RADIOISOTOPES IN DOMESTIC WASTEWATER and THEIR FATE IN WASTEWATER TREATMENT

by

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ABSTRACT

Modern medical therapies involving radioisotopes provide radionuclide contamination in wastewater. These radioisotopes present in wastewater increase the possibility of human exposure to radiation. The objective of this work was to study the fate of radionuclides of medical sources in wastewater, and to determine the distribution of various radionuclides in different stages of wastewater treatment. Influent, return activated sludge and effluent samples were collected from four wastewater facilities in Massachusetts. Samples were collected approximately twice a month over 4 months. The radionuclides and their decay products were tested by inductively coupled plasma with mass spectrometry (ICP-MS) and broad energy germanium detector analysis (BEGe). The samples were analyzed to determine the content and radioactivity of each target radionuclide and decay product for three treatment stages (influent, return activated sludge and effluent) from each facility at different sampling times. The results indicated that I-131 is the only radionuclide in wastewater, however many decay products were identified. Recommendations are put forward according to the testing results.

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CHAPTER 1: INTRODUCTION

In general, isotopes can be categorized as radioactive isotopes and non-radioactive isotopes. Radioactive isotopes are termed radioisotopes or radionuclides. To achieve a more stable status, radionuclides will decay over time. In the decay process, emitted particles or energy emitted as electromagnetic waves are known as radiation. Radionuclides are widely used in industry and in medicine.

The application of radionuclides is usually divided into three categories, which are:

1. Application as tracers,
2. Application as a radiation source, and
3. Application as an energy source.

Thus, in medical applications, radionuclides are used as tracers to help determine an infected organ or area; used as radioactive imaging sources; and used as an oral or injected drug to kill tumors and infected cells.

However, medical radioactive waste is produced during the application and operation of nuclear medicine. Medical radioactive wastes exist as liquid wastes, gaseous wastes and solid wastes. In the U.S., discharges from medical use and from other licensed radionuclide discharge facilities are required to ensure that the radioactivity is not detectable before discharge. However, when patients leave after exposure, some medically applied radionuclides can be discharged into the domestic wastewater from the patients.

In order to investigate the possibility of radionuclides in wastewater as mentioned above, wastewater samples from four local treatment facilities were studied. The presence and concentration/radioactivity of six common medically applied radioisotopes were evaluated in this research. Based on the results, analysis and conclusions are provided on radionuclide contamination distribution and potential risk.

CHAPTER 2: BACKGROUND

Isotopes are different forms of one particular chemical element. They have the same number of protons in each atom, thus, the same atomic number, while differing in number of neutrons. Some isotopes are radioactive which are termed radioisotopes or radionuclides. Isotopes without radioactivity are called stable isotopes.

2.1 Radioactive Decay

A radionuclide consists of a particular combination of protons and neutrons (Stabin, 2007). It is unstable and it continuously and spontaneously emits particles or energy, until it changes into another stable isotope in a process called nuclear decay (Farris, 1989). During the decay process, the mass of the parent nuclide gradually decreases, whereas the daughter nuclide increases. If the parent radionuclide transforms into a stable daughter nuclide after one decay process, then it is a single decay (Figure 2-1). Sometimes, the parent radionuclide may undergo several decay processes; each intermediate daughter nuclide is radioactive. In this situation, decay process will continue to take place until the final stable daughter nuclide is reached. This whole process is called continuous decay (Figure 2-1), also known as a decay chain or radioactive cascade. In the majority of the decay processes, one parent nuclide only transforms into one daughter nuclide after a single decay. However, there is another decay form known as branching decay (shown in Figure 2-1), which refers to those radionuclides that have two or more decay modes, thus, transforming into two or more daughter nuclides.

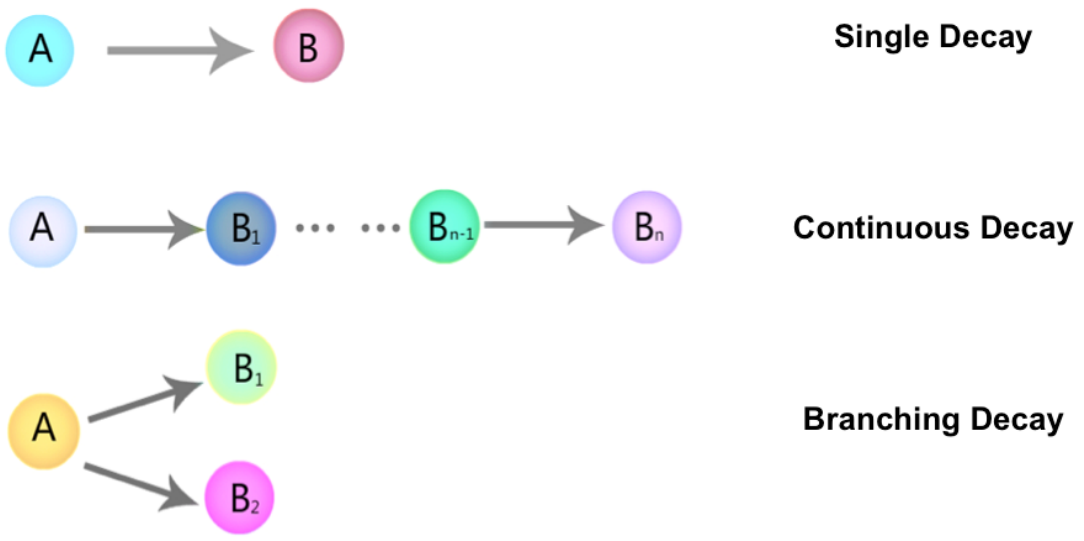

Figure 2-1 Different Types of Radioactive Decay

Half-life ($t_{1/2}$) represents the time that passes for the quantity of parent radionuclide to be reduced to half of its initial value. Each radionuclide has an inherent half-life, ranging from a few microseconds to millions of years. Generally, radioactive decay is a process which is not affected by physical or chemical changes in the environment. It is a natural occurrence which cannot be explicitly predicted; as a result, a probability range is used to describe the decay occurrence (Loveland, 2005). Suppose every single nuclide roughly has the same decay probability, the amount of one nuclide which has an hour half life will be half of its initial amount after one hour, and a quarter left after two hours, thus, one-eighth left after three hours, etc.

2.2 Radiation

In the decay process, emitted particles or energy as electromagnetic waves are known as radiation. Radiation is classified according to the energy of the emitted particles as ionizing radiation or non-ionizing radiation. Ionizing radiation carries more than 10 eV energy, which is capable of ionizing atoms and molecules, and breaking chemical bonds. It has short wavelength and high frequency, and includes alpha radiation, beta radiation, gamma radiation, neutron radiation and X-ray (Strettan, 1965). Non-ionizing radiation is a type of electromagnetic radiation that does not carry enough energy (< 10 eV) per quantum to ionize atoms and molecules; hence, it is not able to completely remove an electron from an atom or molecule (U.S. EPA, 2007). Unlike ionizing radiation, non-ionizing radiation has long wavelength and low frequency, including ultraviolet light, visible light, microwave, radio waves, thermal radiation and blackbody radiation. For radionuclides, ionizing radiation is of concern.

2.2.1 Alpha Radiation

Alpha (α) decay is a process whereby a heavier (i.e. has a larger atomic number) atomic nucleus transforms to a lighter atomic nucleus by emitting an alpha particle. The emitted alpha particle is a nucleus of a helium-4 (He-4) atom with two neutrons and two protons. Thus, He-4 is used to represent an α particle in physics. It has a stable mass of 6.64×10^{-27} kg, has a typical kinetic energy of four to seven MeV and has a speed of about 15,000,000 m/s (Vřtes, 2011). A typical example of an alpha decay process is when an U-238 forms Th-234.

Only heavy radionuclides with atomic numbers greater than 83, such as radon, actinium or thorium can release alpha particles (Bodansky, 2004). Since they are relatively heavy and positively charged, alpha particles usually have a very short mean free path. Alpha particles tend to lose kinetic energy in short distances from their source. The alpha decay range is several centimeters in the air, and even shorter in liquid and solid. Thus, alpha particles from common alpha decay do not penetrate the outer layers of skin cells and barely cause damage to the living tissues below (IAEA, 2008). However, because of its strong ionizing capability, alpha radiation is highly dangerous when alpha-emitting radioisotopes are ingested (breathed or swallowed).

2.2.2 Beta Radiation

Beta (β) decay is a process whereby a proton is transformed into a neutron if there are excess number of protons in the atomic nucleus, or vice versa. The result of this transformation is beta radiation involving the emission of beta particles, which are high-energy electrons or positrons (Konya, 2012). Beta decay is divided into two types, known as beta plus decay and beta minus decay. In beta minus decay, a neutron turns into a proton, with the emission of an electron and an antineutrino: $n \rightarrow p + e^{-} + \nu_e$. For instance, an atom of carbon-15 (with 6 protons) transmutes into an atom of nitrogen-15 (with 7 protons). In beta plus decay, a proton turns into a neutron, with the emission of a positron and a neutrino: $p \rightarrow n + e^{-} + \nu_e$. An example of this is an atom of fluorine-18 (with 9 protons) becoming an atom of oxygen-18 (with 8 protons) (Martin, 2013).

