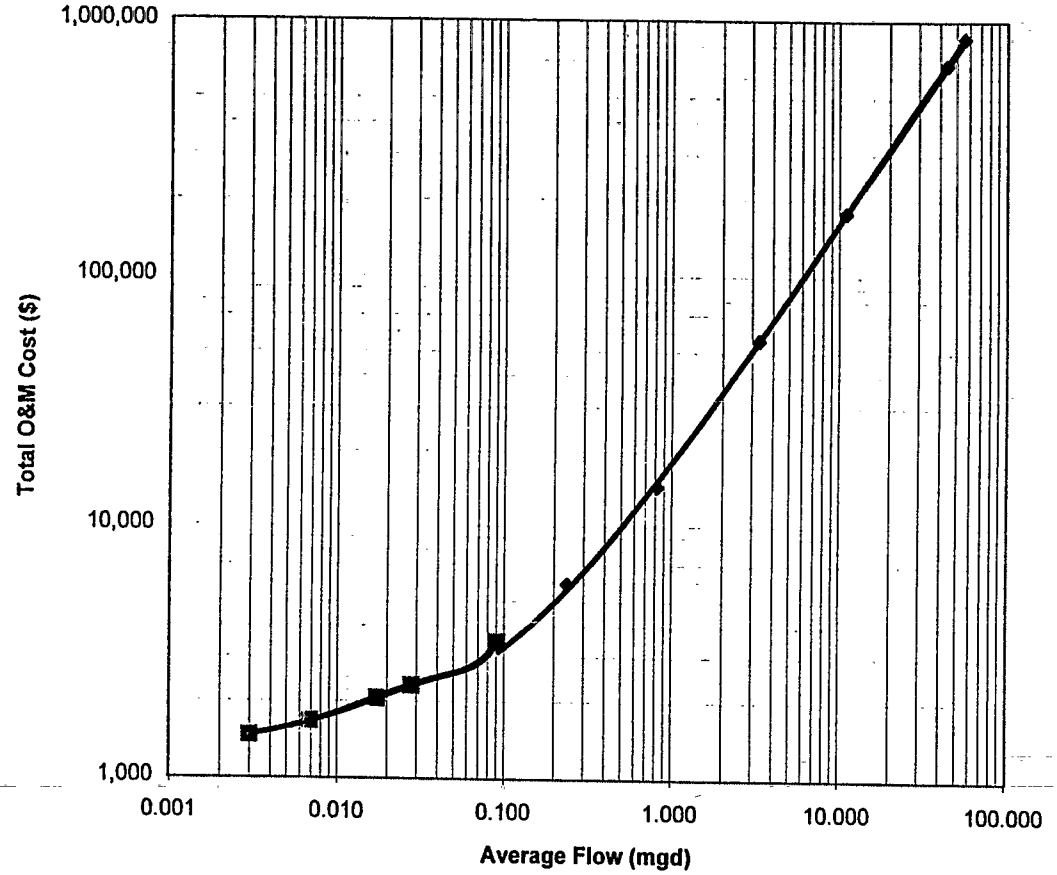


Figure A.1-6 O&M Costs for 99% Removal of Radon Using PTA (10 minute detention)



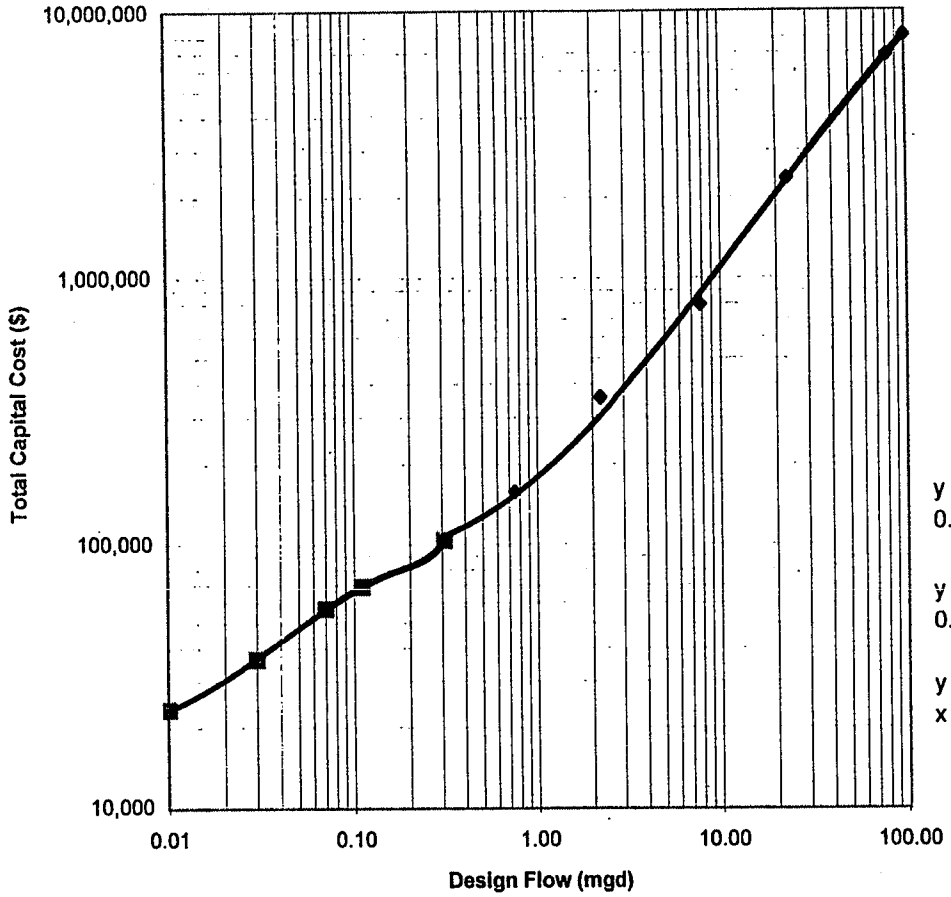
Cost Equation

$y = 7E+06x^3 - 1E+06x^2 + 59164x + 1305.6$
$0.003 <= x <= 0.091$

$y = 0.5695x^3 - 52.841x^2 + 16608x + 1609.4$
$0.091 < x <= 56$

y = O&M Costs ($)
x = Average flow (mgd)

Figure A.1-7 Capital Costs for 80% Removal of Radon Using PTA (10 minute detention)



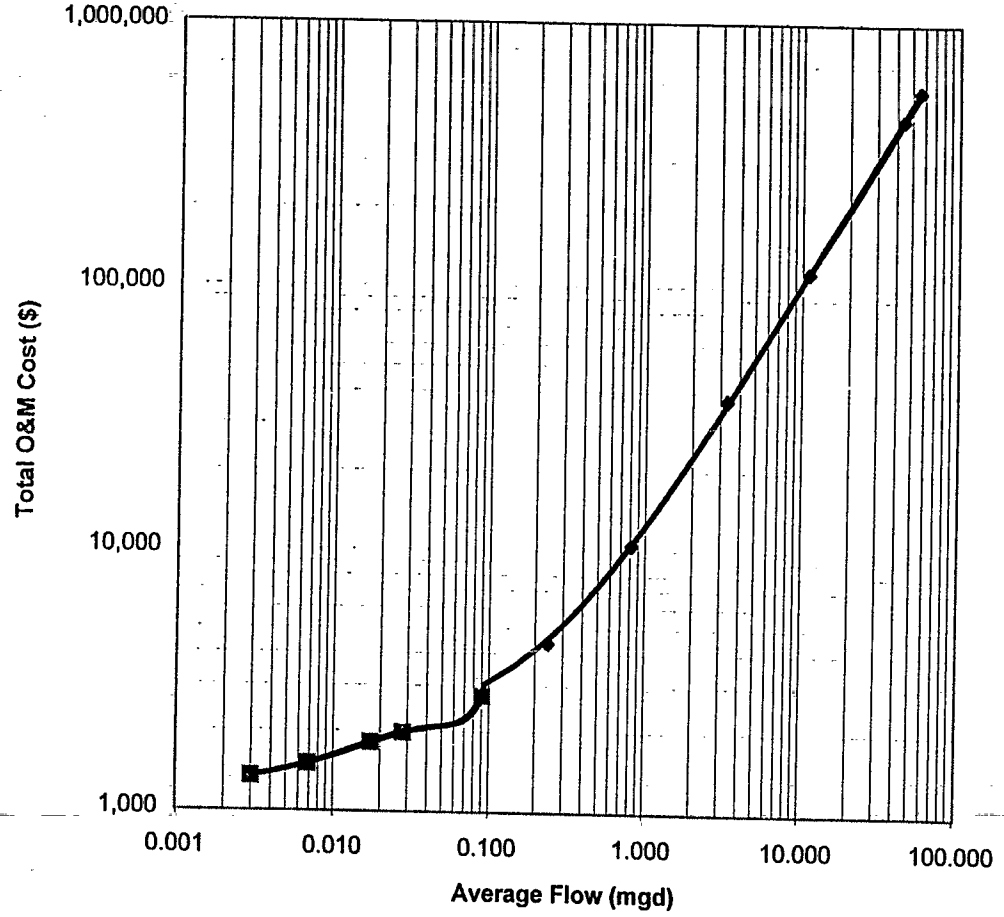
Cost Equation

$y = 6E+06x^3 - 4E+06x^2 + 809237x + 15546$
$0.01 <= x <= 0.31$

$y = 0.8242x^3 - 330.21x^2 + 104903x + 74847$
$0.31 < x <= 100$

y = Capital Costs ($)
x = Design Fow (mgd)

Figure A.1-8 O&M Costs for 80% Removal of Radon Using PTA (10 minute detention)



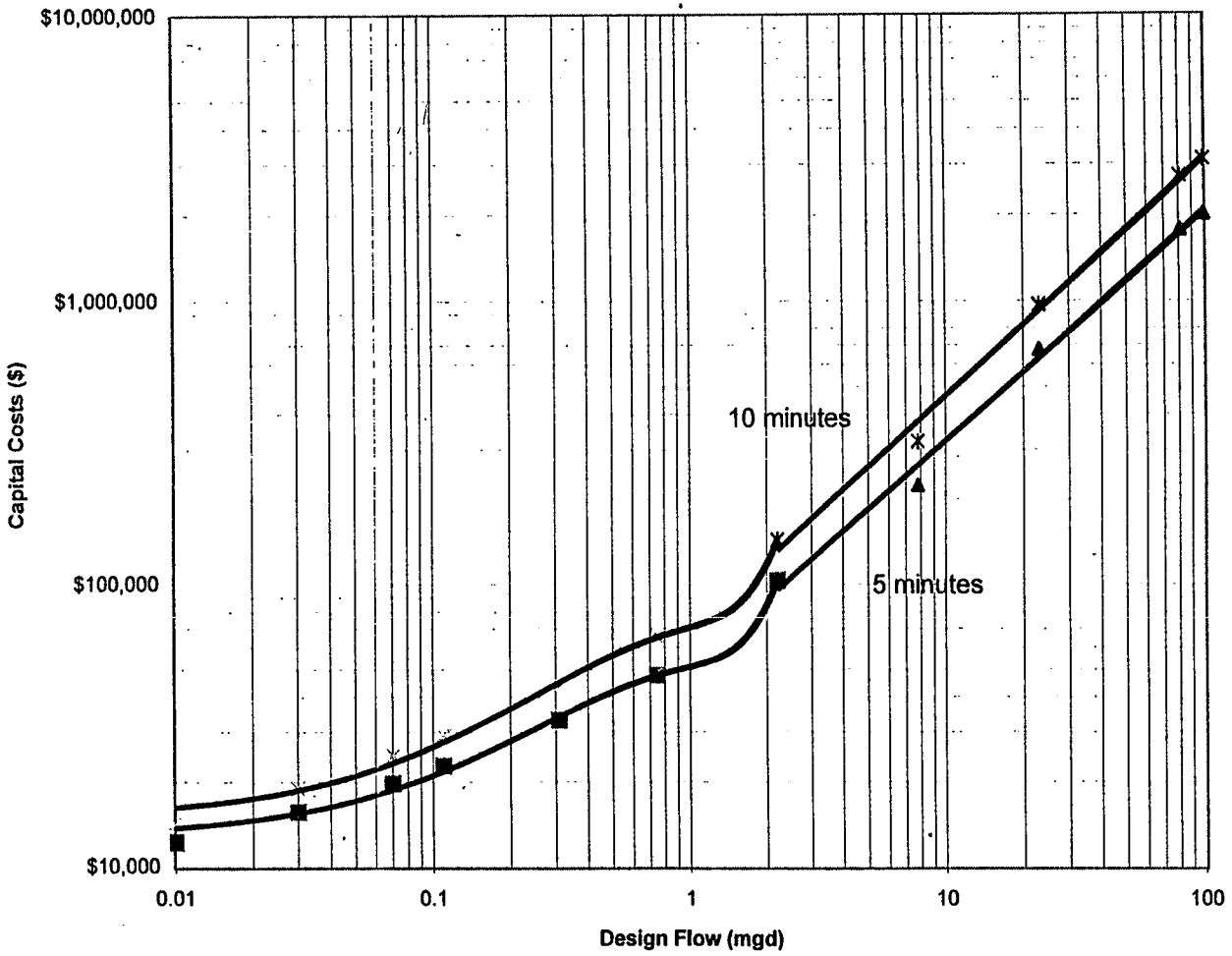
Cost Equation

$y = 7E+06x^3 - 965596x^2 + 49550x + 1197.9$
$0.003 <= x <= 0.091$

$y = 0.3359x^3 - 26.071x^2 + 10453x + 2069.2$
$0.091 < x <= 56$

y = O&M Cost ($)
x = Average Flow (mgd)

Figure A.1-9 Capital Costs for Clearwell (for 80% and 99% Removal)



Cost Equation: 5 minutes Detention

$y = 24214x^3 - 75137x^2 + 89312x + 12860$

$0.01 <= x <= 2.2$

$y = 50835x^{0.8022}$

$2.2 < x <= 100$

Cost Equation: 10 minute Detention

$y = 33104x^3 - 103388x^2 + 125982x + 14982$

$0.01 <= x <= 2.2$

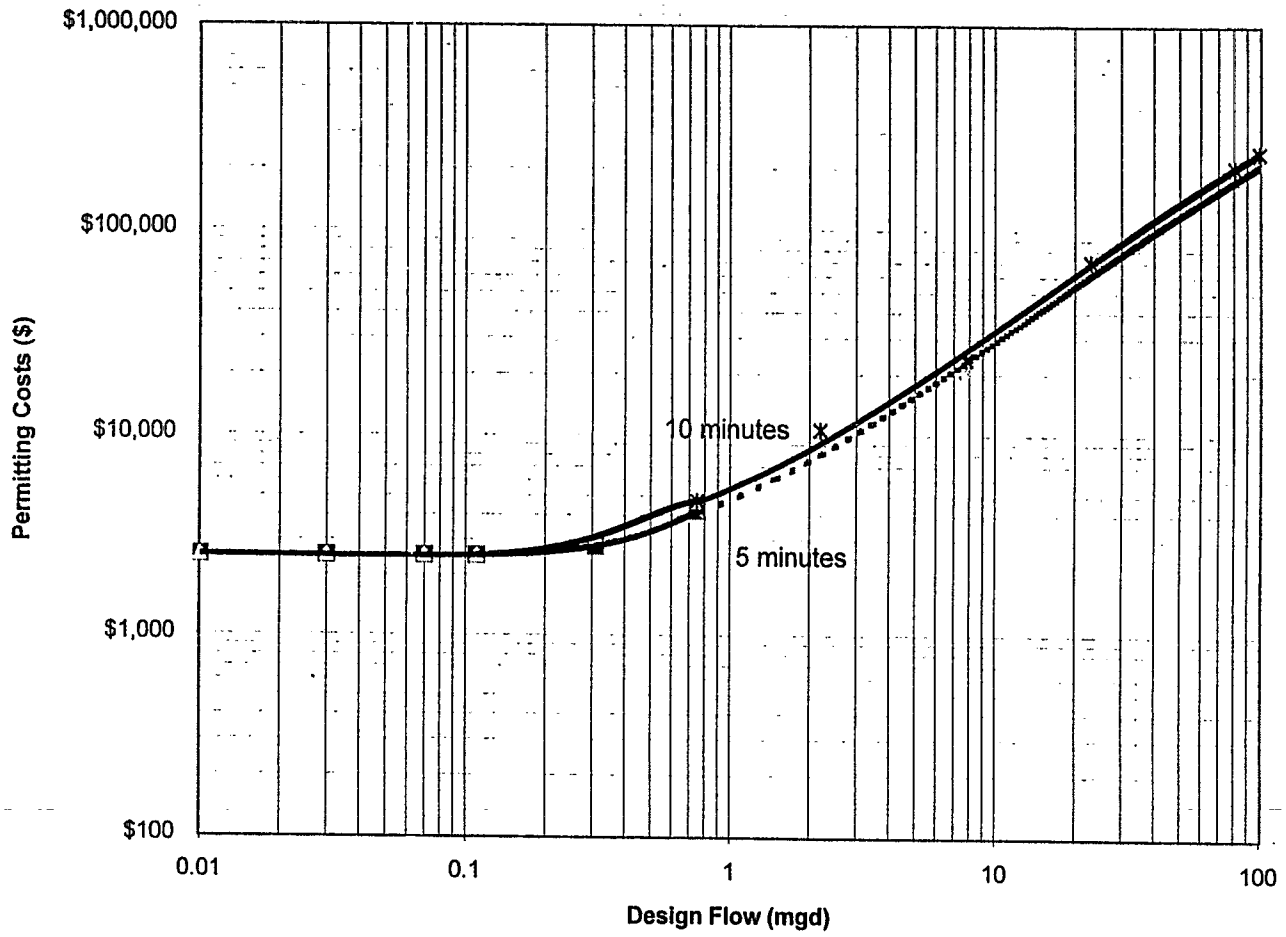
$y = 68618x^{0.8298}$

$2.2 < x <= 100$

y = Clearwell Costs ($)

x Design Flow (mgd)