Compared to α radiation, β radiation has a stronger penetration capability, but it causes less damage when it goes through the same distance as α radiation. Most beta particle radiation can be decreased by skin or clothes and can be stopped by a few millimeters of aluminum (Martin, 2013). Its ionizing capability is lower than alpha radiation, but it is still dangerous when taken into the body.

2.2.3 Gamma Radiation

Gamma (γ) decay is a process in which an atomic nucleus transforms from a high-energy state to a lower energy state with the emission of high-energy photons (known as gamma rays). It normally occurs after other forms of decay like alpha or beta decay; because after that process, the daughter nucleus is usually in an excited state, which is unstable. Thus, gamma radiation is emitted while the nucleus transforms into a relatively stable state. Typically, the isotopes that form gamma radiation has very short half-lives (from about 10^{-9} to 10^{-14} sec), frequencies above 10^{19} Hz and wavelengths less than 10^{-11} m (Haroche, 2013). When the half-lives of gamma emission are measurable, nuclei in the higher energy state before radiating photons and the daughter nuclei in the lower energy state after radiating photons are called nuclear isomers (Tsoulfanidis, 1983). A common example of gamma decay is when Plutonium-240 becomes stable after emitting gamma rays.

The penetration capability of gamma rays is stronger than that of alpha and beta emissions. Compared to alpha and beta particle emissions, shielding for gamma rays requires the greatest amount of materials, with high density and large atomic numbers.

2.2.4 Other Forms of Radiation

There are other forms of ionizing radiation including neutron radiation, X-ray and ultraviolet radiation (UVR). Neutron radiation, often called indirectly ionizing radiation, happens during the process of nuclear fission or nuclear fusion (Bodansky, 2004). It emits free neutrons, which have no charge. Neutron radiation is used for both research applications and medical treatment of various cancers. X-ray radiation, a type of electromagnetic radiation, is widely used in medical radiography (such as chest X-ray and abdominal X-ray). Another typical electromagnetic radiation is ultraviolet radiation, which is present in sunlight. According to ISO 21348 (ISO, 2007), ultraviolet radiation can be subdivided as UVA, UVB, UVC, NUV, MUV, FUV, H Lyman-α, VUV and EUV depending on their wavelength (from long to short). UVB rays play an important role in sunburn and skin cancer.

2.3 Application

The application of radionuclides is usually divided into three categories as described earlier (tracers, radiation sources, and energy source). Radioactive tracer technology is a method for detecting the physical variation of a target system by introducing some specific radionuclides into it. Such methods include the use of both non-isotopic tracers and isotopic tracers. The application of radiation utilizes certain interacting effects of radiation. These effects can be described in two different categories. One category involves ionizing, exciting and activating effects; and the other involves scattering, weakening, absorbing and moderating effects. For example, the widely used radionuclide instrument introduces the above-described interacting effects when radiation is irritating

the target substance. The application of decay energy mainly refers to harnessing radionuclide decay energy or ray energy. A common implementation is a nuclear battery, also known as an isotope battery, whose main energy source is radionuclide-based. Nowadays, radionuclides are widely used in industry, medicine, agriculture and in a variety of research studies.

2.3.1 Industrial Applications

In the industrial application of radionuclides, radiation is used as a source of energy to induce specific chemical, physical, and biological changes (Guizerix, 1987). These radioactive applications are associated with the use of computer-controlled systems to achieve automatic product processing, reduce labor intensity, improve product efficiency, and bring more significant economic benefits.

2.3.1.1 Industrial Measuring Instruments

Radiation-based level gauges, radioactive thickness gauges and radioactive densometers have been widely used in industrial processing management and product quality control. Since these types of instruments have the capability to detect without direct contact with the target object, they can be used in environments of high-temperature and high-pressure, and on target objects having an explosive, toxic or corrosive nature.

The following are specific examples of radionuclide instrumentation used in various industries:

- In the construction industry, the neutron moisture meter has become an important method of measuring the moisture of soils, concrete dams and highway subgrade constructions. This device has a high-energy neutron source, americium-241 for instance. When the neutrons go through water, their velocity is attenuated due to the hydrogen content of water. Additionally, this moisture meter has a low-energy neutron detector in it. Then, the instrument calculates moisture of an object from the detected low-energy neutrons (Köksal, 2011).
- In the mining industry, the Portable X-ray Fluorescence (PXRF) device is widely used for the rapid site analysis of ore grade. Moreover, in product quality monitoring of the coal mining industry, the coal carbon content meter is used at a number of coal processing plants (IAEA, 2005).
- Neutron radiography and γ imaging devices have also been widely used for nondestructive testing (flaw detection, crack detection, corrosion detection) of metallic materials and some composite materials (Lin, 2013). Furthermore, they are also used for testing containers, components, pipes and pipe welds made from these materials (IAEA, 2005).
- Static eliminators using polonium-210, plutonium-238 and other radionuclides as radiation sources have been applied in film, printing, paper and textile industry (IAEA, 2005).

2.3.1.2 Radiation Processing

Radiation processing is a technology using atomic radiation (mainly e, X and UV rays) and nuclear radiation (mostly gamma ray) to process materials. This is a new processing technology innovated in the 1970s after mechanical, thermal and chemical processing technologies (Guizerix, 1987). Its approach is to irradiate target objects using rays or electron beams produced by a particle accelerator to improve the quality or performance of the organic structure of these objects. The structural molecules of the irradiated objects will display processes like fission, fusion, cross-linking, grafting, curing, shape-memory foam, vulcanization, etc. (Chmielewski, 2005). These processes do not always lead to desired results; therefore, the objects are evaluated. Then the irradiating parameters for those objects with improved quality and performance are recorded and utilized in volume production.

Radiation processing technology has the following advantages:

1. The irradiation process is not affected by temperature, and the irradiated object can be in any phase: gas, liquid or solid.
2. High-energy electron beams or γ-rays have high penetrability, so the process can focus on the object through packaging without causing any damage.
3. These processes do not need the addition of other chemical reagents and catalysts, so it ensures product purity.

2.3.1.3 Industrial Tracer Applications

In petroleum industry, radionuclide tracer microspheres are widely used to map the water-absorbing profile of water injection wells, which contribute to the formation evaluation, formation rehabilitation and the distribution of water injection rate. They are also applied for real-time leakage detection of underground petroleum pipelines (Coffin, 2008). In the field of hydrology, radionuclide tracer technology has been applied to river flow rate measurement, dam leakage inspection, and observation of sediment distribution and movement of rivers, harbors and bays (Pikaev, 1997).

In the chemical industry, one application of radioisotope tracer technology is the determination of mercury content in electrolytic tank at chlor-alkali plants. The mercury content can be accurately calculated from the specific activity of the diluted radionuclide solution (Bouchez, 2015). In the mechanical industry, the main radioisotope tracer application is kryptonate (Kr-85) technique and mechanical wear study (Fries, 1977). In addition, due to the high sensitivity of krypton 85, it is also applied for the flaw detection of mechanical products, mechanical components, metal vacuum system and semiconductor devices (Fries, 1977).

2.3.2 Medical Applications

Radionuclide applications in medicine are mainly classified as applications in medical research and in clinical diagnosis. In medical research, technology employing radionuclide tracers has become a sensitive and effective approach to explore metabolism, reaction mechanisms, cell division, genetic engineering and abiogenesis.

The clinical applications generally focus on radionuclide imaging including organ function test and diagnose, radioimmunoassay and radioactive therapy. Important parameters of the introduced isotopes in this section are listed in Table 2-1.

2.3.2.1 Use of Radionuclides in Medical Imaging

Radionuclides are used in medical imaging in a method that forms two-dimensional or three-dimensional images of specific organs or sections by using a radioactive detector to detect the distribution of labeling reagents in the body. According to Langer (2008), the process can be described as follows. First, a specific radioactive drug that can be specifically absorbed is injected into the patient. Due to the special chemical characteristics of the drug, it is selectively gathered at some human tissue and organ of interest for imaging, while the host's tissues and organs will not be disturbed or harmed. Then, a specific detector (γ radiography for instance), which is sensitive to the radioactivity of the drug, is used to capture the radiation. Finally, the captured radiation is transformed into images by a transformer.

Radionuclide imaging is classified into two different types, which are traditional radiology imaging and nuclear medicine imaging. Traditional radiology imaging focuses on a particular section of the body like chest, abdomen, head, etc. (Brody, 2013). And the common representatives are X ray scan, Computed Tomography (CT) and Magnetic Resonance Imaging (MRI). Nuclear medicine imaging focus more on organ, tissue or disease infected areas like brain, bone, heart tumor and others (Brody, 2013). And its common representatives are Positron Emission Tomography (PET) and Single-Photon

Emission Computed Tomography (SPECT). Both PET and SPECT provide 3D images and use gamma cameras to detect gamma-emitting tracers. PET scanning is mainly applied during oncology treatment and uses radioisotopes with short half-lives such as carbon-11, fluorine-18, and gallium-68 (Miele, 2008). SPECT scanning is mainly applied to organ diagnoses and uses radioisotopes with longer half-lives compared to PET scanning. According to D'Auria (2013), some typically-used examples are technetium-99, gallium-67, iodine-123, iodine-131, indium-111, thallium-201, and xenon-133. For example, technetium-99 is used in bone scans, brain scans, white cell scans, myocardial perfusion scans and Sestamibi parathyroid scans. Gallium-67 is used in scans for tumors, inflammation, and both acute and chronic infections. Iodine-123 and iodine-131 are used in neuroendocrine and neurological tumor scans. Indium-111 is also used on white cell scan, detection of carcinoid tumors and other uncommon neuroendocrine tumors. Thallium-201 is used on heart scan and Xenon-133 is used on lung scan.

2.3.2.2 Radioimmunoassay

Radioimmunoassay (RIA) is a method that uses a radioactive labeling technique to achieve a sensitive *in vitro* assay. The basic principle of RIA is using the competitive inhibition between radiolabeled antigens (labeled antigens) and unlabeled antigens when they are binding to limited number of specific antibodies. According to Grange (2014), the process can be described as follows. Since a labeled antigen and an unlabeled antigen have the same immune activity, they have the same affinity to a specific antibody. When the number of labeled antigen and antibody is a constant, and the total amount of antigens is larger than the number of antibodies, antigen-antibody complexes will decrease as the increase of unlabeled antigens, whereas free-labeled antigens increase as the increase of

unlabeled antigens. Thus, the amount of unlabeled antigens can be calculated from the detected amount of labeled antigens. Commonly-used radioisotopes in antigen labeling are hydrogen-3, iodine-131, and iodine-125 (Grange, 2014).

2.3.2.3 Radioactive Therapy

Radiotherapy aims to use rays to locate and kill cancer cells. When using rays to irradiate a group of malignant or infected cells, a large number of target cells will be destroyed and killed, making the tumor smaller or even disappear. Currently there are three main methods of radiotherapy: external beam therapy (EBT), brachytherapy, and systemic radionuclide therapy.

External beam therapy, also known as external radiation therapy, is a method that delivers a beam or several beams of rays to a tumor or infected cells from a source outside of the body. These beams consist of electrons, X-rays, protons (γ-rays), carbon ions or other positive ions. This technique is commonly applied on brain tumors, head cancer, neck cancer, esophageal cancer, lung cancer, breast cancer, colorectal cancer and in prostate cancer treatment (Yorke, 2011). The X-rays used in EBT are produced from electrons, which are accelerated to achieve high energy. The protons (γ-rays) used in EBT are derived from radioisotopes such as cobalt-60, caesium-137, iridium-192 or radium-226 (Haller, 2012).

Brachytherapy, also known as internal radiation therapy, is a method where a sealed radiation source is placed directly inside the tumor or near the target area to shrink

tumors or kill cancer cells. Compared to EBT, brachytherapy allows higher total doses, results in less harm to surrounding healthy tissue, and is able to treat a smaller area with a shorter time (Jin, 2013). It is widely used to treat cancers throughout the body such as eye cancer, head cancer, neck cancer, lung cancer, breast cancer, skin cancer, gallbladder cancer, rectum cancer, uterus cancer, cervix cancer, vagina cancer and prostate cancer (Jin, 2013). The common sources used in brachytherapy are cobalt-60, palladium-103, ruthenium-106, iodine-125, cesium-137, iridium-192 and radium-226 (Sadeghi, 2010).

Systemic radionuclide therapy, also known as systemic radioisotope therapy (RIT), is a method to treat specific tissues or organs using small doses of various in-body radioactive drugs, which are introduced into the body by intravitreal injection, intravenous injection, oral administration or other routines. Radioactive drugs are selected by their isotope or chemical properties, because some specific tissues or organs can effectively absorb the majority of the radioactive drugs. This particular character allows radioactive drugs to work on target tissues or organs. For example, the treatment of thyroid cancer uses a sodium iodine-131 capsule (NCI, 2002). The thyroid absorption capability of I-131 is thousands of times greater than other organs. I-131 is introduced to the bloodstream after digestion, and thyroid cancer cells pick up I-131 from blood. RIT is also widely used on neuroblastoma treatment, neuroendocrine tumor treatment, bone metastasis treatment, liver tumor treatment, liver metastases treatment, etc. (Loke, 2011). The common isotopes used in RIT are strontium-89, yttrium-90, iodine-131, samarium-153 and lutetium-177 (Muramatsu, 2012).

Table 2-1. Radioisotopes Used in Medical Application

Radioisotope	Symbol		Protons (Z)	Half-life ($T_{1/2}$)	Decay	Product
Hydrogen-3	^{3}H	H-3	1	12.3 y	β^-	Helium-3
Fluorine-18	^{18}F	F-18	9	109.7 m	β^+	Oxygen-18
Cobalt-60	^{60}Co	Co-60	27	5.3 y	β^-	Nickel-60
Gallium-67	^{67}Ga	Ga-67	31	3.3 d	ec	Zinc-67
Gallium-68	^{68}Ga	Ga-68	31	1.1h	β^+	Zinc-68
Strontium-89	^{89}Sr	Sr-89	38	50.6 d	β^-	Yttrium-89
Yttrium-90	^{90}Y	Y-90	39	2.7d	β^- , γ	Zirconium-90
Technetium-99m	^{99m}Tc	Tc-99m	43	6.0h	γ	Technetium -99
Palladium-103	^{103}Pd	Pd-103	46	17.0 d	ec	Rhodium-103
Ruthenium-106	^{106}Ru	Ru-106	44	373.6 d	β^-	Rhodium-106
Indium-111	^{111}In	In-111	49	2.8d	ec , γ	Cadmium -111
Iodine-123	^{123}I	I-123	53	13.3h	ec	Antimony-123
Iodine-125	^{125}I	I-125	53	59.4d	β^+, ec	Tellurium-125
Iodine-131	^{131}I	I-131	53	8.0 d	β^- , γ	Xenon-131
Xenon-133	^{133}Xe	Xe-133	54	5.2 d	β^- , γ	Cesium-133
Cesium-137	^{137}Cs	Cs-137	55	30.2 y	β^-	Barium-137
Samarium-153	^{153}Sm	Sm-153	62	46.3 h	β^-	Europium-153
Lutetium-177	^{177}Lu	Lu-177	70	160.4 d	β^-	Hafnium-177
Iridium-192	^{192}Ir	Ir-192	77	73.8 d	β^-	Platinum-192
Thallium-201	^{201}Tl	Tl-201	81	3.0 d	ec , γ	Mercury-201
Radium-226	^{226}Ra	Ra-226	88	160 y	α	Radon-222

(Data Source: Encyclopædia Britannica, 2013)

2.4 Pollution from Isotopes and Treatment

Medical radioactive waste is produced during the application and operation of nuclear medicine. Medical radioactive wastes can be classified into three categories, which are liquid waste, gaseous waste and solid waste. Liquid radioactive waste includes contaminated water, solvents, blood or other body fluids, discarded liquid radioactive drugs, human body discharges (wound or oral discharges, urine) and chemotherapy agents. There are not many gaseous radioactive wastes. The most common ones are xenon-133 and krypton-81. Radioactive solid wastes include contaminated containers, gloves, masks, overshoes, protective clothing, paper wipes, plastic sheets and bags, organs and tissues, etc. In addition, sealed source is considered as one particular solid radioactive waste.

Radioactive pollution has been found all over the word. In Germany, the reported total release of I-131 to ambient air and water was about 230 MBq in 2006 (BMU, 2007), and the allowed maximum I-131 body activity of a patient with radioactive treatment discharged from the hospital in Germany is 250 MBq (Fischer, 2009). In Australia, since 1995, I-131 has been detected in iodine-accumulating macroalgae, which grow near the coastal outfall of the Cronulla sewage treatment plant (Veliscek, 2011).

In United States, according to the Nuclear Regulatory Commission (NRC, 2002): “The Department of Energy (DOE) is responsible for radioactive waste related to nuclear weapons production and certain research activities. The NRC and some states regulate commercial radioactive waste that results from the production of electricity and other

non-military uses of nuclear material." The regulations require license for the utilization of radioactive materials and decay-in-storage before disposal. The facilities are required to ensure the radioactivity is not detectable before discharge. However, the regulations (NRC RG 8.39, 1997) allow patients with radioiodine therapy to be treated as outpatients with the potential direct discharge to the patients' sewer systems.

Radioactive waste cannot easily be managed and treated using the same methods as used for treating common domestic waste. Radioactive waste management includes on-site management and centralized management, and consists of collection, storage, disposal and treatment. For medical radioactive waste, the most common treatment method is storage in a decay tank to allow for significant decay time to pass before discharge. Radionuclides used in nuclear medicine are usually in a liquid state, which typically have short lives and low concentrations. The liquid residues of radioactive therapy should be disposed of after a proper period of decay storage until their radioactivity is not detectable. The decay tank is connected to the patient ward and discharges to the public sewer system. A decay tank is often made of stainless steel and allows radionuclide decay for an adequate time (usually corresponding to 6 to 8 half-lives) prior to final discharge. Since urine can carry radionuclides, it is suggested that the restroom of the radioactive therapy ward should also be connected to the decay tank (IAEA, 2005).