Figure A.1-10 Permitting costs for 80% Radon Removal



Cost Equation: 5 minute Detention

$y = -2339.7x^3 + 5593.1x^2 - 622.57x + 2510.2$

$0.01 <= x <= 0.75$

$y = 0.0372x^3 - 10.891x^2 + 2794.7x + 1996.6$

$0.75 < x <= 100$

y = Permitting Cost ($)

x = Design Flow (mgd)

Cost Equation: 10 minute Detention

$y = -11549x^3 + 14666x^2 - 1565.3x + 2525.3$

$0.01 <= x <= 0.75$

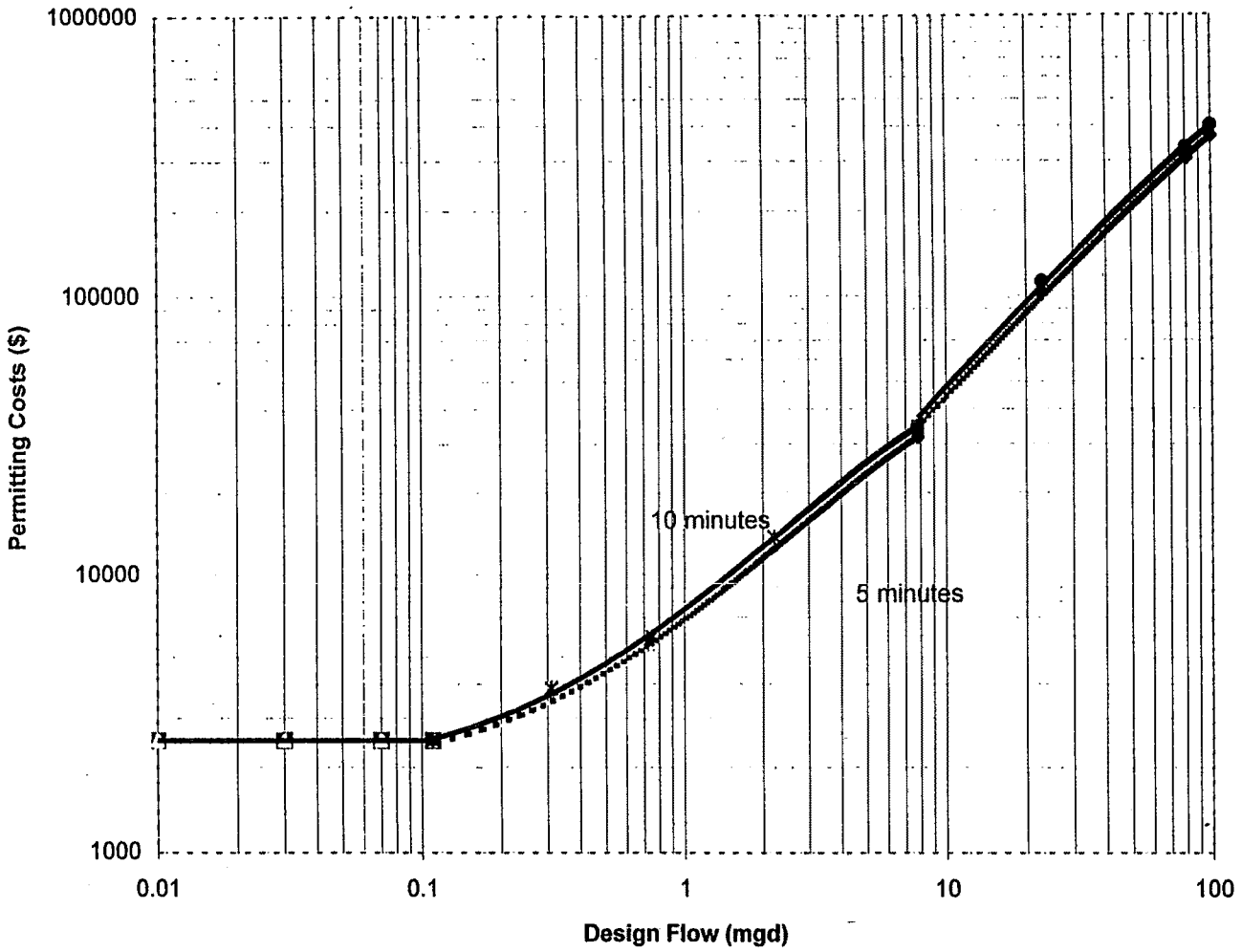
$y = 0.0241x^3 - 9.7921x^2 + 3141.2x + 2307.9$

$0.75 < x <= 100$

y = Permitting Cost ($)

x = Design Flow (mgd)

Figure A.1-11 Permitting Costs for 99% Radon Removal



Cost Equation: 5 minutes Detention

$y = -2E\text{-}11x + 2500$

$0.01 \le x \le 0.11$

$y = -169.77x^2 + 5154.3x + 1865.7$

$0.11 < x \le 7.8$

$y = -8.7626x^2 + 4535x - 309.85$

$7.8 < x \le 100$

Cost Equation: 10 minutes Detention

$y = 1116.2x^2 - 88.04x + 2501.1$

$0.01 \le x \le 0.11$

$y = -204.89x^2 + 5793.8x + 1900.9$

$0.11 < x \le 7.8$

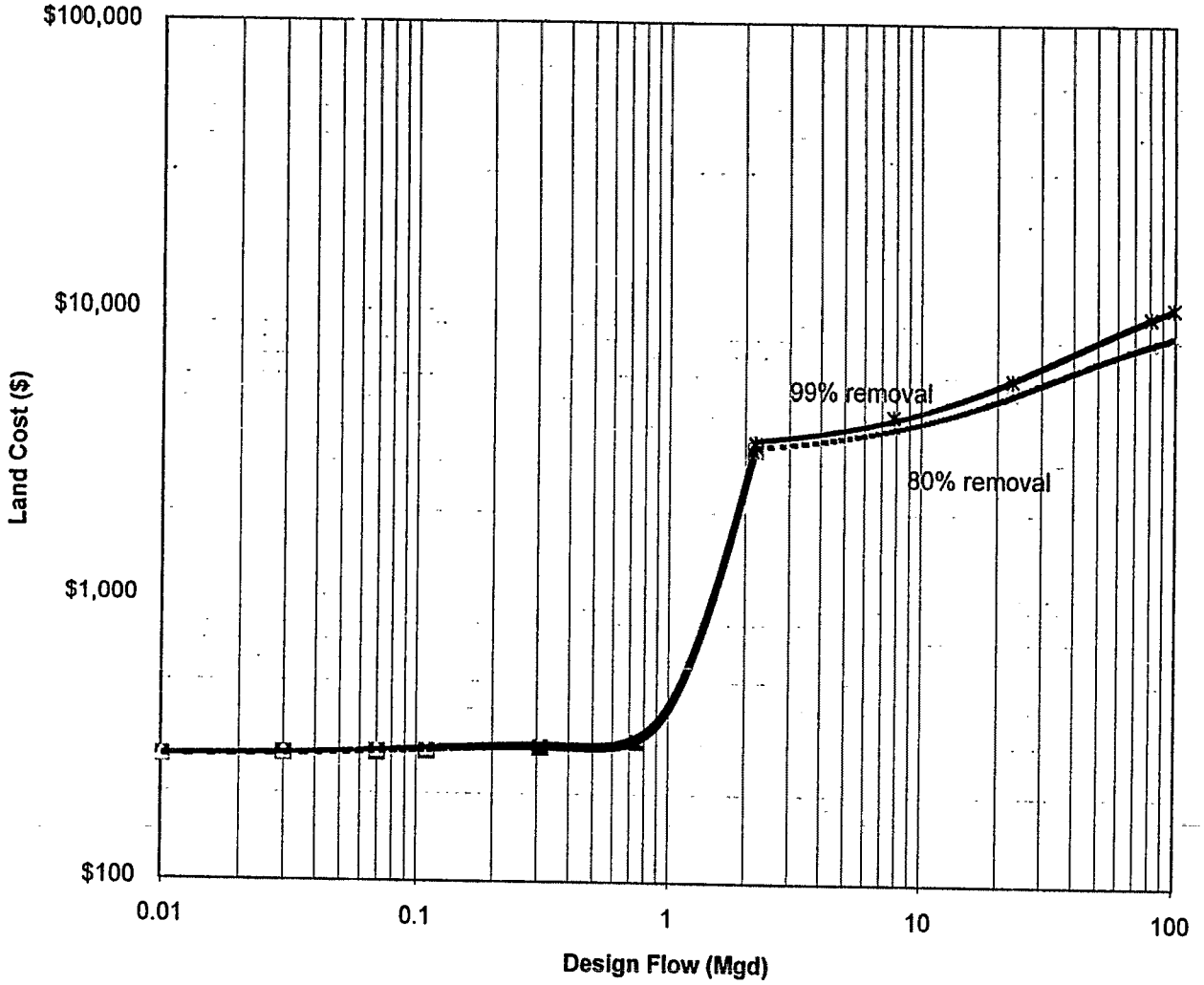
$y = -9.92x^2 + 4988.7x - 1077.1$

$7.8 < x \le 100$

y = Permitting costs ($)

x = Design flow (mgd)

Figure A.1-12 Land Costs for Radon Removal (80% & 99% Removals)



Cost Equation : 80% removal

$y = 515.87x^3 - 595.99x^2 + 209.55x + 267.42$

$0.01 \le x \le 2.2$

$y = 0.0029x^3 - 0.8614x^2 + 109.94x + 3157.5$

$2.2 < x < 100$

y = Land Costs ($)

x = Design Flow (mgd)

Cost Equation: 99%

$y = 552.19x^3 - 654.27x^2 + 246.86x + 269.67$

$0.01 \le x < 2.2$

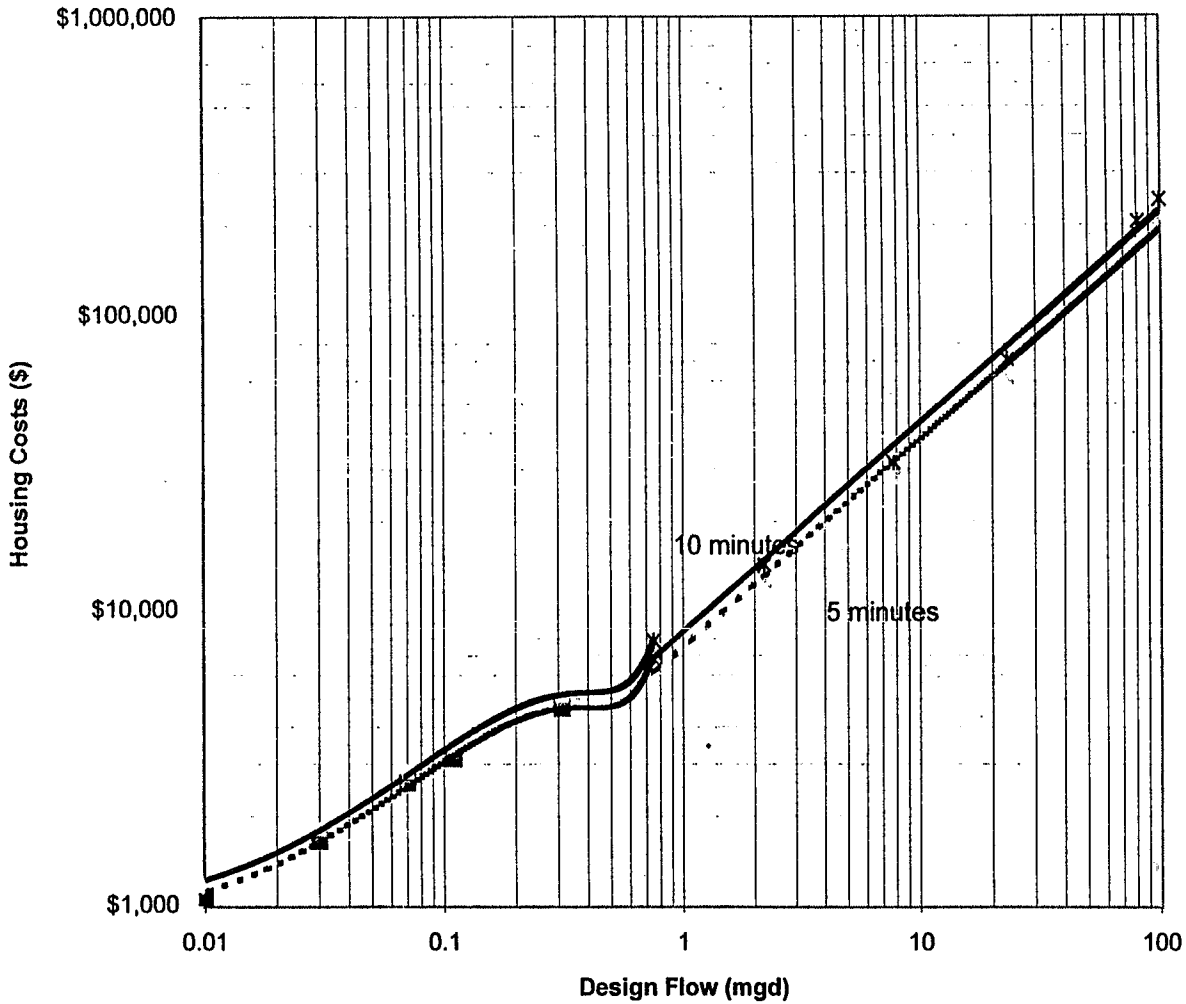
$y = 0.0025x^3 - 0.8654x^2 + 133.03x + 3308$

$2.2 < x \le 100$

y = Land Costs ($)

x = Design Flow (mgd)

Figure A.1-13 Housing Costs for 80% Radon Removal



Cost Equation: 5 minutes Detention

$y = 58662x^3 - 71361x^2 + 28749x + 834.48$

$0.01 <= x <= 0.75$

$y = 7519x^{0.7041}$

$0.75 < x <= 100$

y = Housing Costs ($)

x = Design Flow (mgd)

Cost Equation: 10 minutes Detention

$y = 62515x^3 - 76365x^2 + 31399x + 914.07$

$0.01 <= x <= 0.75$ mgd

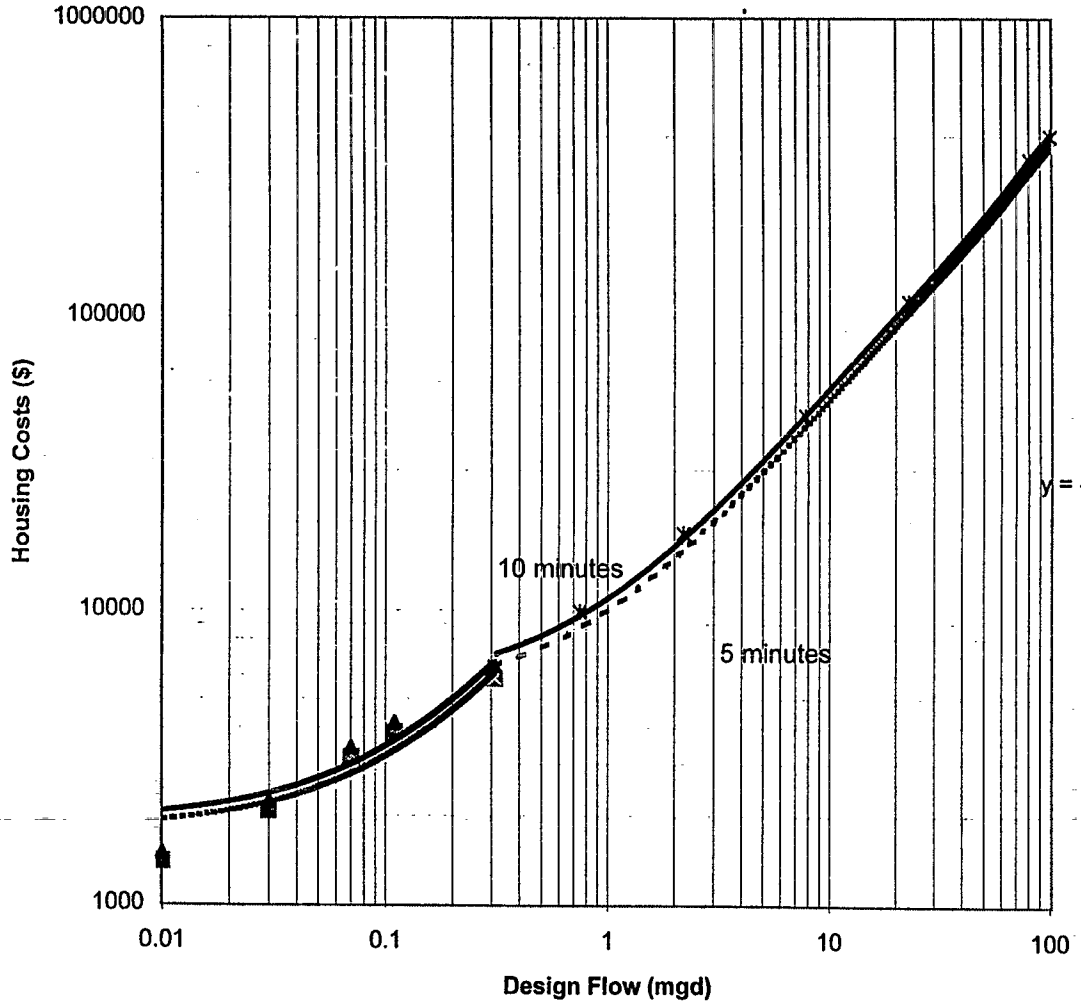
$y = 8465.3x^{0.7102}$

$0.75 < x <= 100$

y = Housing Costs ($)

x = Design Flow (mgd)