2.5 Sampling Site Descriptions

The samples used in this study consist of samples taken from influent water, return activated sludge and effluent water, and were collected from four different facilities in Massachusetts. Figure 2-2 shows the sampling facility locations and the district served by each facility. The facilities are described below.

A. The Upper Blackstone Water Pollution Abatement District (UBWPAD): In order to provide regional wastewater treatment services to the greater Worcester area, UBWPAD was founded in 1986. The district's wastewater treatment facility and ash landfill (ash from sludge incineration) is approximately 90 acres, located off of Route 20 in Millbury, Massachusetts. District members include the town of Auburn, Cherry Valley Sewer District in Leicester, the towns of Holden, Millbury, Rutland, West Boylston, and the city of Worcester. Furthermore, the district's facility provides treatment to portions of non-member communities, including Shrewsbury, Sutton, Oxford, and Paxton. According to the district's Annual Report for Fiscal Year 2013 (UBWPAD, 2013), "the advanced wastewater treatment plant is permitted for an average daily wastewater flow of 56 million gallons per day (mgd), and peak flows of 160 mgd. The treated wastewater is discharged to the Blackstone River".

B. The Marlborough Westerly Wastewater Treatment Plant: The Marlborough Westerly Wastewater Treatment Plant, which started operations in the mid 1960's, is an advanced wastewater treatment facility designed to handle an annual average flow of 2.89 million gallons per day (NPDES Permit No. MA0100480, 2009). It was designed to service only the central portion of Marlborough, MA, but nowadays it treats sewage under an inter-municipal agreement handling the westerly portion of

Marlborough (west of Route 495) and the Town of Northborough. In addition, the daily average flow increased to 4.15 MGD in 2008 with a peak flow of 11.62 MGD peak hour flow (Blue Water Technologies, 2012). Its site encompasses about 5 acres located on Boundary Street in Marlborough near the Assabet River, where the final discharge is directed.

C. The Charles River Pollution Control District (CRPCD): The CRPCD's facility is located on Village Street in Medway, MA. It is an advanced wastewater treatment facility designed to handle a daily average flow of 4.5 million gallons per day with a triple peak flow (NPDES Permit No. MA0102598, 2012). Seven communities contribute the influent of the facility - Franklin (around 3.1 mgd), Medway (around 0.8 mgd), Millis (around 0.3 mgd), Bellingham (0.3 mgd) and Norfolk, Dover and Sherborn (less than 50,000 gpd total) (CDM Smith, 2009). The final effluent is discharged to the Charles River.

D. The Webster Wastewater Treatment Plant: The Webster MA Wastewater Treatment Plant was founded in 1988 in order to serve the towns of Webster and Dudley. It is permitted with an average daily flow of 6 million gpd. The facility collects and treats both municipal and industrial wastewater. The wastewater from the two towns are pumped separately to two areas of the facility and combined before the treatment process. The plant is located on Hill Street in Webster, on the eastern side of the French River, where the final discharge is directed (NPDES Permit No. MA0100439, 2006).

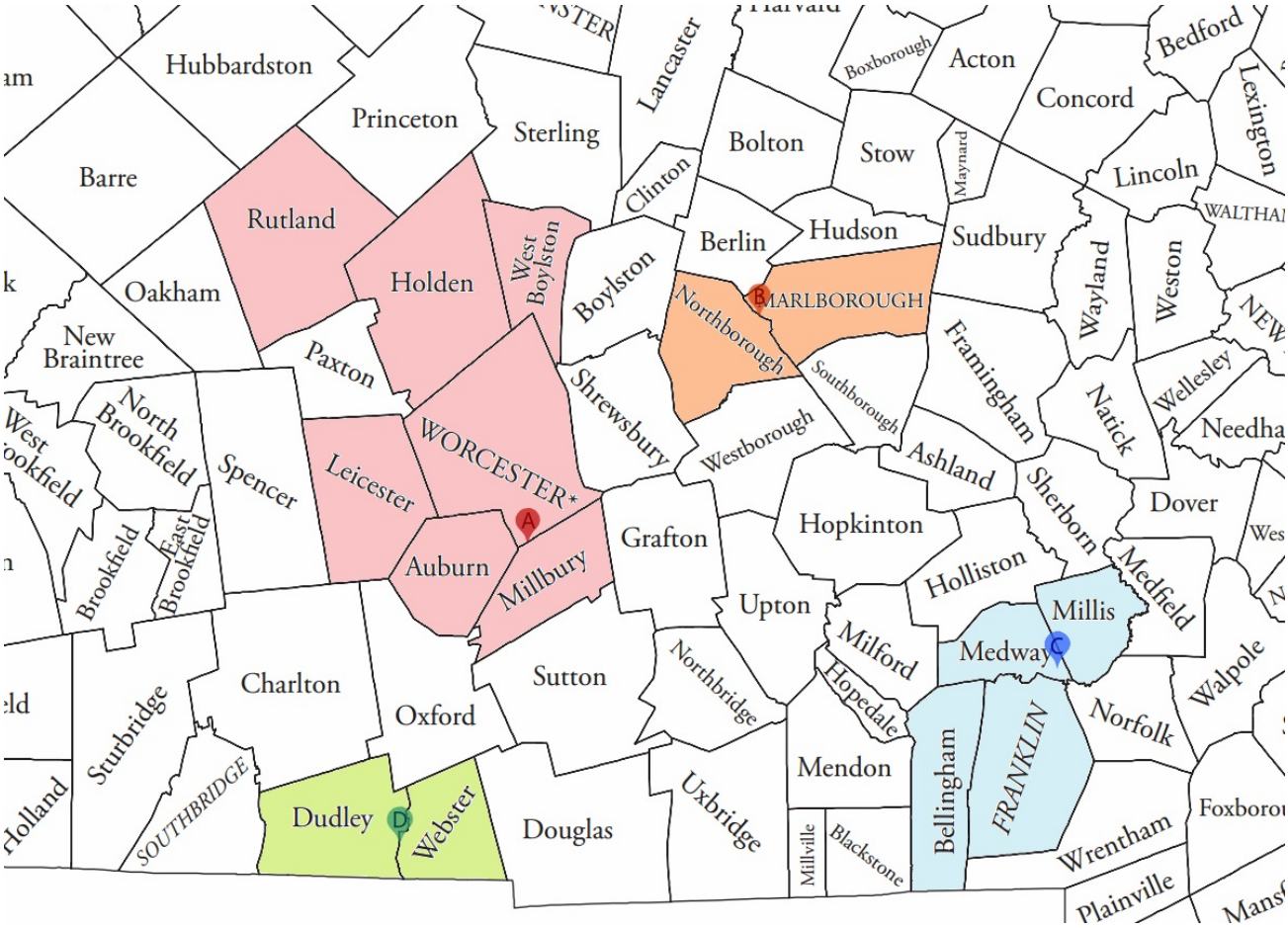

Figure 2-2. Sampling Facility Locations (Citizen Information Service of Massachusetts, accessed 2016)

CHAPTER 3: METHODS

The objectives of this research were to identify the presence of radioisotopes from medical applications in wastewater going into treatment facilities, and to evaluate the fate of these radioisotopes in conventional treatment facilities. Samples were taken at wastewater treatment plants from influent, return activated sludge, and effluent locations, and radioisotopes identified both qualitatively and quantitatively.

3.1 Sample Collection

Samples were collected from four wastewater treatment facilities in Massachusetts: Upper Blackstone Water Pollution Abatement District in Millbury MA, Marlborough Westerly Wastewater Treatment Plant in Marlborough MA, Charles River Pollution Control District in Medway MA, and Webster Wastewater Treatment Plant in Webster MA. The details of these facilities are discussed above. Sample collection within 48 hours of high precipitation events was avoided. Sample volumes of 250 ml were collected from the treatment plant influent, in the return activated sludge (RAS) line and in the effluent line from each facility. Sample collection details are listed in Table 3-1.

The sample containers were 250 mL wide-mouth HDPE plastic sample bottles with Polyethylene crew caps, which were cleaned before use by detergent wash, followed by purified water rinse. Samples were stored on ice in a cooler during transportation followed by storage in a refrigerator at 4 °C until analyses.

Table 3-1 Summary of Sampling Details

Date	Facility	Precipitation 24 hours preceding (in)	Inflow (MGD)
2/2/16	UBWPAD	0.00	24.5
2/12/16	Marlborough Westerly WWTP	0.00	2.1
2/19/16	CRPCD	0.00	6.9
3/3/16	Webster WWTP	0.00	4.8
3/9/16	UBWPAD	0.00	23.8
3/17/16	Marlborough Westerly WWTP	0.00	2.3
3/30/16	CRPCD	0.00	6.2
4/5/16	Webster WWTP	0.00	4.3
4/22/16	Marlborough Westerly WWTP	0.00	2.2
4/29/16	CRPCD	0.00	6.4
5/11/16	Webster WWTP	0.00	4.5
5/16/16	UBWPAD	0.00	24.2

3.2 Sample Preparation

Specific sample preparation was required prior to analysis. In this research, Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and Broad Energy Germanium Detectors (BEGe) were utilized to analyze samples. ICP-MS can be only used for aqueous sample testing, while BEGe analysis obtained the best sensitivity with dry samples.