Figure A.1-14 Housing Costs for 99% Radon Removal



Cost Equation: 5 minutes Detention

$y = 13972x + 1800.6$

$0.01 \le x \le 0.75$

$y = -0.0031x^4 + 0.6952x^3 - 54.625x^2 + 5216.6x + 4866$

$0.75 < x \le 100$

Cost Equation: 10 minutes Detention

$y = 15349x + 1925.1$

$0.01 \le x \le 0.75$

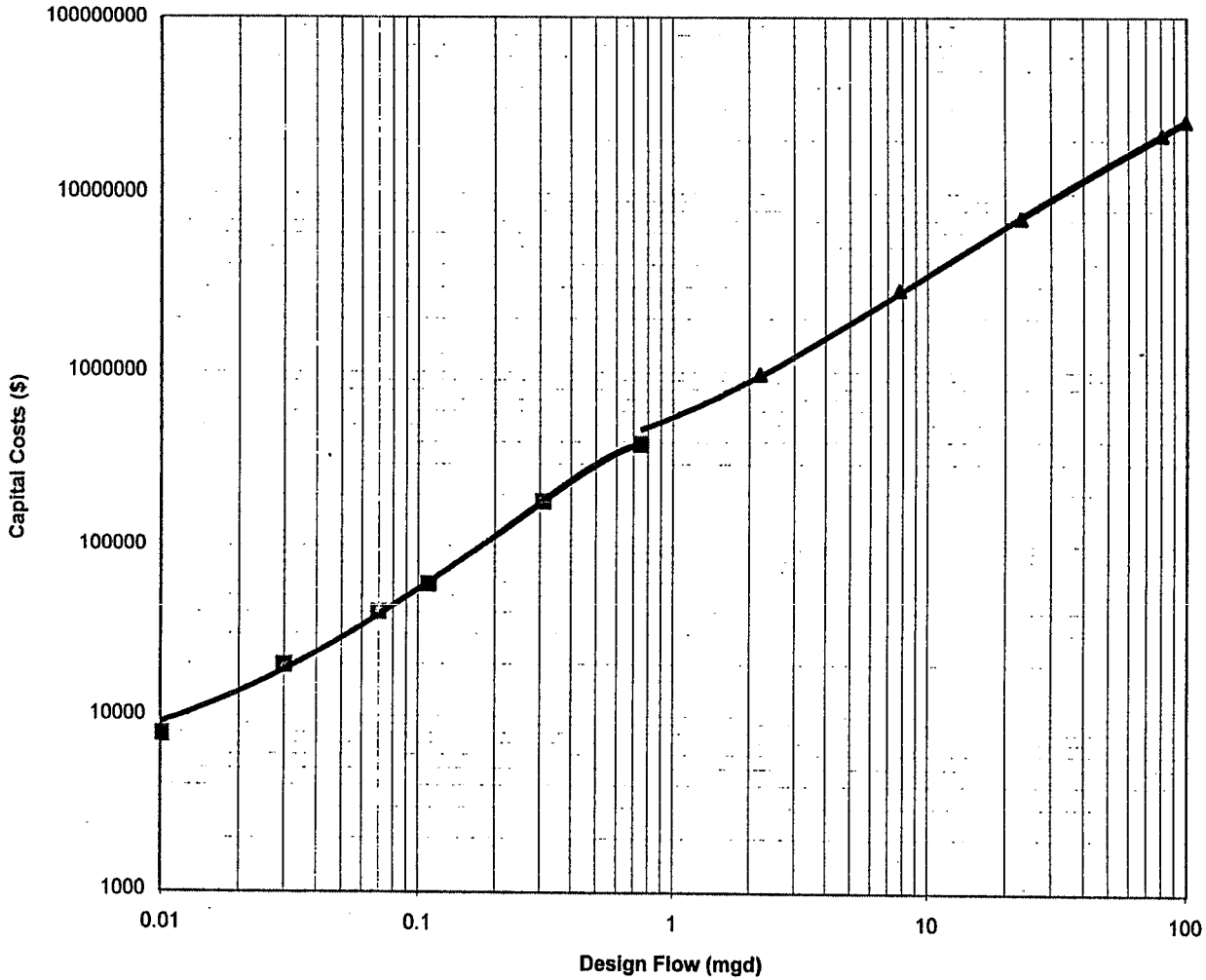
$y = -0.0039x^4 + 0.8598x^3 - 64.162x^2 + 5719.7x + 5347.4$

$0.75 < x \le 100$

y = Housing Costs ($)

x = Design Flow (mgd)

Figure A.1-15 Capital Costs for Pre-Treatment



Cost Equation

$y = -775153x^3 + 682813x^2 + 437962x + 4759.8$

$0.01 <= x <= 0.75$

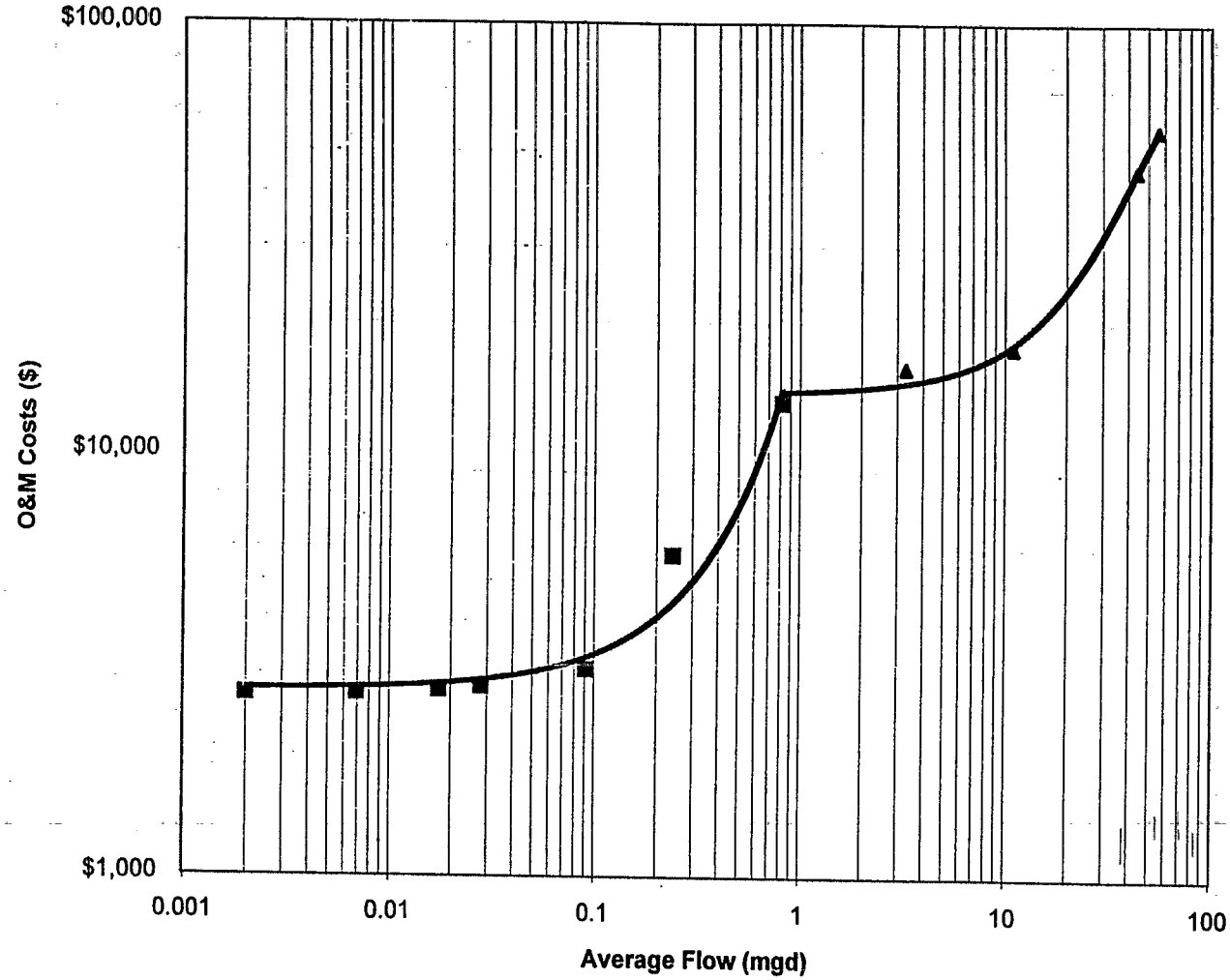
$y = 5.9266x^3 - 1451.8x^2 + 341048x + 216032$

$0.75 < x <= 100$

y = Capital Costs ($)

x = Design Flow (mgd)

Figure A.1-16 O&M Costs for Pre-Treatment



Cost Equation

$y = 2746.4e^{1.9885x}$

$0.003 <= x <= 0.82$

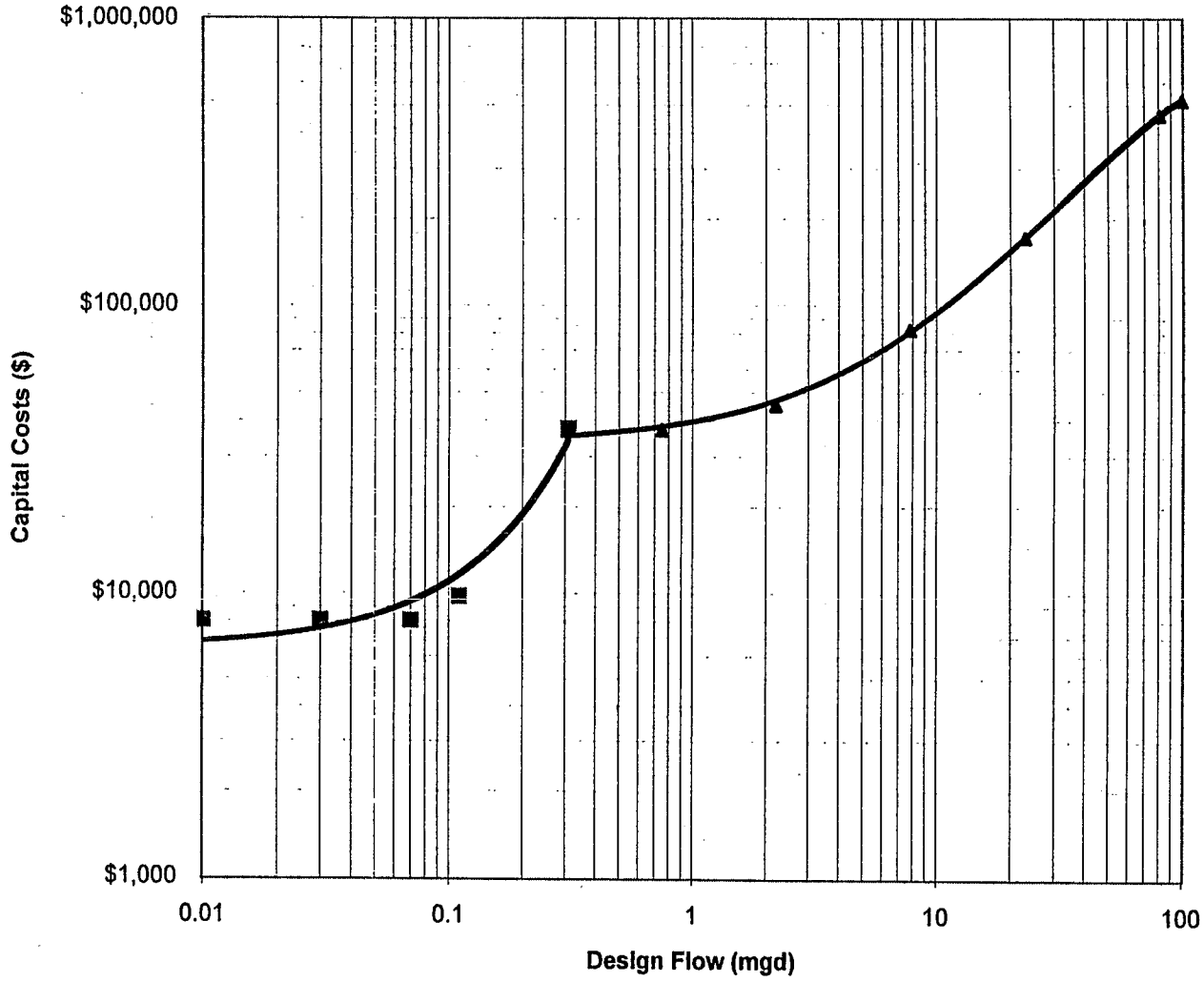
$y = -0.1373x^3 + 17.551x^2 + 209.99x + 13723$

$0.82 < x <= 56$

y = O&M Costs

x = Average Flow (mgd)

Figure A.1-17 Capital Costs for Post-Treatment



Cost Equation

$y = 6419.8e^{5.3948x}$

$0.01 <= x <= 0.31$

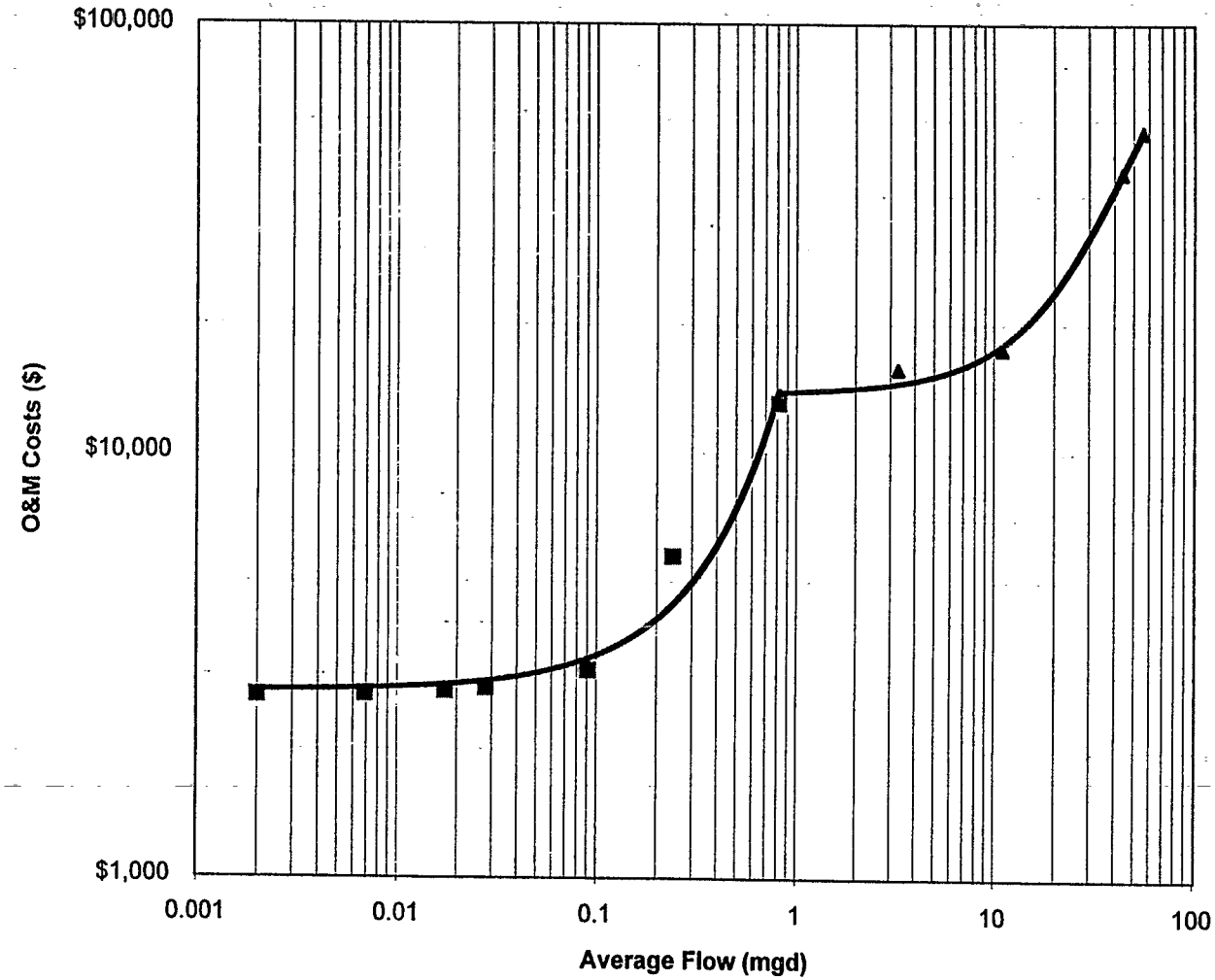
$y = -0.113x^3 - 1.4464x^2 + 6155.8x + 33526$

$0.31 < x < 100$

y = Capital Costs ($)

x = Design Flow (mgd)

Figure A.1-18 O&M Costs for Post-Treatment



Cost Equation

$y = 2746.4e^{1.9885x}$

$0.003 <= x <= 0.82$

$y = -0.1373x^3 + 17.551x^2 + 209.99x + 13723$

$0.82 < x <= 56$

y = O&M Costs ($)

x = Average Flow (mgd)

Appendix A-2
Raw Design and Cost-Estimating Data and Cost Curves for Direct Engineered PTA

APPENDIX A.2

Summary of Capital and O&M Costs for Direct Engineered PTA

Flows (gpm)		Capital costs		O&M costs	
Design	Average	80% removal	99% removal	80% removal	99% removal
30	15	$27,300	$29,000	$8,700	$8,700
50	25	$28,600	$30,700	$8,700	$8,800
90	45	$28,700	$31,000	$8,800	$8,900
250	125	$36,600	$41,800	$9,900	$10,600
500	250	$50,400	$57,200	$10,600	$11,900
750	375	$57,800	$69,000	$12,200	$15,700
1000	500	$59,900	$70,100	$12,200	$15,700
2000	1000	$82,000	$99,400	$12,800	$17,500