3.2.1 Sample Preparation for ICP-MS Testing

A standard solution (10 ul – 14.5 ml, 20 ppm Sc, 60 ppm Th, 200 ppm In, 100 ppm Ge) was added to ensure instrument stability and sensitivity.

- Influent samples: 50 ml influent sample was transferred to 50 ml PP centrifuge tubes (Fisherbrand) and centrifuged (Eppendorf centrifuge 5804) at 3200 rpm for 10 min to separate aqueous sample from solids. The samples were subsequently filtered with 45 um syringe filters (MILEX, PVDF membrane) Samples were then acidified with 2.5 ml concentrated HNO_3 (Fisher Chemical, 67-70%, TraceMetal Grade).
- Effluent samples: Samples were filtered with 45 um syringe filters and then acidified with 2.5 ml concentrated HNO_3. 35 ul standard solution was added to each sample by 50 ul pipette before analysis.
- Return activated sludge samples:
    a) Digestion: 50 ml RAS was transferred to 100 ml beakers, followed by acidification with 2.5 ml concentrated HNO_3. The samples were digested, covered with a glass plate at 80°C until it was reduced in volume to 20 ml (about 2 hr) (Eaton, A. D., 1995).
    b) Purified water was added to bring the sample volume back to 50 ml.
    c) The samples were centrifuged (Eppendorf centrifuge 5804) at 3200 rpm for 10 min to separate the aqueous samples from solids followed by filtration with 45 um syringe filters. 35 ul standard solution was added to each sample before analysis.
    d) An acidified blank with 35 ul standard solution was prepared as a

background sample.

3.2.2 Sample Preparation for BEGe Testing

The influent, RAS, and effluent samples were subjected to BEGe analysis as well as the background (blank or purified water sample). The sample preparation method is described below.

50 ml samples were transferred to glass petri dishes, followed by acidification with 2.5 ml concentrated HNO_3. 35 ul standard solution was added to the samples, and then covered and heated at 105 °C until dry.

3.3 Instrumental analysis

The instruments used for analysis were ICP-MS and BEGe. The ICP-MS was a NexION 350X from PerkinElmer (Figure 3-1) and the BEGe was from CANBERRA (Figure 3-2).

3.3.1 ICP-MS Analysis

Inductively Coupled Plasma Mass Spectrometry is amulti-element analysis technique for inorganic elements, using inductively coupled plasma as an ion source and a mass spectrometer as its detector. It is able to detect various elements at concentrations as low as one part in 10^{15} (part per quadrillion, ppq). According to the USGS (accessed 2016), the detecting process can be described as follows. A targeted testing substance is transformed into aerosol or gas form and then sent into the high-frequency electric field. The ionization process will take place under the rapid change of the electric field ($M \rightarrow M^{+}$). The negative air pressure of sampling cone and skimmer lead to the transportation of

ions from electric field to a vacuum chamber. After that, ions will enter into the vertical electric quadrupole field under the effect of horizontal electric field. In the end, those ions are separated according to their mass-to-charge ratio (m/Z) under the vertical changings of electric fields, and concentrate in the counter. As a result, the intensities of various elements in the tested sample can be calculated.

The ICP-MS was warmed up for at least half an hour before the testing commenced. Before the sample test, a STD performance check was run to ensure proper resolution, mass calibration, sensitivity and stability of the instrument. The sampler and sampling tube was rinsed in between every sample (PerkinElmer, accessed 2016)

The targeted isotopes were Ga-67, Y-90, Tc-99m, In-111, I-131, Xe-133 and Tl-201. The ICP-MS was able to detect the signal intensity for the given atomic number element (or elements). For example, when Ga-67 is evaluated by incorporation into the method, the result of the testing shows the intensity of Ga-67 and Zn-67. In order to eliminate the effect of Zn-67, Zn-66 is tested and Zn-67 intensity is calculated from the natural ratio of Zn-66/Zn-67. When considering the final signal intensity of Ga-67 or its decay product, the natural existing Zn-67 portion of the signal was subtracted from the total intensity to arrive at the true Ga-67 signal. More details are provided in Data Analysis section.

The device was set with 25 sweeps per reading, one reading per replicate and three replicates. Details of the method are shown in Table 3-2, and a complete list of parameter settings are listed in Appendix I.

Table 3-2 ICP-MS Method Details

	Sample Flush	Read Delay	Analysis	Wash
Time (sec)	50	20		55
Speed (+/- rpm)	-48.0	-25.0	-25.0	-24.0

Analyte	Mass	Scan Mode	MCA Channels	Dwell Time per AMU (ms)	Integration Time (ms)	Mode	Cell Gas A	RPa	RPq
Zn	66	Peak Hopping	1	50	1250	Standard	0	0	0.25
Ga	67	Peak Hopping	1	50	1250	Standard	0	0	0.25
Y	90	Peak Hopping	1	50	1250	Standard	0	0	0.25
Tc	99	Peak Hopping	1	50	1250	Standard	0	0	0.25
Ru	101	Peak Hopping	1	50	1250	Standard	0	0	0.25
In	111	Peak Hopping	1	50	1250	Standard	0	0	0.25
Cd	113	Peak Hopping	1	50	1250	Standard	0	0	0.25
I	131	Peak Hopping	1	50	1250	Standard	0	0	0.25
Xe	132	Peak Hopping	1	50	1250	Standard	0	0	0.25
Xe	133	Peak Hopping	1	50	1250	Standard	0	0	0.25
Tl	201	Peak Hopping	1	50	1250	Standard	0	0	0.25
Sc	44.9559	Peak Hopping	1	50	1250	Standard	0	0	0.25
Tb	158.925	Peak Hopping	1	50	1250	Standard	0	0	0.25
In	114.904	Peak Hopping	1	50	1250	Standard	0	0	0.25
Ge	73.9219	Peak Hopping	1	50	1250	Standard	0	0	0.25