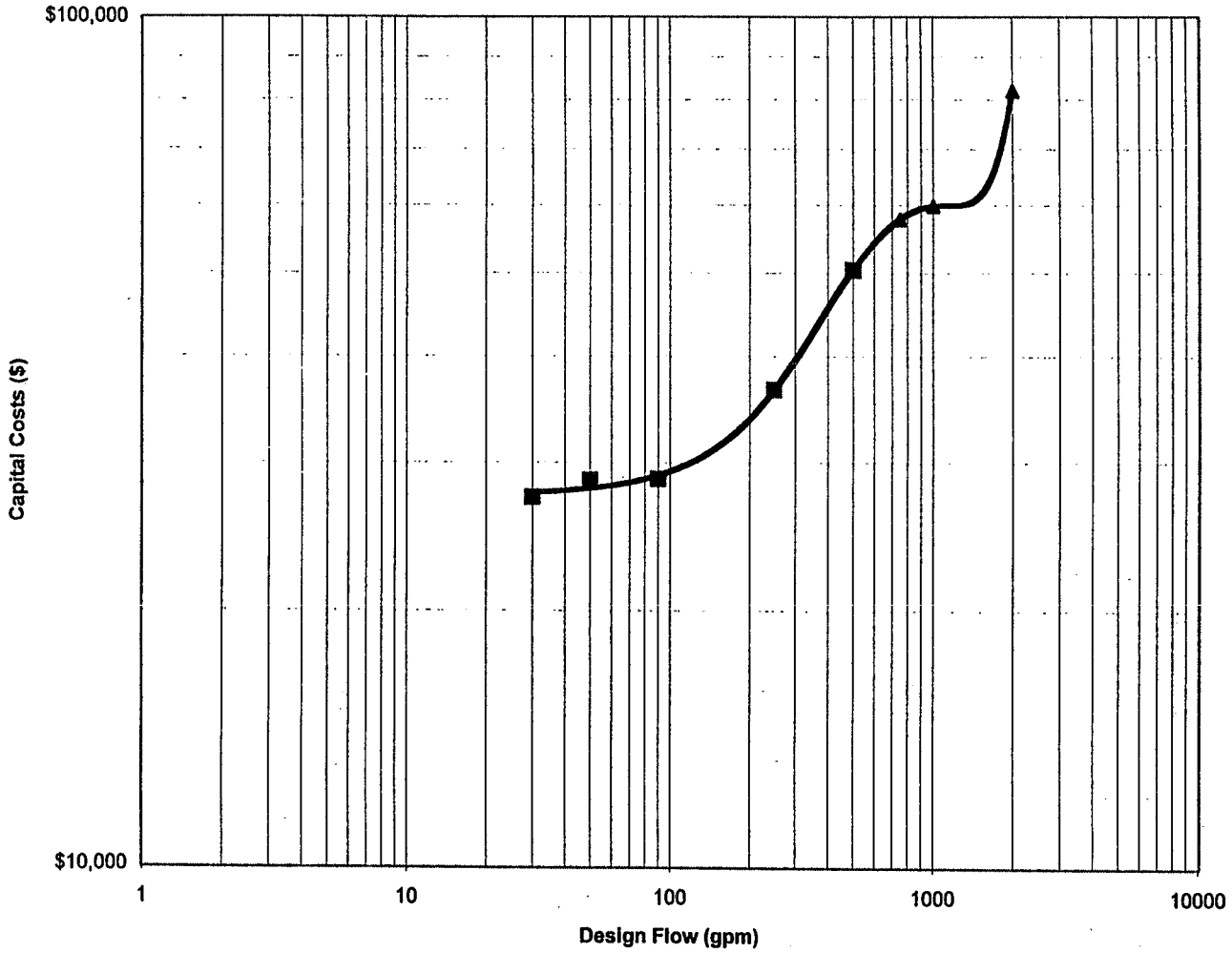
Summary of Capital and O&M Costs for Direct Engineered DBA

Flows (gpm)		Capital costs		O&M costs	
Design	Average	80% removal	99% removal	80% removal	99% removal
30	15	$19,100	$19,100	$8,600	$8,600
50	25	$20,300	$20,300	$8,600	$8,600
90	45	$20,000	$20,000	$8,600	$8,600
250	125	$22,300	$22,300	$9,200	$9,200
500	250	$34,700	$34,700	$9,200	$9,200
750	375	$37,800	$37,800	$10,300	$10,300
1000	500	$40,900	$40,900	$10,300	$10,300
2000	1000	$56,900	$56,900	$10,300	$10,300

Summary of Capital and O&M Costs for DBA (same for 80% and 99% removals)

Design Flow (gpm)	Average Flow (gpm)	Capital Cost	O&M Cost
2000	1000	$56,900.00	$10,300.00
1000	500	$40,900.00	$10,300.00
750	375	$37,800.00	$10,300.00
500	250	$34,700.00	$9,200.00
250	125	$22,300.00	$9,200.00
90	45	$20,000.00	$8,600.00
50	25	$20,300.00	$8,600.00
30	15	$19,100.00	$8,600.00

Figure A.2-1 Capital Costs for Direct Engineered PTA (80% removal)



Cost Equation

$y = -0.0002x^3 + 0.1911x^2 + 1.5247x + 27449$

$30 <= x <= 500$

$y = 4E\text{-}05x^3 - 0.1224x^2 + 140.41x + 6360$

$500 < x <= 2000$

y = Capital Costs ($)

x = Design Flow (gpm)

Figure A.2-2 O&M Costs for Direct Engineered PTA (80% removal)

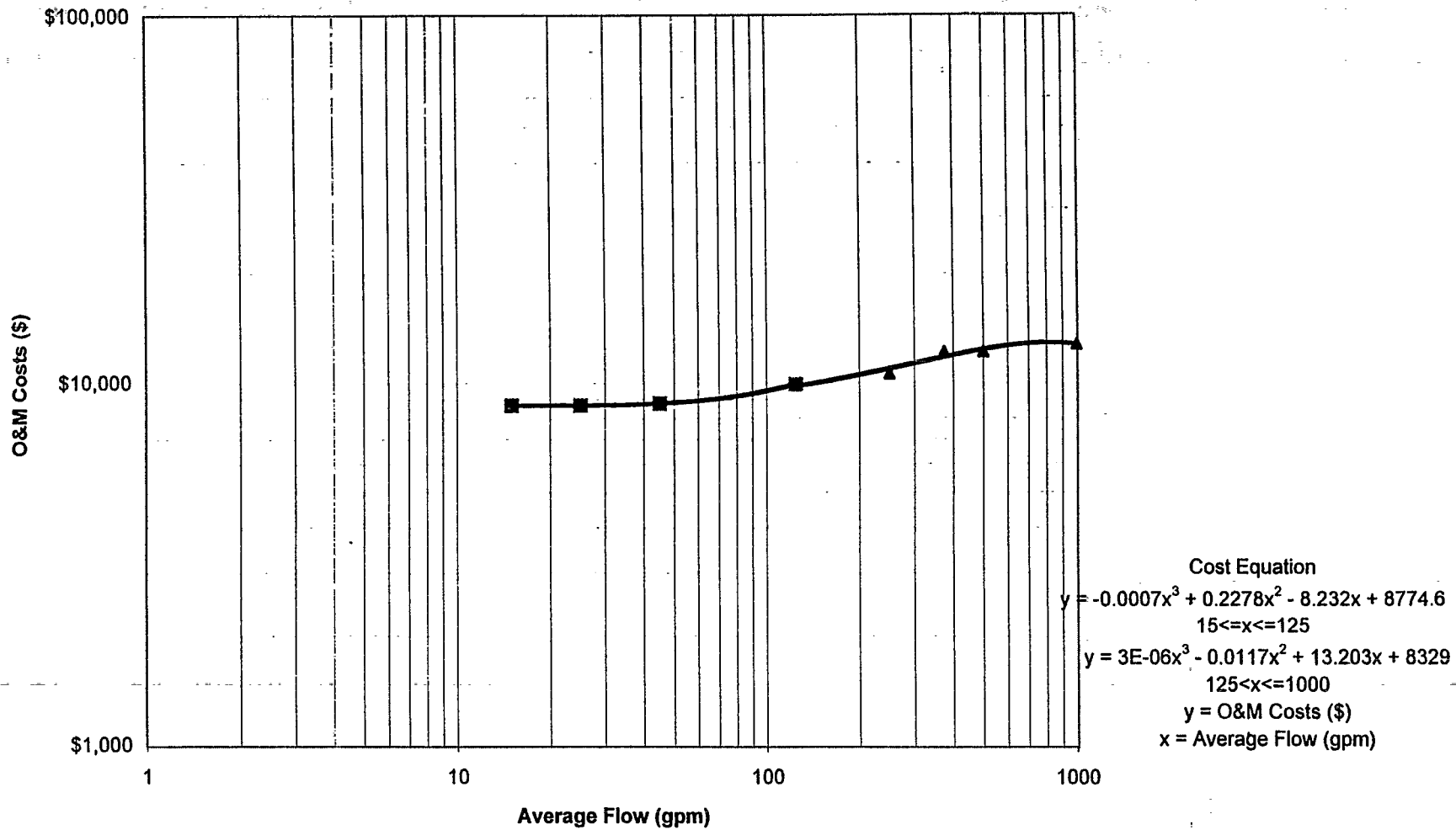
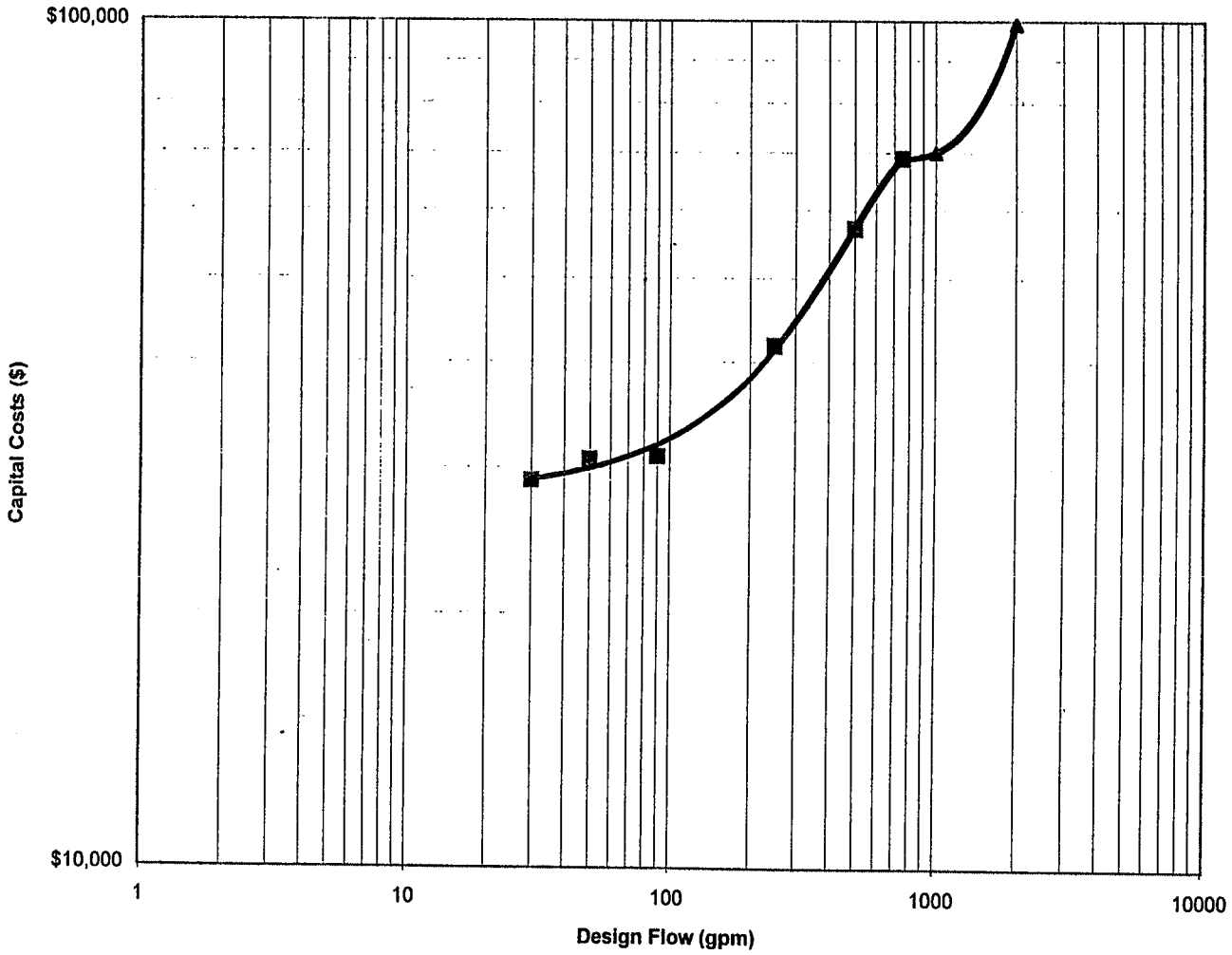


Figure A.2-3 Capital Costs for Direct Engineered PTA (99% removal)



Cost Equation

$y = -7E\text{-}05x^3 + 0.0716x^2 + 41.084x + 27751$

$30 <= x <= 750$

$y = 0.0199x^2 - 30.46x + 80640$

$750 < x <= 2000$

y = Capital Costs ($)

x = Design Flow (mgd)

Figure A.2-4 O&M Costs for Direct Engineered PTA (99% removal)

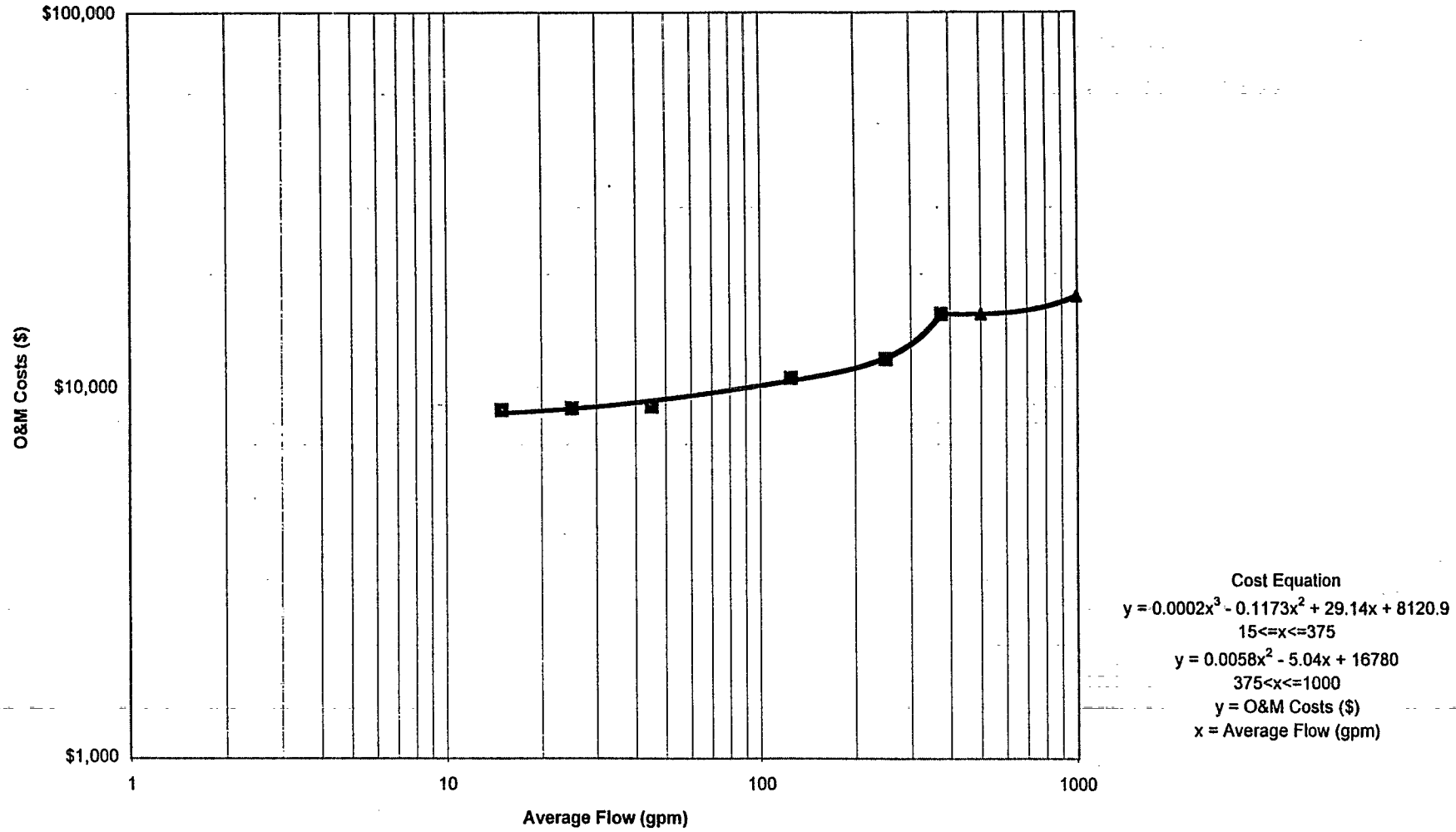
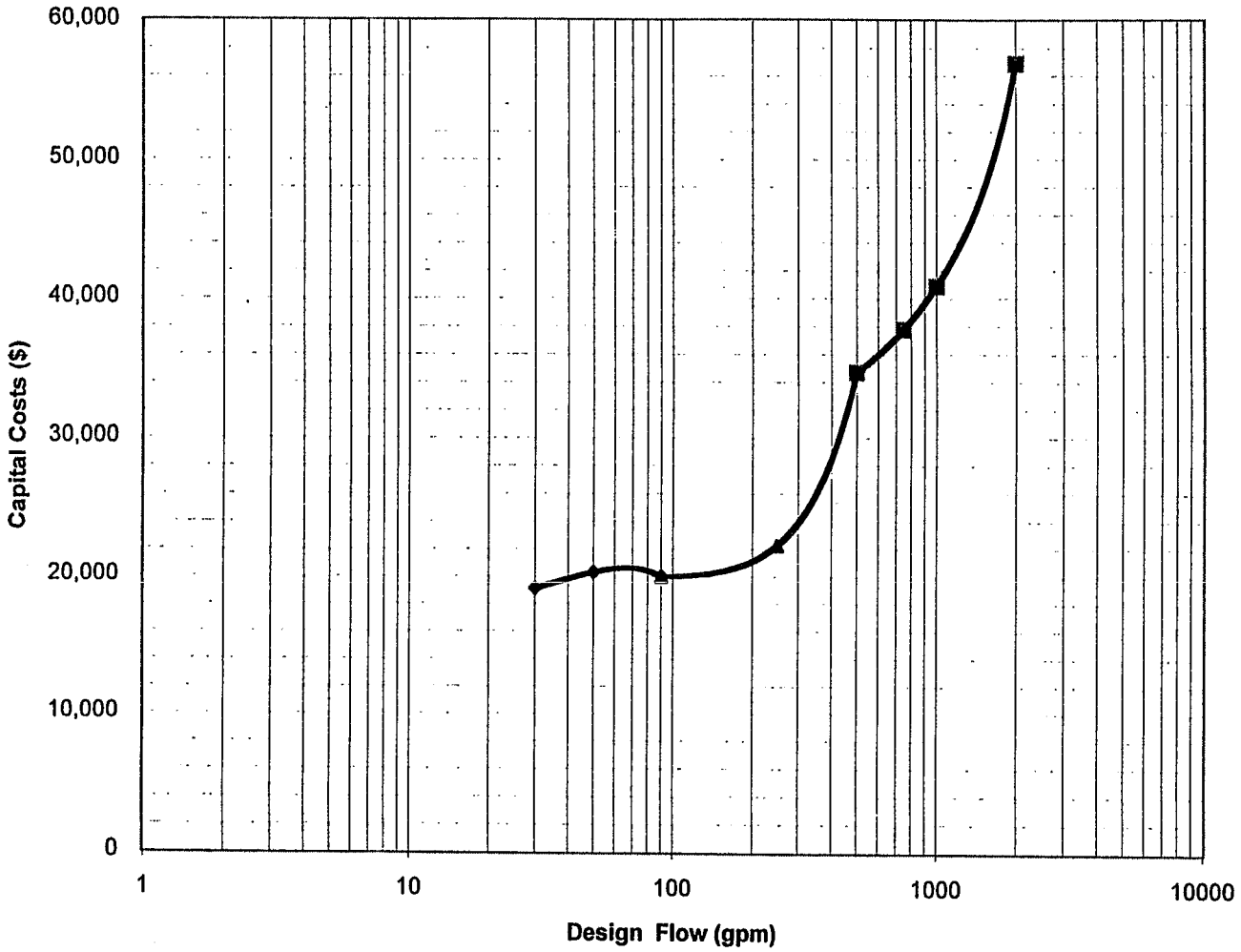


Figure A.2-5 Capital Costs for Direct Engineered DBA (80% and 99% removals)



Cost Equation

$y = -1.125x^2 + 150x + 15613$

$30 <= x <= 90$

$y = 0.0859x^2 - 14.836x + 20639$

$90 < x <= 500$

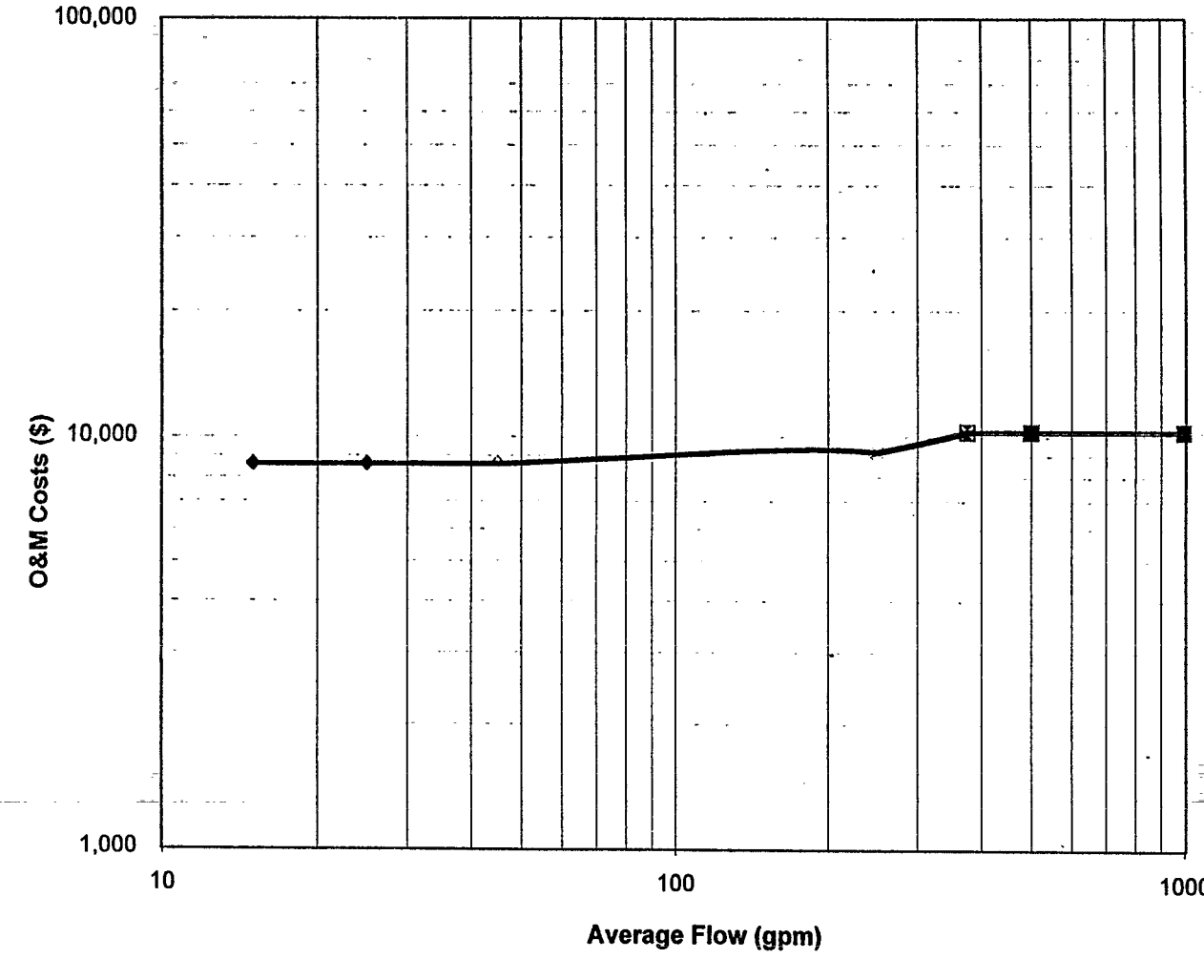
$y = 2E\text{-}06x^3 - 0.0043x^2 + 15.52x + 27780$

$500 < x <= 2000$

y = Capital Costs ($)

x = Design Flow (gpm)

Figure A.2-6 O&M Costs for Direct Engineered DBA (80% and 99% removals)



Cost Equation

$y = 8600$

$15 \le x \le 45$

$y = -0.0366x^2 + 13.72x + 8056.7$

$45 < x \le 250$

$y = 8.8x + 7000$

$250 < x \le 375$

$y = 10300$

$375 < x \le 1000$

y = O&M Costs ($)

x = Average Flow (gpm)

Appendix A-3
Detailed Breakdown of Estimated Costs for GAC and Cost Curves Based on GAC-Cost Model

APPENDIX A.3

Table A.3.1 Detailed Breakdown of Cost Components for GAC (50% removal)

Design Flow (mgd)	Average Flow (mgd)	Initial Process	Effluent Pumping	Revised Process	Engg.	Construction	Total Capital	GAC O&M	Clearwell	Permitting	EBCT (days)	Land (ft2)	Land	Contactor Volume (m3)	Housing	Pre-Tmt. Capital	Post-Tmt. Capital	Pre-Tmt. O&M	Post-Tmt. O&M	Tot.GAC O&M
0.01	0.002	$63,936	$840	$80,071	$40,036	$80,071	$200,178	$12,971	$15,295	$6,005	0.010	11,547	$265.08	12.87037991	$12,787	$179,209	$8,062	$19,113	$2,680	$15,650
0.03	0.0069	$95,851	$1,852	$117,293	$58,647	$117,293	$293,233	$14,907	$19,590	$8,797	0.010	11,722	$269.11	38.61113974	$19,170	$198,870	$8,062	$19,265	$2,701	$17,608
0.07	0.01745	$136,567	$3,408	$164,747	$82,374	$164,747	$411,868	$16,974	$24,773	$12,356	0.010	11,943	$274.17	90.09265939	$27,313	$234,008	$8,062	$19,590	$2,748	$19,722
0.11	0.028	$186,897	$4,717	$200,162	$100,081	$200,162	$500,405	$18,355	$28,548	$15,012	0.010	12,106	$277.92	141.574179	$33,379	$264,024	$9,773	$19,913	$2,795	$21,149
0.31	0.091	$270,516	$6,301	$318,190	$159,095	$318,190	$795,474	$23,586	$41,373	$23,864	0.010	12,663	$290.69	398.9817773	$54,103	$356,555	$37,155	$21,807	$3,086	$26,672
0.75	0.24	$456,101	$9,413	$525,464	$262,732	$525,464	$1,313,660	$31,712	$59,950	$39,410	0.010	13,447	$308.70	965.2784934	$91,220	$497,077	$37,155	$26,068	$5,761	$37,472
2.2	0.82	$960,220	$15,348	$1,078,176	$770,126	$1,232,201	$3,080,503	$63,266	$102,608	$92,415	0.010	15,083	$3,462.57	2831.483581	$192,044	$1,106,166	$45,229	$37,495	$13,109	$76,374
7.8	3.3	$2,401,546	$27,276	$2,653,482	$1,895,344	$3,032,550	$7,581,376	$165,512	$224,660	$227,441	0.010	18,865	$4,330.85	10038.89633	$480,309	$2,728,856	$82,905	$185,447	$15,774	$181,286
23	11	$5,228,425	$44,579	$5,780,726	$5,780,726	$7,707,635	$19,269,087	$421,489	$507,723	$578,073	0.010	25,468	$5,846.55	29601.8738	$1,045,685	$5,645,460	$172,516	$567,802	$17,561	$439,050
81	44	$13,553,489	$78,981	$14,959,530	$14,959,530	$19,946,040	$49,865,101	$1,449,885	$1,327,060	$1,495,953	0.010	42,542	$9,766.19	104250.0773	$2,710,698	$19,881,836	$462,668	$1,999,649	$45,314	$1,494,999
100	56	$15,951,850	$86,915	$17,550,097	$17,550,097	$23,400,130	$58,500,325	$1,784,407	$1,511,333	$1,755,010	0.010	47,244	$10,845.74	128703.7991	$3,190,370	$24,545,476	$521,555	$2,468,702	$56,378	$1,840,785

Table A.3.2 Detailed Breakdown of Cost Components for GAC (80% removal)

Design Flow (mgd)	Average Flow (mgd)	Initial Process	Effluent Pumping	Revised Process	Engg.	Construction	Total Capital	GAC O&M	Clearwell	Permitting	EBCT (days)	Land (ft2)	Land	Contactor Volume (m3)	Housing	Pre-Tmt. Capital	Post-Tmt. Capital	Pre-Tmt. O&M	Post-Tmt. O&M	Tot.GAC O&M
0.01	0.002	$86,693	$840	$102,828	$51,414	$102,828	$257,071	$13,100	$15,295	$7,712	0.022	11,672	$267.95	29.88409671	$17,339	$179,209	$8,062	$19,113	$2,680	$15,779
0.03	0.0069	$136,276	$1,852	$157,718	$78,859	$157,718	$394,296	$15,269	$19,590	$11,829	0.022	11,941	$274.12	89.65229013	$27,255	$198,870	$8,062	$19,265	$2,701	$17,970
0.07	0.01745	$199,533	$3,408	$227,713	$113,856	$227,713	$569,282	$17,779	$24,773	$17,078	0.022	12,281	$281.92	209.188677	$39,907	$234,008	$8,062	$19,590	$2,748	$20,527
0.11	0.028	$246,654	$4,717	$279,918	$139,959	$279,918	$699,796	$19,605	$28,548	$20,994	0.022	12,533	$287.72	328.7250638	$49,331	$264,024	$9,773	$19,913	$2,795	$22,400
0.31	0.091	$446,886	$6,301	$494,560	$247,280	$494,560	$1,236,400	$27,256	$41,373	$37,092	0.022	13,399	$307.60	926.406998	$89,377	$356,555	$37,155	$21,807	$3,086	$30,342
0.75	0.24	$805,613	$9,413	$874,977	$437,488	$874,977	$2,187,442	$39,980	$59,950	$65,623	0.022	14,636	$336.00	2241.307253	$161,123	$497,077	$37,155	$26,068	$5,761	$45,741
2.2	0.82	$1,878,970	$15,348	$1,998,926	$1,426,376	$2,282,201	$5,705,503	$92,278	$102,608	$171,165	0.022	17,268	$3,964.20	6574.501276	$375,794	$1,106,166	$45,229	$37,495	$13,109	$105,386
7.8	3.3	$4,385,455	$27,276	$4,637,391	$3,312,422	$5,299,875	$13,249,687	$267,143	$224,660	$397,491	0.022	23,573	$5,411.61	23309.59543	$877,091	$2,728,856	$82,905	$185,447	$15,774	$282,918
23	11	$9,847,323	$44,579	$10,399,624	$10,399,624	$13,866,166	$34,665,414	$747,899	$507,723	$1,039,962	0.022	35,110	$8,060.19	68733.42243	$1,969,465	$5,645,460	$172,516	$567,802	$17,561	$765,460
81	44	$26,133,166	$78,981	$27,539,207	$27,539,207	$36,718,942	$91,797,355	$2,628,487	$1,327,060	$2,753,921	0.022	66,776	$15,329.65	242061.1834	$5,226,633	$19,881,836	$462,668	$1,999,649	$45,314	$2,673,801
100	56	$30,856,335	$86,915	$32,454,583	$32,454,583	$43,272,777	$108,181,943	$3,243,189	$1,511,333	$3,245,458	0.022	75,794	$17,399.81	298840.9871	$6,171,267	$24,545,476	$521,555	$2,468,702	$56,378	$3,299,568

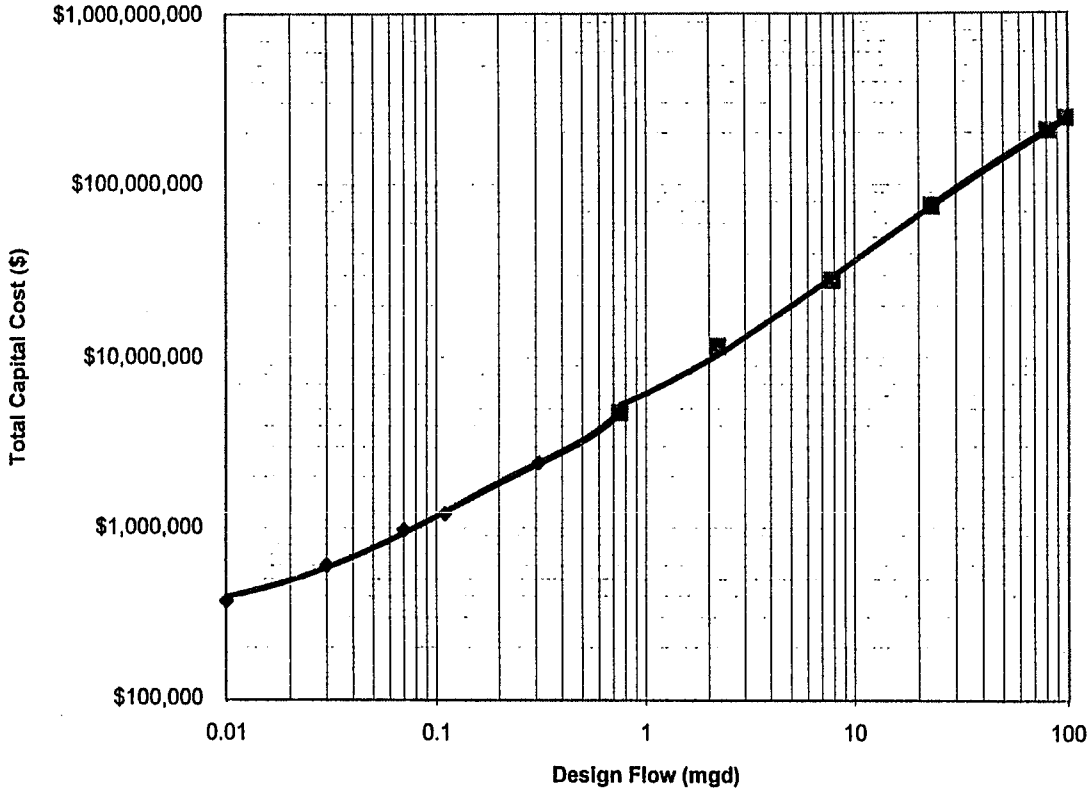
Table A.3.3 Detailed Breakdown of Cost Components for GAC (99% removal)