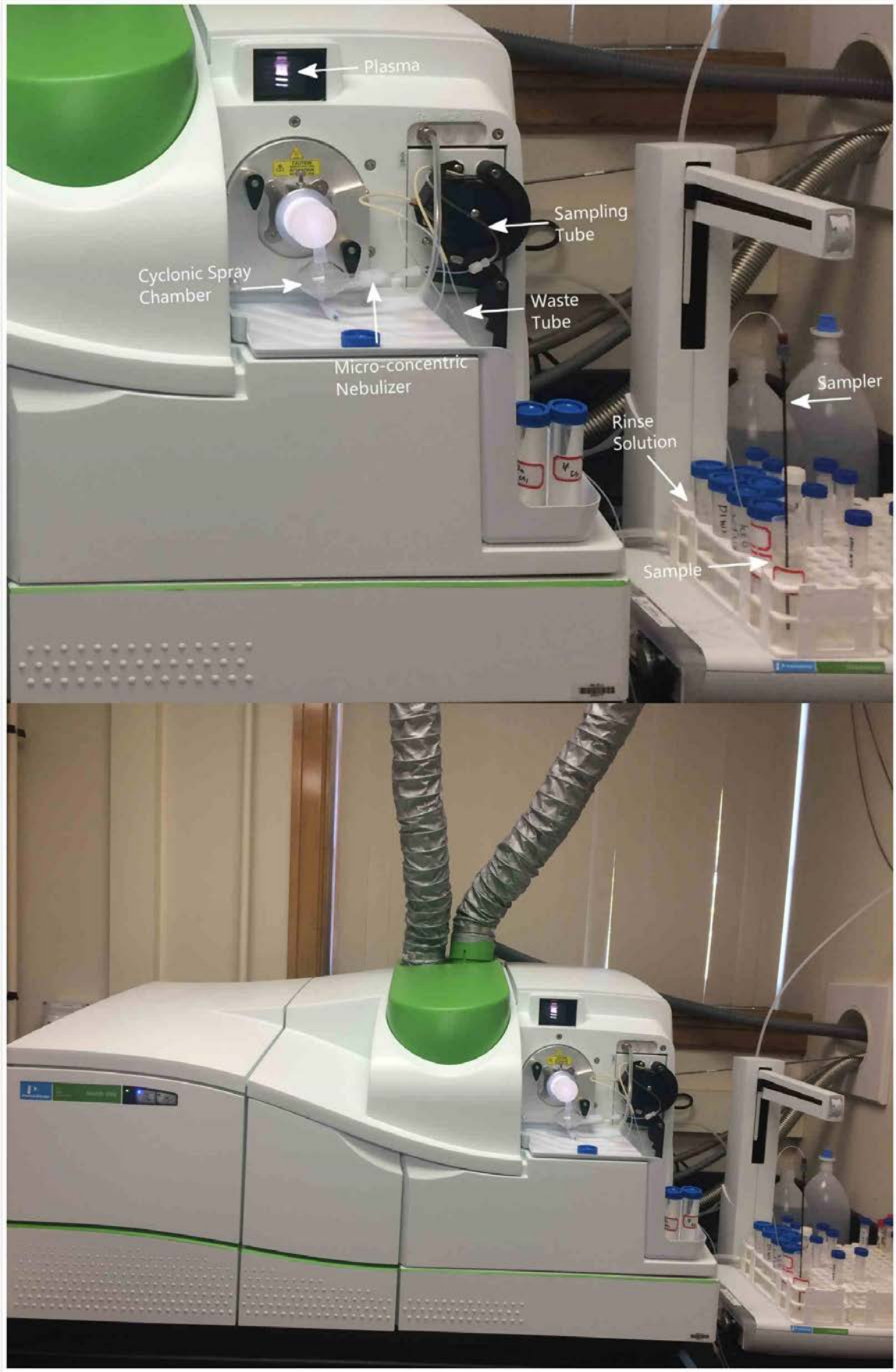

Figure 3-1 ICP-MS

3.3.2 BEGe Analysis

The CANBERRA Broad Energy Germanium Detector can detect radionuclides covering the energy range of 3 keV to 3 MeV. Its resolution at low energies is comparable to that of CANBERRA Low Energy Germanium Detector (LEGe) and its resolution at high energy is equivalent to that of CANBERRA Standard Electrode Coaxial Germanium Detector (SEGe). The electrode structure of the device is designed to improve the low energy resolution. Thus, high purity germanium is selected in the production and the charge collection in high-energy area is improved (so that resolution and peak shape are improved). The detector has a good resolution and peak shape in the medium energy range, which is particularly important for the analysis of complex spectra of uranium and plutonium (CANBERRA, accessed 2016).

In order to protect the detector head, liquid nitrogen is used (in a Dewar) to control the temperature. The testing time is set to 24 hr. The energy range is set between 0 keV to 1500 keV to provide improved accuracy.

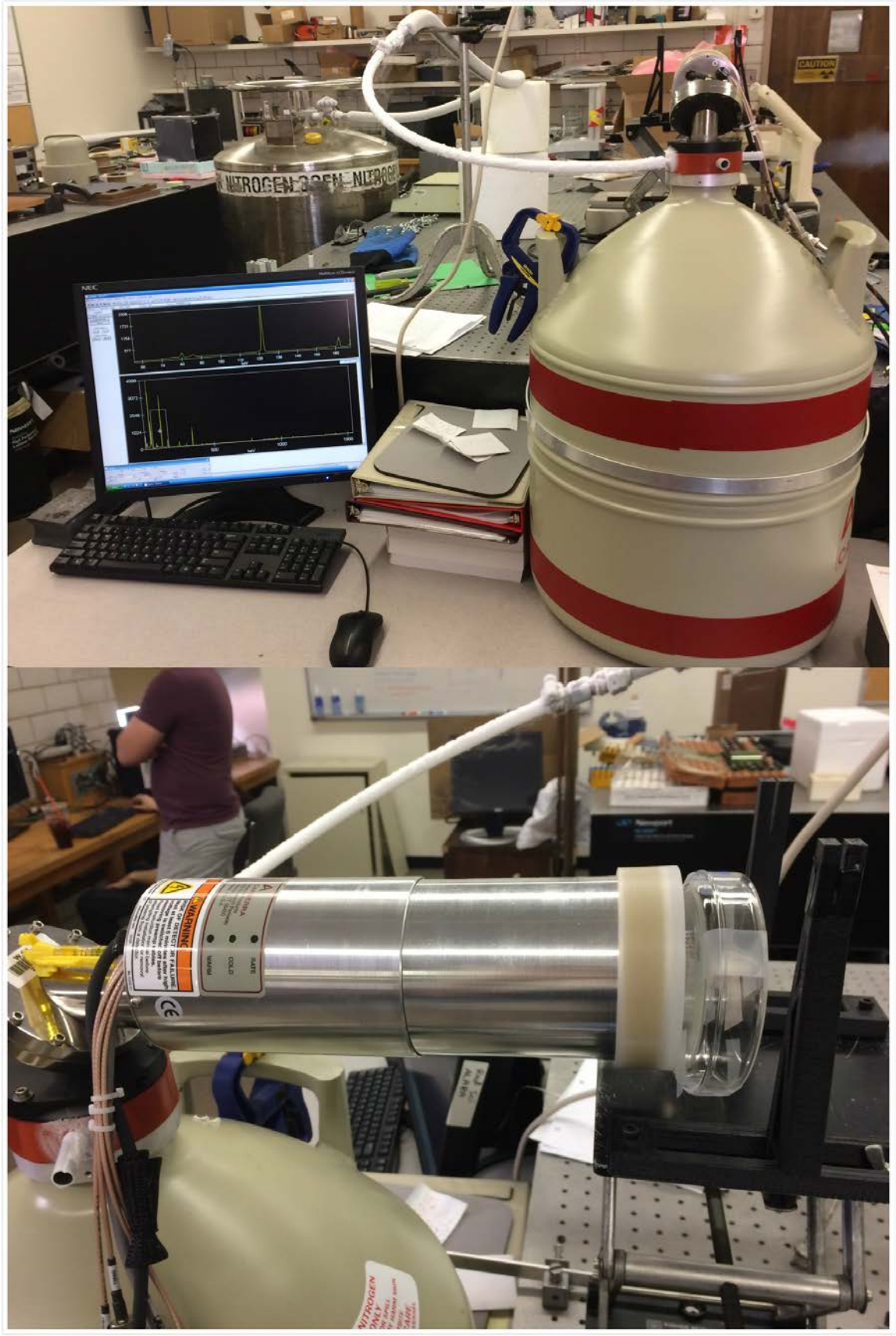

Figure 3-2 BEGe

CHAPTER 4: RESULT AND DISCUSSION

4.1 Data Analysis and Result

4.1.1 ICP-MS Data

ICP-MS is able to pick up the signal intensities of certain elements injected into the instrument. The output intensities are called raw intensities, which are also the original data (Appendix II). In order to account for the effects of background of water, laboratory-purified water was analyzed with the same method. To eliminate the signal of isotopes with the same masses as target radionuclides, the corresponding isotopes of the target isotopes were tested. For example, the raw intensity of Ga-67 could be the summation of the intensity of Ga-67 and the intensity of the original Zn-67. Thus, the intensity of Zn-66 was obtained and the intensity of original Zn-67 can be calculated from Zn-66 intensity by using abundance ratios. As a result, the intensity after this calculation represents the summation of Ga-67 intensity and the intensity of Zn-67, which is the product of Ga-67 decay process. The relative abundance of the natural isotopes is listed in Table 4-1. In addition, the instrument has variable sensitivities for each running period (the sensitivity changes after sleep or shutdown). Thus, the mean “In” value recorded during the performance check was considered when the final relative intensity was calculated.

For example, for the measurements of the samples collected on 3/29/16, the intensity of Ga-67 in purified water was 108.8, and the intensity of Ga-67 in the UBWPAD RAS aqueous samples was 157873.1. The mean "In" value in the performance check for this sample series was 60,261.9, and it was set to 60,000 (for all running periods). The corresponding isotope of Ga-67 is Zn-67 (4.1%). Therefore, Zn-66 (27.9%) was tested and its intensity found to be 1,024,602.7. So the final relative intensity of Ga-67 was 7,263.4, and the calculation is described below.

Ga-67 Relative Intensity

$$= \frac{Set\ Mean\ In}{Raw\ Mean\ In}[(\text{Raw RAS } {}^{67}\text{Ga} - \text{Raw DI Water } {}^{67}\text{Ga}) - (\text{Raw RAS } {}^{66}\text{Zn} - \text{Raw DI Water } {}^{66}\text{Zn}) \times \frac{4.1\%}{27.9\%}]$$

$$= \frac{60000}{60261.9}[(157{,}873.1 - 108.8) - (1{,}024{,}602.7 - 678.2) \times \frac{4.1\%}{27.9\%}] = 7263.4$$

Table 4-1 Relative Abundance of the Natural Isotopes (Source from IUPAC, 1991)

Target Isotope	Corresponding Isotope	% Abundance
Ga-67	Zn-66	27.9
	Zn-67	4.1
In-111	Cd-111	12.8
	Cd-113	12.22
I-131 Xe-133	Xe-131	21.2
	Xe-132	26.9

Table 4-2 provides a summary of analytical intensities for each target radioisotope for three different time periods. The concentrations of the target radionuclides are not provided, as standard solutions for these radionuclides would be needed. As shown in Table 4-2, I-131 was not found with ICP-MS analysis in any of the samples. The intensities of Tc-99m and Tl-201 were relatively lower than the intensities of other detectable target radionuclides.