Design Flow (mgd)	Average Flow (mgd)	Initial Process	Effluent Pumping	Revised Process	Engg.	Construction	Total Capital	GAC O&M	Clearwell	Permitting	EBCT (days)	Land (ft2)	Land	Contactor Volume (m3)	Housing	Pre-Tmt. Capital	Post-Tmt. Capital	Pre-Tmt. O&M	Post-Tmt. O&M	Tot.GAC O&M
0.01	0.002	$133,503	$840	$149,638	$74,819	$149,638	$374,096	$13,457	$15,295	$11,223	0.064	11,926	$273.78	85.50895325	$29,928	$179,209	$8,062	$19,113	$2,680	$136,182
0.03	0.0069	$219,428	$1,852	$240,870	$120,435	$240,870	$602,176	$16,309	$19,590	$18,065	0.064	12,387	$284.36	256.5268597	$48,174	$198,870	$8,062	$19,265	$2,701	$222,129
0.07	0.01745	$360,284	$3,408	$388,464	$194,232	$388,464	$971,159	$20,229	$24,773	$29,135	0.064	12,975	$297.86	598.5626727	$77,693	$234,008	$8,062	$19,590	$2,748	$363,031
0.11	0.028	$450,271	$4,717	$483,536	$241,768	$483,536	$1,208,840	$23,365	$28,548	$36,285	0.064	13,415	$307.97	940.5984857	$96,707	$264,024	$9,773	$19,913	$2,795	$453,066
0.31	0.091	$912,935	$6,301	$960,609	$480,304	$960,609	$2,401,522	$37,347	$41,373	$72,048	0.064	14,947	$343.13	2650.777551	$192,122	$356,555	$37,155	$21,807	$3,086	$916,021
0.75	0.24	$1,847,413	$9,413	$1,916,777	$958,388	$1,916,777	$4,791,942	$76,408	$59,950	$143,758	0.064	17,186	$394.53	6413.171493	$383,355	$497,077	$37,155	$26,068	$5,761	$1,853,174
2.2	0.82	$3,987,922	$15,348	$4,085,878	$2,918,484	$4,669,574	$11,673,936	$175,475	$102,608	$350,218	0.064	22,121	$5,078.23	18811.96971	$817,176	$1,106,166	$45,229	$37,495	$13,109	$3,981,030
7.8	3.3	$9,624,236	$27,276	$9,876,171	$7,054,408	$11,287,053	$28,217,632	$588,849	$224,660	$846,529	0.064	34,653	$7,955.16	66696.98353	$1,975,234	$2,728,856	$82,905	$185,447	$15,774	$9,640,010
23	11	$22,201,119	$44,579	$22,753,421	$22,753,421	$30,337,894	$75,844,735	$1,762,002	$507,723	$2,275,342	0.064	59,237	$13,599.02	196670.5925	$4,550,684	$5,645,460	$172,516	$567,802	$17,561	$22,218,660
81	44	$60,328,504	$78,981	$61,734,545	$61,734,545	$82,312,727	$205,781,817	$6,249,214	$1,327,060	$6,173,455	0.064	132,147	$30,336.83	692622.5213	$12,346,909	$19,881,836	$462,668	$1,999,649	$45,314	$60,373,818
100	56	$71,585,265	$86,915	$73,163,512	$73,163,512	$97,551,350	$243,878,375	$7,809,316	$1,511,333	$7,316,351	0.064	153,739	$35,293.57	855089.5325	$14,632,702	$24,545,476	$521,555	$2,468,702	$56,378	$71,621,643

Key for Tables A.3.1-A.3.3

Item	Assumption/Rationale
Design Flow	The selected design flow for cost analysis (11 plant sizes).
Average Flow	The average flow for the selected design flow (11 plant sizes).
Initial Process	Process equipment cost calculated by GAC-COST Model.
Effluent pumping	When clearwell is added, a pump is necessary to pump to distribution system. Pump costs estimated by regression of pump cost versus pump size from RS Means Plumbing Cost Data.
Revised process	The sum of initial process and effluent pumping costs
Engineering	*Small systems (<1 mgd):* 50 percent of Revised Process cost (20 percent of total capital costs) as per TDP recommendations. *Medium systems (1 to 10 mgd):* 71 percent of Revised Process cost (25 percent of total capital costs) based on TDP recommendations. *Large systems (>10 mgd):* 100 percent of Revised Process cost (30 percent of total capital costs) as per TDP recommendations.
Construction	*Small systems (<1 mgd):* 100 percent of Revised Process cost (40 percent of total capital costs) as per TDP recommendations. *Medium systems (1 to 10 mgd):* 114 percent of Revised Process cost (40 percent of total capital costs) as per TDP recommendations. *Large systems (>10 mgd):* 133 percent of Revised Process cost (40 percent of total capital costs) as per TDP recommendations.
Total Capital	The sum of Revised Process, Engineering, and Construction.
GAC O&M	Output from GAC-COST model (includes transportation and disposal costs).
Clearwell	The cost of a clearwell estimated using the PTA-COST Model.
Permitting	The greater of 3 percent of Total Aeration Capital or $2,500 based on TDP guides.
EBCT	Empty bed contact time as output from the GAC-COST Model using a mean Kss of 3.0 from a range of values reported by AWWARF 1997..
Land (sq ft)	Land area is based on process footprint plus a sixty foot buffer zone between plant and adjacent land. Calculated as $(SQRT(1.5*flow*EBCT/depth/\pi + 60))^2 * \pi$.
Land ($)	The utility can purchase land for $1,000 per acre in rural areas (<1 mgd), or $10,000 per acre in urban areas (>1 mgd).
Contactor Volume	Calculated as flow * EBCT.
Housing	20% of Revised Process costs.
Pre-treatment Capital	Generalized capital cost equations for iron and manganese removal were used.
Post-treatment Capital	Generalized capital cost for disinfection following GAC.
Pre-treatment O&M	Pre-treatment O&M costs based on generalized O&M equations.
Post-treatment O&M	O&M costs based on generalized O&M equations.
Total GAC O&M	The sum of Pre-treatment O&M, Post-treatment O&M, and GAC O&M.

Figure A.3-1 Capital Costs for 50% Removal of Radon by GAC



Cost Equation

$y = 1E+07x^3 - 1E+07x^2 + 1E+07x + 298885$

$0.01 <= x <= 0.75$ mgd

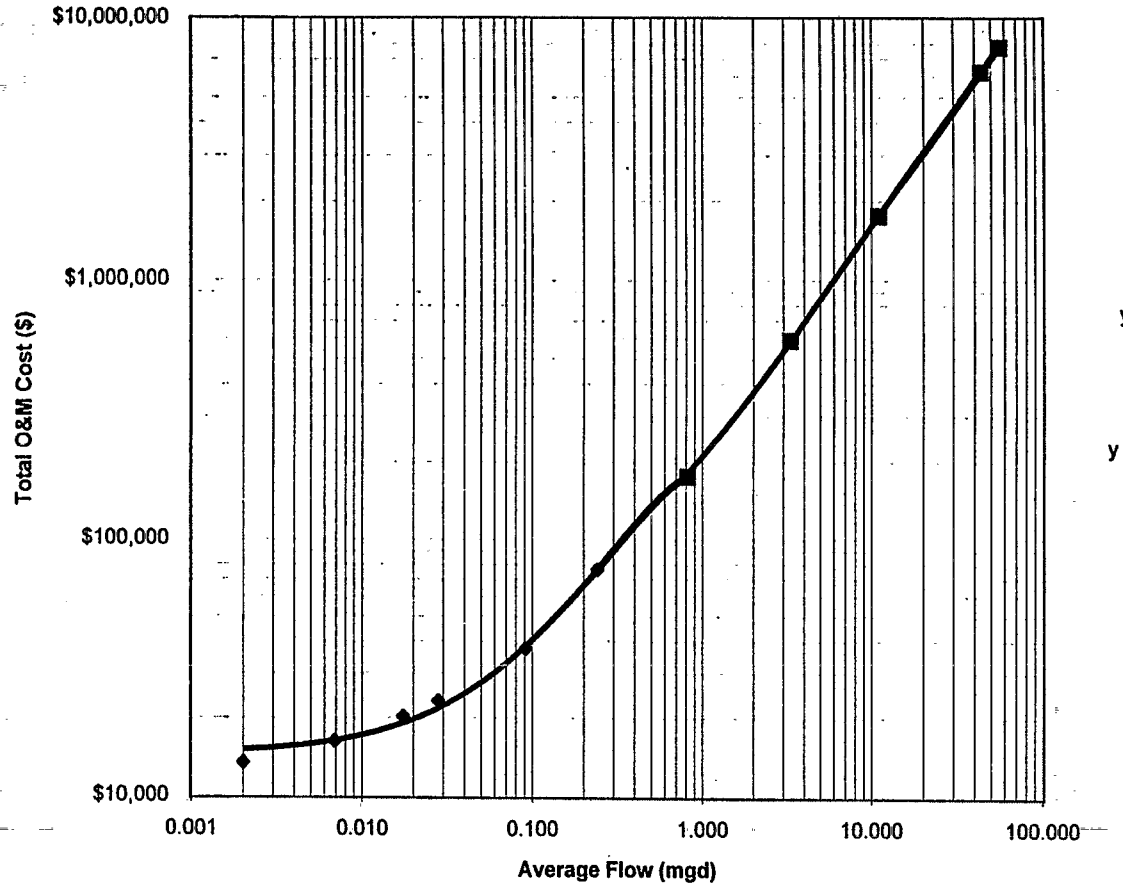
$y = 80.787x^3 - 19730x^2 + 4E+06x + 3E+06$

$0.75 < x < 100$ mgd

y = Capital Costs ($)

x = Design Flow (mgd)

Figure A.3-2 O&M Costs for 50% Removal of Radon by GAC



Cost Equation

$y = -109383x^3 + 11128x^2 + 260630x + 14589$

$0.002 <= x <= 0.82$ mgd

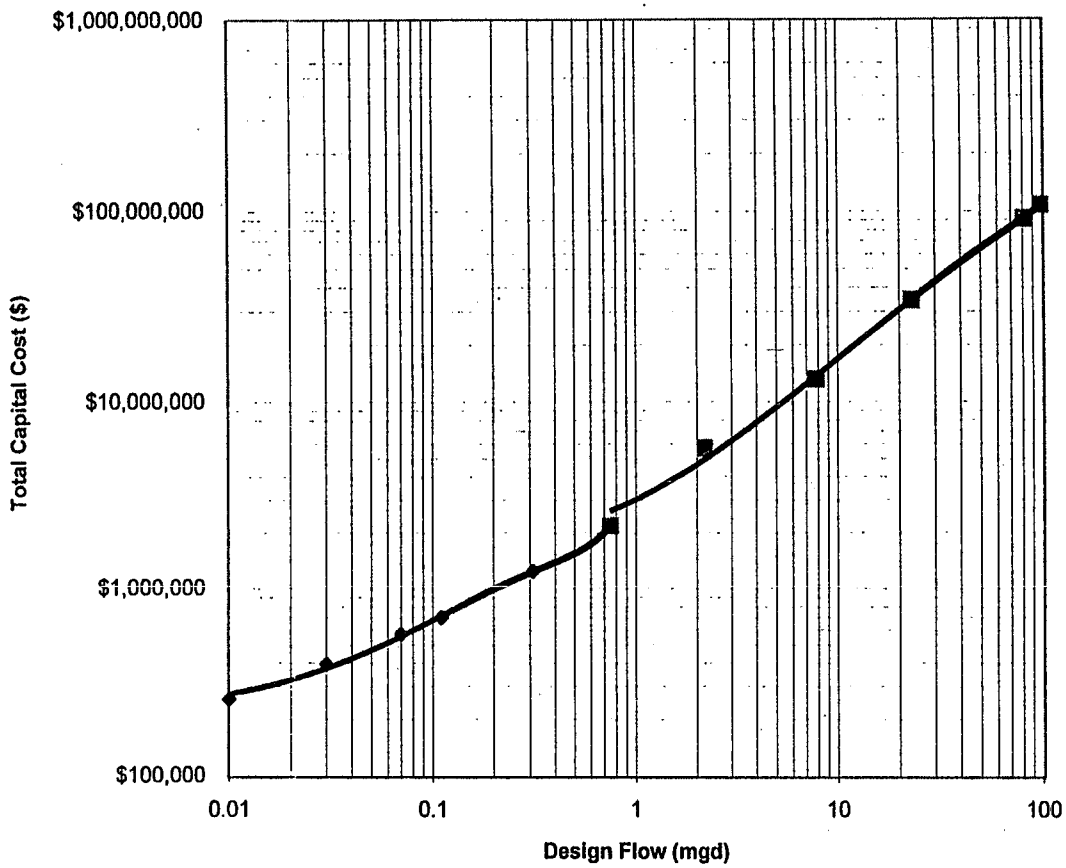
$y = 5.9326x^3 - 787.46x^2 + 164106x + 47197$

$0.82 < x <= 56$ mgd

y = O&M Costs ($)

x = Average Flow (mgd)

Figure A.3-3 Capital Costs for 80% Removal of Radon by GAC



Cost Equation

$y = 7E+06x^3 - 9E+06x^2 + 5E+06x + 221221$

$0.01 \leq x \leq 0.75$ mgd

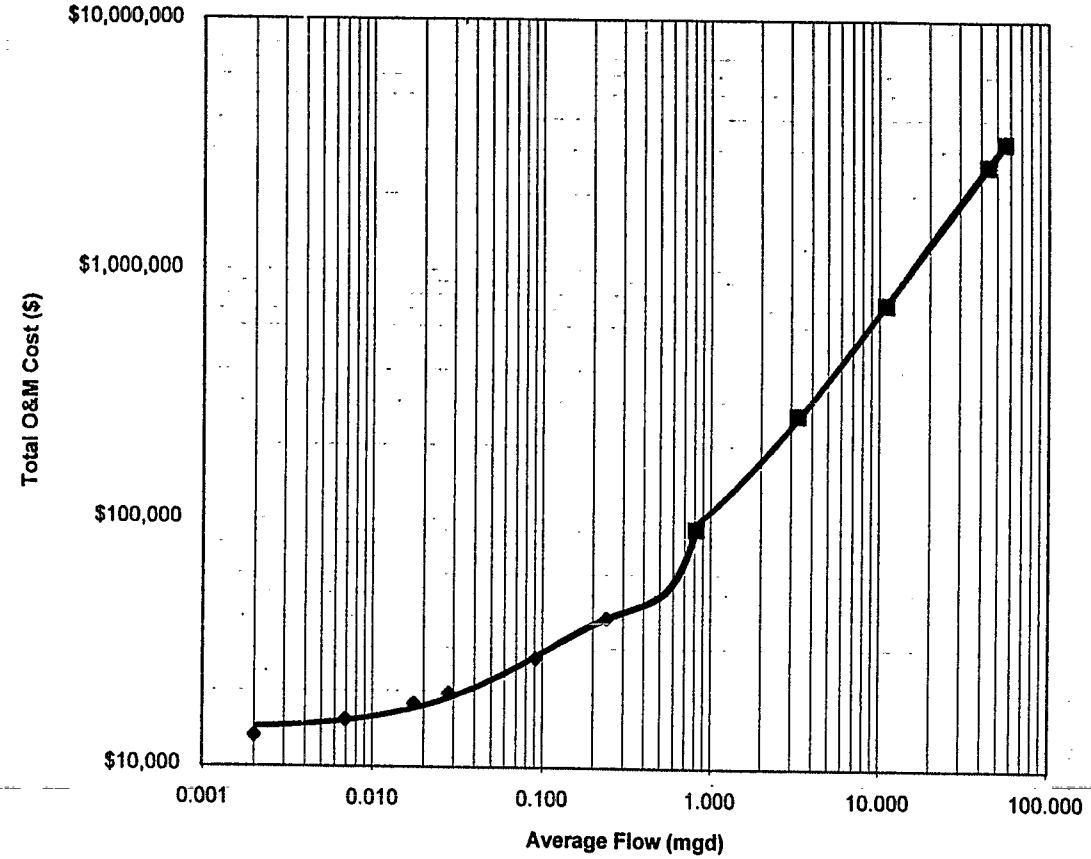
$y = 39.689x^3 - 9739.2x^2 + 2E+06x + 1E+06$

$0.75 < x < 100$ mgd

y = Capital Costs ($)

x = Design Flow (mgd)