Table 4-2: Summary of ICP-MS Analytical Result

Facility	Isotope	Feb-Mar			Mar-April			April-May		
		Influent 1	RAS 1	Effluent 1	Influent 2	RAS 2	Effluent 2	Influent 3	RAS 3	Effluent 3
		Intensity	Intensity	Intensity	Intensity	Intensity	Intensity	Intensity	Intensity	Intensity
UBWPAD	Ga-67	0.0	0.0	0.0	927.4	35989.0	582.0	504.0	46892.3	228.4
	Y-90	39373.7	228217.5	1202.4	37848.7	343044.0	1207.3	14368.1	397543.4	0.0
	Tc-99m	0.0	74.9	0.0	17.8	85.0	0.3	2.6	50.2	3.3
	In-111	0.0	0.0	0.0	0.0	97530.4	1071.7	203.5	76325.8	425.8
	I-131	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Xe-133	49151.7	137883.8	33711.1	26541.9	321144.4	30807.3	15995.4	110366.9	21217.0
	Tl-201	119.1	2099.8	11.3	82.0	3442.9	9.3	6.8	2486.3	3.5
Marlborough Westerly WWTP	Ga-67	0.0	0.0	0.0	886.6	7263.4	309.5	856.0	4651.1	319.9
	Y-90	46635.1	3584242.5	3277.8	21248.0	643849.5	549.4	18957.0	589971.6	366.6
	Tc-99m	0.0	57.5	0.0	49.1	104.7	25.5	34.8	72.9	26.3
	In-111	0.0	0.0	0.0	273.4	5766.7	329.8	5492.4	4157.2	607.5
	I-131	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Xe-133	10929.6	14707.6	11029.7	12723.8	15089.8	11098.8	10472.5	9818.4	10489.2
	Tl-201	49.0	1776.9	15.4	45.7	1712.4	7.8	7.6	725.3	3.5
CRPCD	Ga-67	0.0	0.0	0.0	1991.2	14706.5	553.7	1583.6	91027.1	790.2
	Y-90	29274.0	1391924.0	3304.4	60288.3	2974171.2	413.1	28508.7	3585296.3	444.2
	Tc-99m	3.1	24.4	7.9	76.0	76.7	105.8	76.0	63.3	22.0
	In-111	0.0	0.0	0.0	1212.9	6613.6	149.6	200.4	6444.2	268.3
	I-131	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Xe-133	3672.5	8036.5	3933.6	4053.2	8039.8	4323.0	4432.9	6083.3	3981.5
	Tl-201	11.4	1034.7	14.9	8.8	614.1	0.9	55.3	648.9	18.7
Webster WWTP	Ga-67	675.8	48783.2	463.1	1077.4	24216.1	655.7	355.2	16699.6	191.1
	Y-90	32070.5	348302.1	1204.0	27779.6	186999.8	0.0	55517.4	240310.7	0.0
	Tc-99m	11.8	90.0	161.1	53.1	70.2	40.6	8.9	86.7	4.1
	In-111	0.0	8086.3	0.0	189.6	25936.6	201.5	232.0	40889.3	231.5
	I-131	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Xe-133	6312.0	68924.0	5938.6	5626.4	50118.4	5145.1	4617.2	54333.5	4811.8
	Tl-201	19.7	4551.7	5.8	8.1	2477.4	0.0	10.5	4205.9	4.3

4.1.2 BEGe Data

For the BEGe testing, only I-131 was found in the RAS samples collected on 2/2/16 and 5/16/16 at UBWPAD, and the RAS sample collected 2/19/16 at CRPCD, and the RAS sample collected 5/11/16 at Webster WWTP. Table 3-3 provides the energy and uncertainty of I-131 detected in the samples. The data are directly from Interference Corrected Activity Reports (Appendix III). The interference of background noise had been automatically eliminated in the reports. Furthermore, in the three background tests, the detectable target radionuclides were not found. Thus, the result of Interference Corrected Activity Report is the net energy of I-131 from the corresponding sample.

Table 4-3 Summary of BEGe Analytical Results

Facility	Sample	Energy (uCi)	Uncertainty	Error %
UBWPAD	RAS 2/2/16	3.53E-05	7.67E-06	21.75%
UBWPAD	RAS 5/16/16	1.71E-05	8.73E-06	51.13%
CRPCD	RAS 2/19/16	1.04E-05	5.56E-06	53.25%
Webster WWTP	RAS 5/11/16	7.74E-06	6.32E-06	81.70%

4.2 Discussion of the Results

As is shown in background chapter, Ga-67 is used for tumor and inflammation scans, Y-90 for liver cancer treatment, Tc-99m for bone, brain and white cell scans, In-111 for white cell, blood cell and neuroendocrine scans, I-131 for thyroid cancer treatment, Xe-133 for lung scans, and Tl-201 for heart scans.

In the area the UBPAD services, there are two medical groups that provide cancer service - UMass Memorial Medical Center and Saint Vincent Medical Group, which are located at 6 miles and 5 miles away from UBPAD, respectively. UMass Memorial Medical Center offers cancer surgery, radiation therapy, hemophilia treatment center and cancer support programs. Saint Vincent Medical Group offers conventional radiation therapy, intensity–modulated radiation therapy, image–guided radiation therapy, stereotactic radiosurgery and cancer rehabilitation service. Both of these two medical groups are expected to discharge Ga-67, Y-90, Tc-99m, In-111, I-131, Xe-133 and Tl-201.

In the Marlborough Westerly WWTP serviced area, UMass Memorial – Marlborough Hospital is located approximately 3 miles away, and offers breast cancer, liver cancer,

lung cancer and blood disorder treatment, and diagnostic imaging. They could be a source of Ga-67, Y-90, Tc-99m, In-111, Xe-133 and Tl-201.

In the CRPCD serviced area, Sturdy Memorial Hospital, located approximately 9 miles away, provides oncology rehabilitation, radiation therapy, cancer surgery and radiation imaging. Thus, this hospital likely discharges Ga-67, Y-90, Tc-99m, In-111, I-131, Xe-133 and Tl-201.

In the area discharging wastewater to the Webster WWTP, Harrington HealthCare, located about 2 miles away, features an advanced diagnostic imaging department, with provisions for CT scans, digital mammography, bone densitometry and cancer rehabilitation service, which could be potential source of Ga-67, Y-90, Tc-99m, In-111, Xe-133 and Tl-201.

Figure 4-1 shows the average natural logarithm of the intensities of the target radionuclides from the four facilities at three different sampling time periods (Feb-Mar, Mar-April and April-May). The positive bar represents the maximum value obtained from ICP-MS analysis, and the negative bar represents the minimum value obtained.

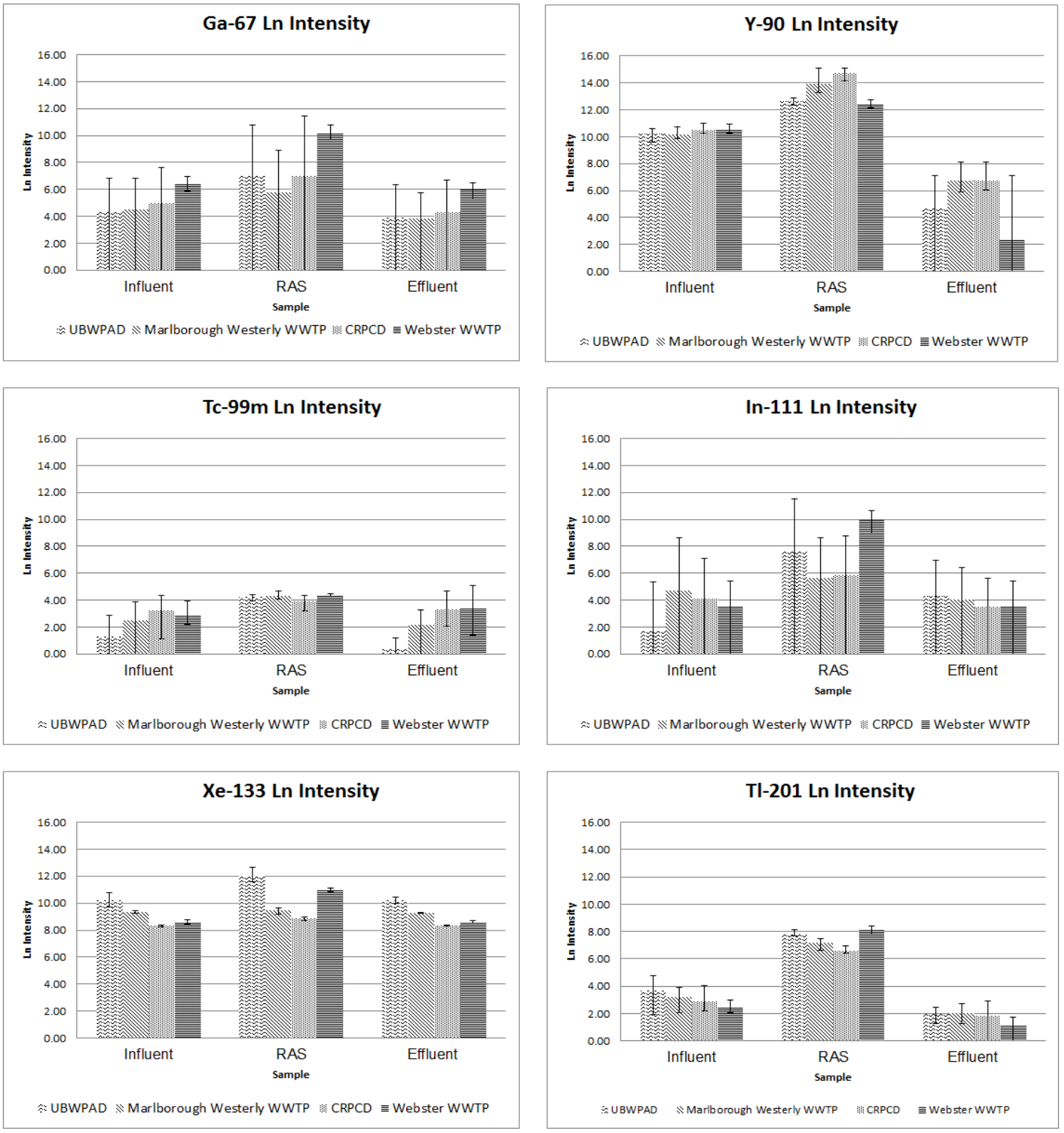

Figure 4-1: Average Natural Logarithm of the Intensities of the Target Radionuclides.