Figure A.3-4 O&M Costs for 80% Removal of Radon by GAC



Cost Equation

$y = 383612x^3 - 428770x^2 + 189279x + 13864$

$0.002 <= x <= 0.82$ mgd

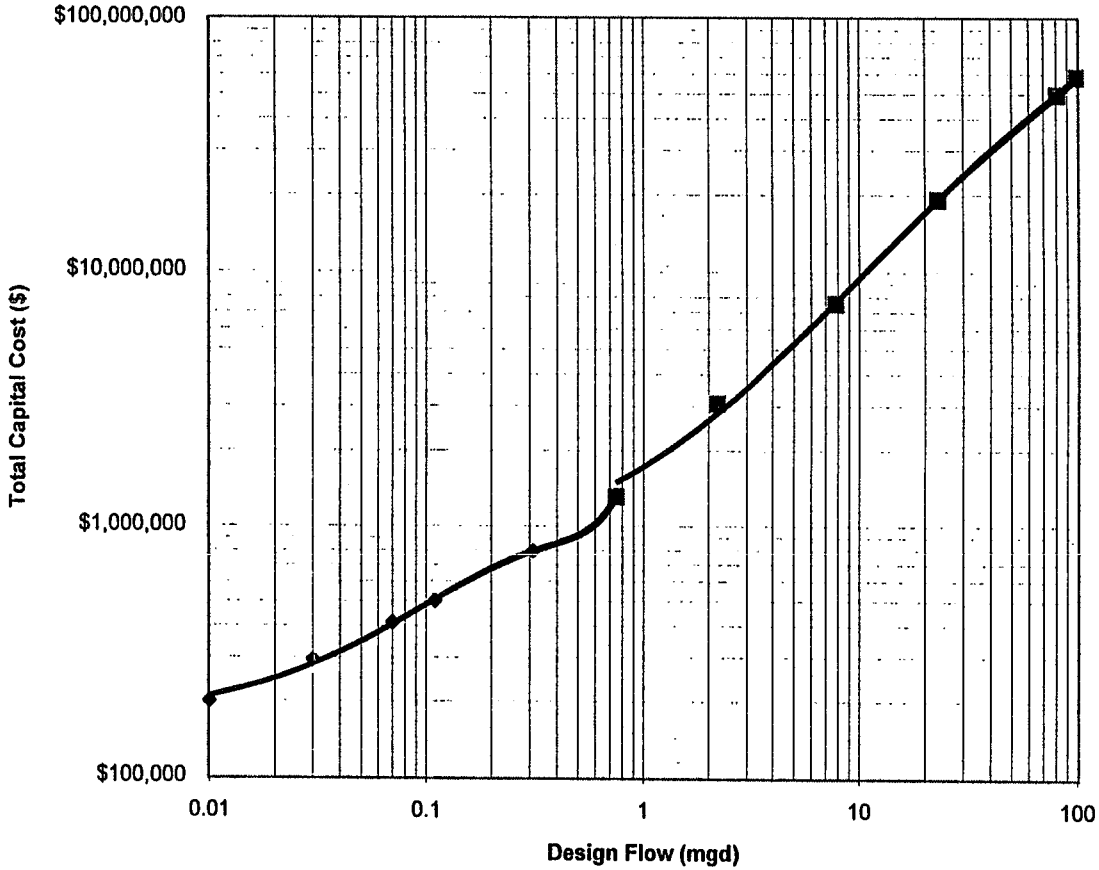
$y = 0.7882x^3 - 212.47x^2 + 66583x + 42636$

$0.82 < x < 56$ mgd

y = O&M Costs ($)

x = Average Flow (mgd)

Figure A.3-5 Capital Costs for 99% Removal of Radon by GAC



Cost Equation

$y = 6E+06x^3 - 8E+06x^2 + 4E+06x + 172842$

$0.01 <= x <= 0.75$ mgd

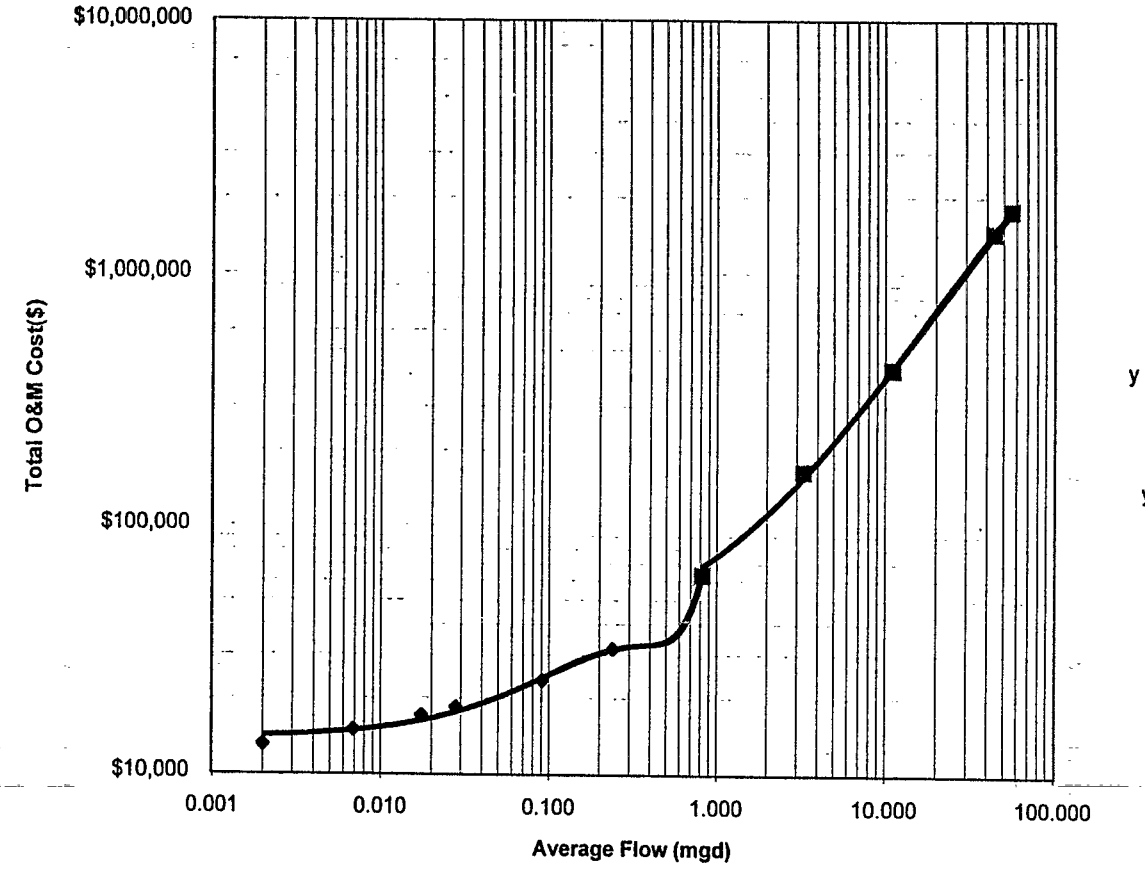
$y = 24.306x^3 - 5912.5x^2 + 925097x + 808365$

$0.75 < x < 100$ mgd

y = Capital Costs ($)

x = Design Flow (mgd)

Figure A.3-6 O&M Costs for 99% Removal of Radon by GAC



Cost Equation

$y = 329892x^3 - 373677x^2 + 144903x + 13815$

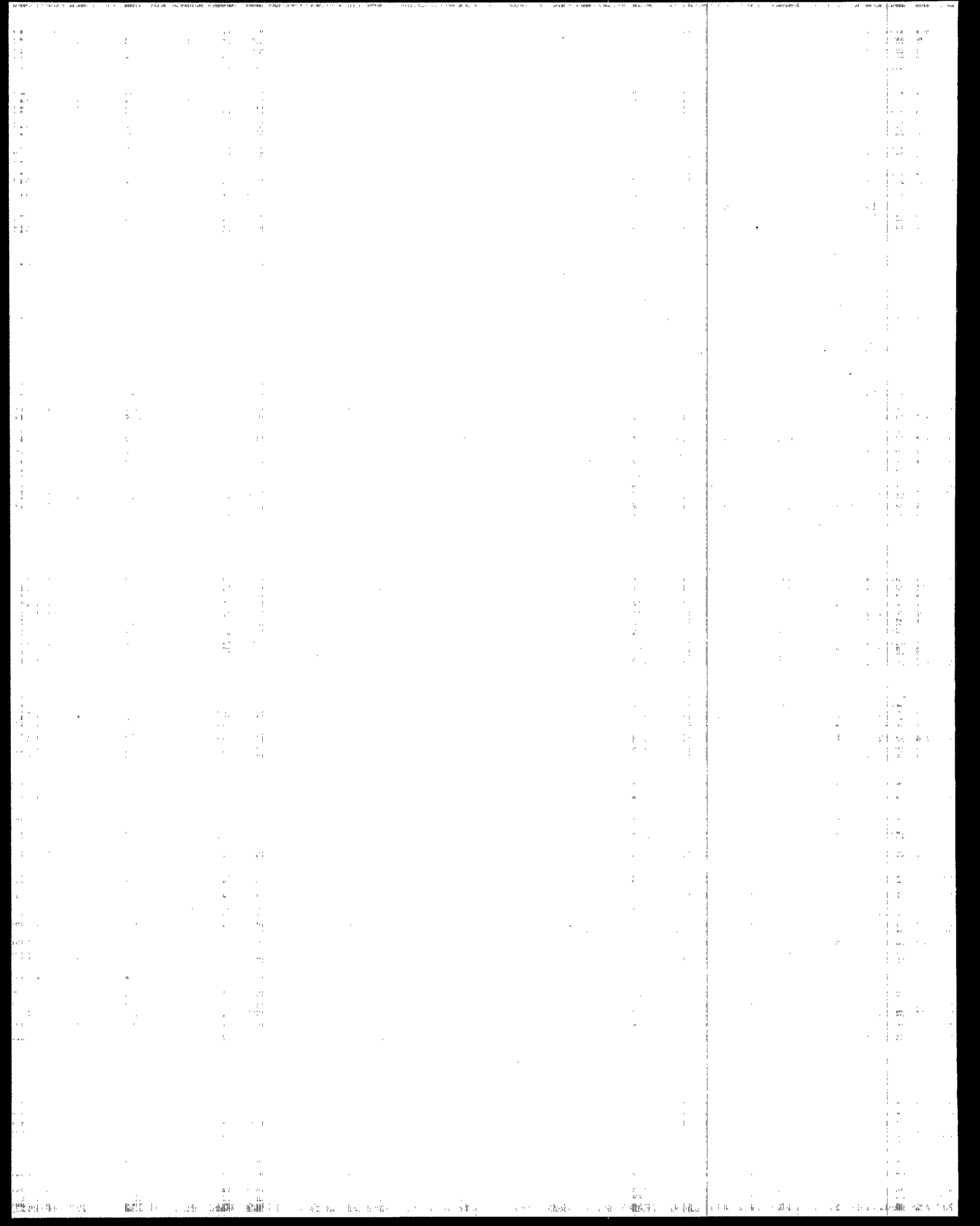
$0.002 <= x <= 0.82$ mgd

$y = 0.3736x^3 - 110.49x^2 + 36184x + 39188$

$0.82 < x < 56$ mgd

y = O&M Costs ($)
x = Average Flow (mgd)

Appendix A-4
Investigation of Possible Off-Gas Emissions Regulations



Appendix A-4
Investigation of Possible Off-Gas Emissions Regulations

Purpose and Methodology

EPA is required by Congress to set a maximum contaminant level (MCL) for radon in drinking water. In order to meet an MCL requirement, many drinking water systems (particularly those using ground water sources) will need to install treatment facilities to remove radon from drinking water. Since air stripping is generally highly effective for removing radon from water, many drinking water systems may install aeration facilities to comply with the radon rule. As part of their operation, aerators generate off-gas emissions, which may result in air permitting requirements in the States.

To assess potential procedures (e.g., permit applications, off-gas risk modeling) and costs that could be associated with radon off-gas from aeration facilities, U.S. EPA gathered information from agencies responsible for air permitting. U.S. EPA contacted representatives from nine air districts in California via telephone to determine the likely response of their district to promulgation of a radon rule with an associated radon MCL requirement. The representatives responded to the following questions:

- What is the likely response of your permitting board to water systems installing aeration treatment to comply with the radon rule?
- What are the likely permitting procedures and costs for water systems installing aeration for radon? Who would be responsible, the permitting board or the water system, for carrying out each procedure and paying the costs?
- Will large water systems and small water systems follow different procedures, or are procedures uniform regardless of water system size (e.g., off-gas volume)? How do permitting costs change with the applicant's system size?
- Will water systems be required to perform off-gas risk modeling as part of the permitting procedure or will they be required to do other environmental impact analyses?
- Would there be annual renewal procedures (e.g., reapplication, compliance monitoring) and costs? Who would be responsible for carrying our the procedures and bearing the costs?
- Is ongoing monitoring likely to be required?

Where possible, representatives provided estimates of time and cost that could be incurred by water systems and the districts as a result of the potential district response to the radon rule.

Results

The likely response to a radon rule is similar across the California air districts contacted. Most districts indicated they are likely to follow the lead of the State. Following the State's lead means that if the State includes radon on its Toxic Air Contaminants List and establishes unit risk factors and exposure levels for radon, air districts will probably regulate drinking water system aeration facilities through permits. Permitting procedures are similar across air districts and generally do not vary for facilities of different sizes. However, permitting costs and who bears those costs can vary significantly from air district to air district. Some portion of the costs are likely to vary based on facility size or emissions level.

A summary table of the information collected is provided below, followed by a more detailed description of each air district's likely response to the radon rule and its associated permitting procedures.

A few of the air district representatives raised the issue of the lack of technologies that water systems could use to treat radon off-gas. As noted in the National Research Council's 1998 report titled *Risk Assessment of Radon in Drinking Water*[1], treatment of radon off-gas emissions from aerators could prove to be problematic since technologies tested for this purpose have shown limited effectiveness. One air district representative suggested the possibility of collecting the radon off-gas emissions and allowing the radon to decay in a controlled space.

[1] *Risk Assessment of Radon in Drinking Water*. 1998. National Research Council, Committee on the Risk Assessment of Exposure to Radon in Drinking Water. National Academy Press, Washington, DC.

Air District*	Off-Gas Regulation	Permitting Procedures** (D=air district, W=water system responsibility)	Cost to Permit
Bay Area AQMD	-depends on limits & concentrations in water -if permitted, probably fall under misc category	-same for all system sizes -perform screening modeling for risk assessment before permitting (D) -if significant risk is based on screening, more detailed modeling & possibly risk assessment (W)	-permitting fees can range from couple hundred dollars to $50,000 (based on category & throughput)
Monterey Bay Unified APCD	-after rule promulgation by EPA, District would assess if regulation of sources needed based on risk -rely on the State to develop exposure & risk values -if potential for exposure & there are risks of concern (at acceptable levels), would require permits	-same for all system sizes -apply for ACP, application should include a risk assessment (W) -review of application; if applicant risk assessment not sufficient, District performs one (D) -if approved, issue permit (D) & construct (W) -inspection to assess compliance (D) & possibly testing (W) -issue PO (D) -annual renewal, no ongoing testing (D & W)	-initial filing & processing fee of about $674 ($103 filing for misc category, $103 toxics fee, $468 processing fee) -if District does risk assessment, water system charged per hour -no fee for permit to operate unless find problems during inspection & more work needed (per hour fee) -annual fee is based on emissions (use surrogate measure like gals of water treated & emissions factor)
Sacramento Metro AQMD	-if State develops limits, District would require permits	-same for all system sizes -apply for ACP (W) -analysis w/likely short-term dispersion screening modeling (D) -if approved, issue permit (D) & construct (W) -apply for PO (W) -testing (W) or inspection (D) -if approved, issue PO (D) -annual renewal needed after compliance check of testing (W) or inspection (D)	-initial permitting fee of generally $880-3,760 (W) -annual renewal fee of half initial fee ($440-1,880) (W) -fee based on air pollution control equipment (#BTU/yr, #motors/unit)

Air District*	Off-Gas Regulation	Permitting Procedures** (D=air district, W=water system responsibility)	Cost to Permit
San Diego County APCD	-depends on likelihood of causing air pollution problem -could involve general or site-specific evaluation (cost of general evaluation ~ $15,000-20,000; site-specific ~$5,000/facility) -if public health impacts, additional site evaluation ~2,000/facility	-submit single application for both construction & operation (W) -evaluation (D) -if approved, issue permit (D) -construction of aerator (W) -inspection (D) & testing (W or D)	
San Joaquin Valley APCD	-likely to regulate if state issues unit risk levels	-apply for ACP (W) -review & analysis (likely modeling, health risk analysis (D) -if approved, issue permit (D) & construct aerator (W) -inspection of facility (D) & possible source testing (W) -if approved, ACP converted to PO (D) -annual renewal (D) & likely some ongoing monitoring (W)	-application fee of $60 (W) -review & analysis cost of ~$1,000 (D) -annual permit fee of ~$75-900 (based on type of facility & size)
San Luis Obispo County APCD	-likely to issue permits to aerators at water systems if there are risk values to model against	-same for all system sizes -apply for ACP (submit screening risk model; if shows significant impacts, than do more detailed modeling (W) -review application & if approved, issue ACP (D) & construct aerator (W) -inspection (D) & possibly testing (W) -if approved, issue PO (D) -annual renewal (D) & possibly testing (W)	-initial fee of $100, except that government facilities do not pay -application review fee of $46/hour for all facilities -inspection fee of $46/hour for about 2 hours of work -PO fee of ~$340 plus about 2 hours processing @ $46/hour -renewal fee of ~ $340

Air District*	Off-Gas Regulation	Permitting Procedures** (D=air district, W=water system responsibility)	Cost to Permit
South Coast AQMD	-likely to regulate if State issues risk values & there are many affected sources -would need to go through rulemaking process to add radon to list of compounds evaluated for permits	-same for all system sizes -apply for permit to construct (also submit design & risk assessment & modeling results to evaluate impacts, possibly also environmental impact report) (W) -evaluation & if approved, issue permit (D) -construct aerator & possibly required to test (W) -inspection (D) & possibly issue public notice (depends on risk & proximity to schools, etc.) (D) -if approved, issue PO (D) -annual renewal (D) (no ongoing or annual testing likely) -whether to require controls for off-gas would be case-by-case determination	-application & processing fee of approximately $2,000 (W) -if district does the application risk assessment, fee of approximately $2,000 (W) -if issue public notice, fee of $400-500 (W) -annual fee of $600-650 (W) -same fees for all, except facilities w/<$500,000 gross income & <10 employees pay 50% less for initial application & processing fee
Tehama County APCD	-likely to issue permits if CA develops risk factors & exposure levels	-submit ACP application (W) -new source review w/likely modeling, emissions projection, risk assessment (D) -if approved, ACP issued (D) & facility constructed (W) -compliance inspection (D) & facility testing (W) -if approved, PO issued (D) -annual PO renewal (W & D)	-new source review cost ~$500-1,000(@ $63/hr)(W) -compliance testing up to $2,000-3,000 (W) -PO fee likely $135 (based on amount of emissions) & paid annually
Ventura County APCD	-depends on action taken by State -would not fall under a current equipment category for air permit	-apply for ACP (W) -evaluation w/likely health risk assessment & modeling (D) -if approved, issue ACP (D) & construct (W) -temporary PO issued (D) & source test done (W) -develop emissions limit & issue PO (D) -annual renewal required (D) likely after facility testing (W) & review of testing protocol (D)	-ACP application fee of $400 & equipment/processing fee of $1,000 (W) -PO fee of $400 & source test cost of ~$600 (W) -annual PO fee of ~$500 w/testing cost of ~$600 (W) -costs could vary across systems & may be based on time & materials -if many facilities to permit, district may hire employee (up to $70,000/yr)

* AQMD = Air Quality Management District, APCD = Air Pollution Control District
** ACP = authority to construct permit, PO = permit to operate

Call to South Coast AQMD - Mohan Balagopalan (909-396-2704) - 2/23/99

Currently, radionuclides (including radon) are on the Toxic Air Contaminant Identification List developed by the California Air Resources Board. The List contains substances identified as toxic air contaminants by the Board. Substances on the List are split into categories, and depending on what category a substance is in, the substance may or may not have potency numbers developed by California's Office of Environmental Hazard Health Assessment (OEHHA) and approved by the State's Scientific Review Panel (SRP). These numbers include unit risk factors and reference exposure levels. At the present time, OEHHA has not published values for radon unit risk factor and reference exposure level. Radon is currently in Category 4A of the List, and is proposed to be evaluated for entrance to Category 3. Substances in Category 3 are considered to be nominated for development of the above values.

Air quality districts generally follow the lead of OEHHA, meaning that if OEHHA publishes a unit risk factor and reference exposure level for radon, air districts would likely evaluate whether radon should be considered in their air permit programs. If OEHHA does not publish the numbers, air districts are not likely to take action because they need unit risk factors and reference exposure levels to establish permit limits. The process would likely be as follows:

1) U.S. EPA publishes an MCL for radon
2) OEHHA decides whether or not to evaluate radon and develop a unit risk factor and reference exposure level (development of values could take as long as 2 years or more)
3) A- If OEHHA publishes values - then some air districts would take action
   For SCAQMD, the first step would be amending Rule 1401 to add radon to the list of compounds to be evaluated for permits. This would require a rulemaking process, which would probably take around 6 months. If SCAQMD thinks there are many sources in its District, they would go through this process. Whether a facility would be required to add controls for radon off-gas from aerators would be a case-by-case determination. Not all air districts would go through the process of looking at health risk assessments and considering controls for aeration towers.
3) B- If OEHHA does not publish values - then air districts would probably not take any action.

SCAQMD is not sure what facilities would do to treat radon off-gas emissions since methods are not readily apparent. One possible approach they might consider is looking at the endpoint of what level facilities would need to meet for the emissions and back calculate to a certain flow rate/volume that a facility would have to stay under (based on the radon level in its source water and assuming all radon is stripped through aeration) in order to meet the emissions limit.

Permitting procedures are the same for all water systems, regardless of size: apply for permit to construct (fee of approximately $2,000 paid by system); the District evaluates application and decides whether or not to issue a permit; a permit is issued and the system constructs the aerator; the District conducts an inspection and the system may or may not have to perform testing; a public notice is issued if required by risk level and proximity of schools (cost of $400-500); the District issues a permit to operate (no fee); the system must pay an annual renewal fee of about $600-650 (no monitoring or inspection likely). Facilities with less than $500,000 gross income and less than 10 employees receive a 50% reduction in the initial permit application fee, but

water systems in SCAQMD are unlikely to be small enough to qualify for this reduction. In determining what controls to require, the District does not look at cost and distinctions are not made based on system size. Water systems are likely to need to do a risk assessment and perform modeling as part of their permit application. Depending on which agency in the water system's municipality takes the lead on the permitting process, the municipality may also produce an environmental impact report (EIR), which could be costly.

Call to Bay Area AQMD - Kenneth Lim (415-749-4710) - 2/23/99

How the Bay Area AQMD (BAAQMD) would address the issue of radon off-gas emissions from aerators at drinking water plants would depend on the concentration limit and the concentration of radon in the water. BAAQMD has not had experience with facilities in the Bay Area that remove radon from water. If the District were to consider issuing a permit to a water system for radon off-gas, the District would perform simple, screening level modeling to compare off-gas concentrations to acceptable exposure levels. The modeling would assume that the aerator is 100% efficient (i.e., all radon is stripped from the water by the aerator), and would take into account factors such as local meteorology and the distance to the nearest residents. The analysis would provide a risk assessment for screening purposes. If the screening analysis shows that the risk is significant, the burden would then shift to the applicant and the applicant would need to do more detailed modeling and may need to do a more comprehensive risk assessment (requirements would depend on the magnitude of the emission loads involved).

BAAQMD has permitting categories that are based on facility type and the contaminants and emissions produced. Permitting fees vary from category to category. A drinking water system being issued a permit for radon off-gas would likely fall under the miscellaneous category since there is currently no category for this type of operation. If permitting this type of facility became a major issue (e.g., affected a significant number of facilities), the District might create a new category. There are a range of permit fees within each category, depending on throughput (e.g., amount of emissions, fuel use, solvent use), so different size water systems could incur different fees. The permitting process would be the same regardless of system size. Permitting fees are automatically doubled if a toxic contaminant is involved. Permitting fees can range from $50,000 for a large industrial facility to a couple hundred dollars for a little aerator at a corner gas station.

Call to San Joaquin Valley APCD (SJVUAPCD) - Steve Bonaker (209-230-6000) - 2/25/99

The impact on SJVUAPCD of a radon rule would largely be unknown since radon is not a criteria air contaminant. If the state developed unit risk levels, SJVUAPCD would likely issue permits to drinking water systems that install aeration treatment for radon. If that occurs and a drinking water system decided to install an aerator to remove radon, the following process would likely occur:

1) Water system submits an application to the District for an authority to construct (AC) permit (application fee is $60).

2) The District evaluates the application. The parts of the evaluation may vary depending on how radon is classified (air toxic, criteria contaminant, public health risk), but would likely include modeling, a determination of whether the source is a major, health risk analysis (acute, chronic, cancer), whether offsets are triggered, etc. The District would perform this analysis. The analysis would probably cost the District around $1,000 (minimum for a typical evaluation is around $480 for 8 hours of an engineer's time at about $60/hr), so the application fee does not cover the cost of the evaluation.

3) If the District approves the construction, the AC permit is issued and the water system would construct the aeration facility. The AC permit contains all operating conditions that will apply to the constructed facility.

4) After construction is complete, the District determines if the facility meets the requirements of the AC permit. To do this, the District inspects the facility and the water system may need to perform source testing and would need to monitor influent and effluent. If requirements are met, the facility is allowed to continue operating and the AC permit is converted to a permit to operate.

5) To continue operating, the facility must pay an annual permitting fee, which is based on the type of facility (aerators would likely fall under the electric motor category due to the power supply to the aerator). Permitting fees vary by category and by size (horsepower for electric motor category) within category (fee range for electric motor category is $74-882/yr). The facility would need to do some ongoing monitoring of the water (influent and effluent).

If a water system had an existing aeration facility, the District would only need to issue the operating permit.

Call to Sacramento Metro AQMD - Bruce Nixon (916-386-6623) - 2/25/99

At the state level, California has its own large toxics board within its Air Resources Board (ARB). The ARB develops air toxics control measures (ATCMs) that the districts use in their permitting process. If a Federal pollutant control level (e.g., a NESHAPS) is promulgated, ARB may directly adopt it, but instead usually performs its own evaluation and develops its own values. Under CA law, a NESHAPS is automatically adopted as an ATCM. Regardless of whether a pollutant control level is established by a NESHAPS or an ATCM, the Sacramento Metro AQMD (SMAQMD) would use the value in its permitting process. The District has six months to adopt a regulation after an ATCM is promulgated; if the District does not, an ATCM automatically becomes enforceable by the District under CA law.

If radon becomes regulated, a facility that wants to construct an aerator for radon removal would need to submit an application to SMAQMD for a construction permit. For most toxics, the District performs short-term dispersion modeling using a screening model. If the District approves the permit, the water system would then construct/install the aeration facility and would need to obtain a permit to operate the facility. To issue the operating permit, the District would need some verification that the facility is in compliance either through the facility performing

testing or the District conducting an inspection. The permit would be valid for one year, and would be renewable each year after verification that the facility is in compliance (through facility's own testing or District inspection). Most permits do not require regular/ongoing testing. Permitting procedures are the same regardless of facility size. Permitting costs are generally associated with the air pollution control equipment (# BTUs/yr or # of motors/unit). Initial permitting costs for most types of facilities range from $880-3,760, with an annual permit renewal cost of half the initial amount.

Call to Ventura County APCD - Kerby Zozula (805-645-1421) - 2/25/99

Air districts do not develop individual toxics rules; the State takes that action. The CA Air Resources Board (ARB) adopts MACTS for the entire State. Most MACTS do not apply to drinking water systems and most systems do not have permits with the Ventura County APCD (VCAPCD) since drinking water plants generally do not have engines, boilers, or similar units that trigger the need for air permits. So VCAPCD may or may not issue permits to aeration facilities at drinking water plants, depending on actions taken by the State.

VCAPCD uses a two-step permitting process. The first step involves an authority to construct (AC) permit, and the second step involves a permit to operate (PO). A facility applies for an AC permit and pays an application filing fee of $400 and an equipment/processing fee of around $1,000. VCAPCD then conducts an evaluation to determine if the facility should be allowed to construct the facility (e.g., if aeration is an acceptable treatment). For point sources that would discharge contaminants with established unit risk values, the District performs a health risk assessment that involves air modeling (estimated cost of $1,000 for about 20 hours of labor at $60/hr). If the proposed facility is approved, the District issues an AC permit and the applicant constructs the facility.

Once the facility is constructed, VCAPCD issues a temporary PO to allow the facility to operate and perform a source test ($400 filing fee is charged to the facility, source test probably costs the facility about $600). The source test is used to develop an emissions limit. The PO is issued for one year, and can be renewed each year for an annual emissions fee that would probably be about $500/yr for a drinking water aerator. The facility would probably be required to perform testing once per year; VCAPCD would evaluate the protocol for the test and oversee the testing (fee would probably be around $600/yr, unclear whether this is in the same as the annual emissions fee or in addition to it). Since a drinking water aerator would not fall under any of VCAPCD's current equipment types for permitting, the District would probably determine permitting fees based on time and materials costs, so the fees could vary from system to system. VCAPCD might need to add a staff person if there are many facilities to address as a result of radon limits (cost could be as much as $70,000/yr).

Call to San Diego County APCD - Mike Lake (619-694-3313) - 2/25/99

If the aeration process could cause an air pollution problem, the San Diego County APCD (SDCAPCD) could require facilities to obtain permits, regardless of what action is taken on the

State level. If the State is not involved and OEHHA does not establish risk factors and exposure levels, SDCAPCD would pursue development of such numbers if the District determined there seemed to be a significant risk. A single district is unlikely to develop public health exposure values on its own since it probably does not have the expertise. They would either join with other districts to develop values, or more likely use any EPA values for acceptable exposure levels for hazardous air pollutants or encourage EPA to develop exposure numbers. The District has a general nuisance rule that can be used to regulate a source thought to be a risk, even if the State has not taken action. For toxic air contaminants, OEHHA generally establishes risk factors and exposure levels which the District then uses.

SDCAPCD does not typically require permits for municipal drinking water systems, so there would be a cost to the District to set up a program. If the District determined after review that emissions for aerators at drinking water systems needed to be controlled, there would a cost and burden associated with developing permits and conducting ongoing inspections. Initially, the District would assess what contaminants would be involved (since there may be contaminants in the water other than radon that would also be removed through the air stripping process) and whether they were at levels that need control. The District might ask facilities intending to use aeration to conduct testing to determine what contaminants are present in the water to be aerated and provide the data to the District for its analysis. An evaluation could take 3-6 months. If the District is conducting a general evaluation to assess whether to permit such facilities, the evaluation would cost around $15-20,000. If the District conducts facility-specific evaluations because of differences in facilities, the cost would be around $5,000/facility. If public health impacts are identified by EPA or OEHHA, SDCAPCD would need to do site-specific studies based on factors such as distance to the nearest residents. These studies would involve the facility's collection of emissions data and submission of data to the District, and then the District's evaluation of the data (District's evaluation would cost about $2,000/facility, with the cost charged to the facility). SDCAPCD is a full cost recovery facility, so all costs incurred by the District need to be recovered through charges to the facilities involved.

If the District determines that aeration facilities at drinking water systems need to be under permit, the water system would submit a single application for both construction of the facility and its operation. The District performs an on-paper evaluation of the application and, if approved, issues a construction permit. The water system then constructs the aerator. SPCAPCD would then inspect the aerator and (District or water system) would conduct onsite testing.

Call to San Luis Obispo County APCD - David Dixon (805-781-5912) - 3/1/99

San Luis Obispo County APCD (SLOCAPCD) has never regulated radiation sources, since they have fallen under the purveyance of the Federal or State government. However, SLOCAPCD does regulate any facility that emits an air contaminant. So the District would likely issue a permit to a water system that intends to install and operate an aerator to remove radon. The District would hope that risk values would be developed that it could use for risk assessment purposes. Any project that comes under permit in the District has to meet criteria of no excess cancer risk greater than one in a million or no excess non-cancer hazard index of more than one.

The permitting process begins when the water system applies for an authority to construct permit (ACP). The application should include a risk assessment and modeling. A screening model is sufficient, but if it shows significant impacts then more detailed modeling must be done. The District then reviews the application and decides whether to issue an ACP. The initial application fee is $100 for non-governmental facilities, with no charge for government facilities. All water system would be charged for application review at a rate of $46 per hour. Once the aerator is constructed, the District would inspect it (approximately 2 hours of labor charged at $46 per hour) and may require the water system to conduct testing to verify compliance with its ACP. If the facility is approved, a permit to operate is issued by the District. The fee is likely to be about $340 (facility would probably be in the miscellaneous category), plus a permit processing fee for about 2 hours of labor at $46 per hour. The permit would need to be renewed every year at a fee of about $340 (no difference for facility size). Annual or ongoing testing may be required.

Call to Tehama County APCD - Gary Bovee (530-527-3717) - 2/26/99

To determine whether to permit aeration facilities at drinking water plants, Tehama County APCD (TCAPCD) would need to assess whether the emissions would be significant enough to warrant permits. TCAPCD does not currently issue permit to either drinking water plants or sewage treatment plants (the county is fairly rural). If the State developed risk factors and exposure levels for radon, TCAPCD would probably issue permits to aeration facilities used to remove radon from drinking water.

The permitting process would entail:

1) Water system applies for an authority to construct (AC) permit (base application fee of $100).

2) TCAPCD conducts a new source review that would likely include modeling, projecting the amount of emissions that would be released, and conducting a risk assessment that looks at the risks to surrounding neighborhoods. The water system would be charged on a per hour basis for the time it takes TCAPCD to process the application (including the source review) at a rate of $63/hr (total cost would probably run between $500 and $1,000 for the AC permit process.

3) If the project is approved, the AC permit is issued and the water system constructs the aeration facility. The District performs a compliance walk-through inspection to check if the facility was built in accordance with the AC permit. The water system would probably be required to conduct some testing to determine if the facility meets the emissions limits it said it would. Testing could cost the water system as much as a couple thousand dollars.

4) If facility is approved to operate, the District issues a permit to operate (PO) that is valid for one year. The water system would be assessed a PO fee that would also need to be paid each year for PO renewal. A drinking water system aeration facility would fall under the miscellaneous category for permits and the fee assessed would be based in the amount of emissions ($135 for up to 5 tons/yr, with an additional $26/ton for amounts over 5 tons). The District does not generally require annual testing in its POs, but the District's Air Pollution

Control Officer (APCO) has the authority to require testing at any time (e.g., when a problem is suspected).

Call to Monterey Bay Unified APCD - Fred Thoits (831-647-9411) - 3/20/99

Monterey Bay Unified APCD (MBUAPCD) has not traditionally treated radon as a point source, so the District has not issued permits for radon. If EPA promulgates a rule for radon, MBUAPCD would assess what action it needed to take, if any, based on the risk presented. MBUAPCD does not develop its own risk values or exposure levels, but relies on the State (OEHHA) to develop values. The District hopes that if EPA regulates radon that it would also issue some health effects data for determining exposure and risk levels. If there is potential for public health exposure and there are risks of concern (but not at unacceptable levels), the District would require permits for aeration facilities and would rely on EPA/OEHHA to develop risk and exposure values.

The permitting process would be the same regardless of facility size. The water system would apply for an authority to construct permit (ACP) and should include a risk assessment with the application. Water system aerators would probably fall under the miscellaneous category, so the ACP fee would likely be $674 ($103 for filing fee, $103 for toxics fee, and $468 for processing). If the applicant did not perform an adequate risk assessment, the District would conduct one during its application review process and would charge the water system on an hourly basis for the work. If the aerator is approved, the District would issue an ACP and the water system would construct the aeration facility. After construction, the District would inspect the facility to determine compliance with ACP conditions and may require the water system to perform testing. If the facility is in compliance, a permit to operate (PO) is issued. There is no fee for the PO unless the inspection finds problems and more work is needed (work would be charged to the water system on an hourly rate basis). The PO would need to be renewed on an annual basis, with the fee based on the amount of emissions. No ongoing testing would likely be required unless the facility was operating near the threshold for health/cancer risks. The facility would need to report the value for a surrogate emissions factor, such as gallons of water treated, that is more easily measured than actual off-gas. The surrogate factor would be developed when the ACP is issued and would be a means of estimating emissions using a multiplier to relate the surrogate to emissions.