The decay products of Ga-67, Y-90, Tc-99m, In-111, Xe-133 and Tl-201 are Zn-67, Zr-90, Tc-99, Cd-111, Cs-133 and Hg-201, respectively. The decay products are all detectable by ICP-MS using one method, except for Hg-201. As is shown above, each decay product has the same atomic number as the corresponding radionuclide. Thus, the testing result of each radionuclide is the sum of the intensity of the radionuclide and its decay product. However, since the ICP-MS was not picking up Hg-201 using the same method, the testing result of Hg-201 is considered as net Hg-201 intensity.

As shown in Figure 4-1, each average Ga-67 natural logarithm intensity in the RAS was noticeably higher than the corresponding average influent Ga-67 natural logarithm intensity. This indicates that Ga-67 was concentrated in the return activated sludge. And, average Ga-67 natural logarithm intensities in the treatment facility effluent were lower than the average influent Ga-67 natural logarithm intensities, which indicates that the conventional wastewater treatment processes resulted in significant removal of Ga-67. The same tend can be noticed for all the target radionuclides. However, since net Tc-99m and net Tl-201 intensity results were lower than the intensity of purified water, the results of Tc-99m and Tl-201 are not expected to be reliable.

The average influent natural logarithm intensities of Ga-67, Y-90 and Xe-133 varied slightly from facility to facility. For the average In-111 natural logarithm influent intensity, the UBWPAD results were lower and the Marlborough Westerly WWTP result was higher compared to the other two facilities. As was recorded, the average inflow on the sampling dates was 24 MGD for UBPAD, 2.2 MGD for Marlborough Westerly WWTP, 6.5 MGD for CRPCD and 4.8 for Webster WWTP. It explains that while UBPAD has two large medical groups discharging to their facility, the influent intensity of each radionuclide is not significantly higher than the other facilities, and even lower sometimes. The reason why I-131 was not detected with ICP-MS could be that ICP-MS has a low sensitivity to I-131 and I-131 was present at low concentrations.

All the influent natural logarithm intensity values did not vary according to the sampling dates, which suggests that the hospital discharge of radionuclides did not vary with time. The example of Ga-67 is shown on Figure 4-2.

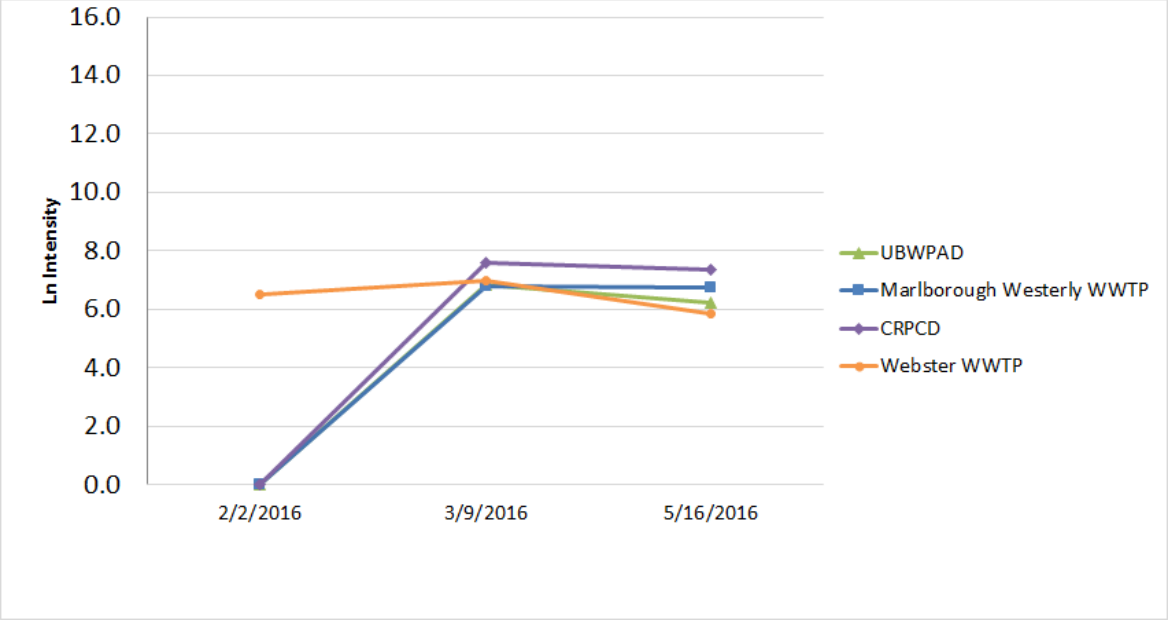

Figure 4-2: Natural Logarithm of Ga-67 Intensities.

The removal percentages of Ga-67, Y-90, Tc-99m, In-111, Xe-133 and Tl-201 in the treatment facilities are shown in Figure 4-3, with the positive bar representing the highest value and the negative bar representing the lowest value. When the radionuclide was not detected in the influent, the corresponding removal percentage was not calculated. When the calculated removal percentage was below zero, the result was considered as zero. The influent Tc-99m and Tl-201 intensities were all close to or below 100. At such a low intensity, the uncertainty is high. Thus, the removal rates of Tc-99m and Tl-201 were not expected to be reliable. As shown the figure, the removal percentages did not differ between the different wastewater treatment facilities. In addition, the ICP-MS has different sensitivities to different radionuclides; thus, it is not possible to compare the removal percentages between different radionuclides.

The removal percentages of Ga-67 at different sampling times are shown in Figure 4-4, and the result of other target radionuclides are listed in original data. When the radionuclide was not detected in the influent, the corresponding removal percentage was not calculated. When the calculated removal percentage was below zero, the result was considered as zero. The figure illustrates that the removal percentages did not vary

appreciably with the different sampling times. The results showed that the removal rates of the treatment facilities for the target radionuclides did not vary with time.

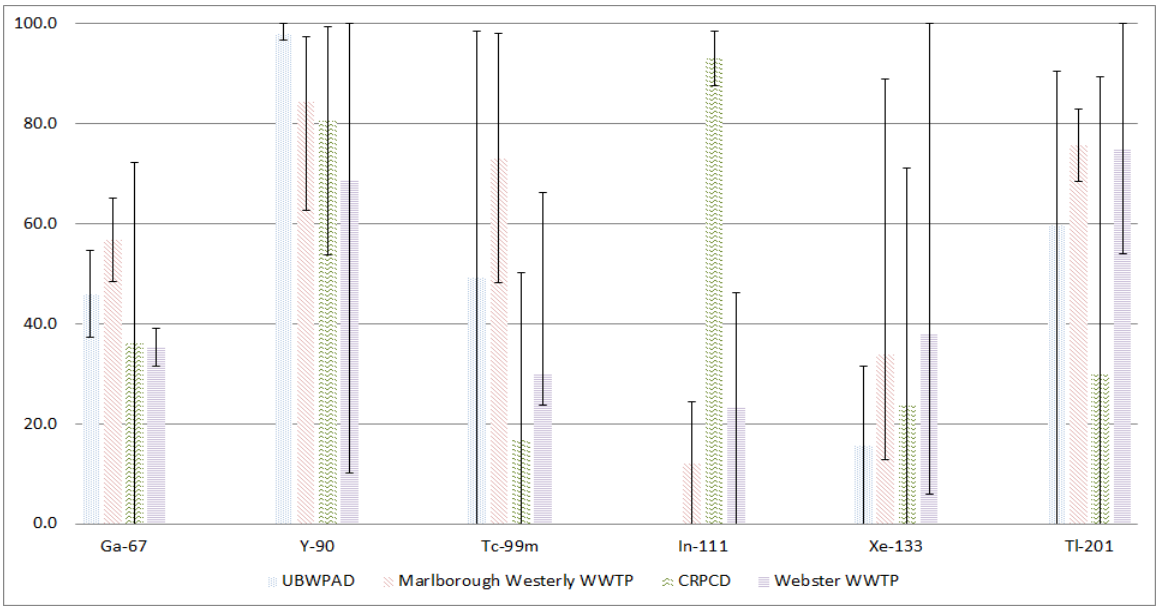

Figure 4-3: Removal Percentages of Target Radionuclides.

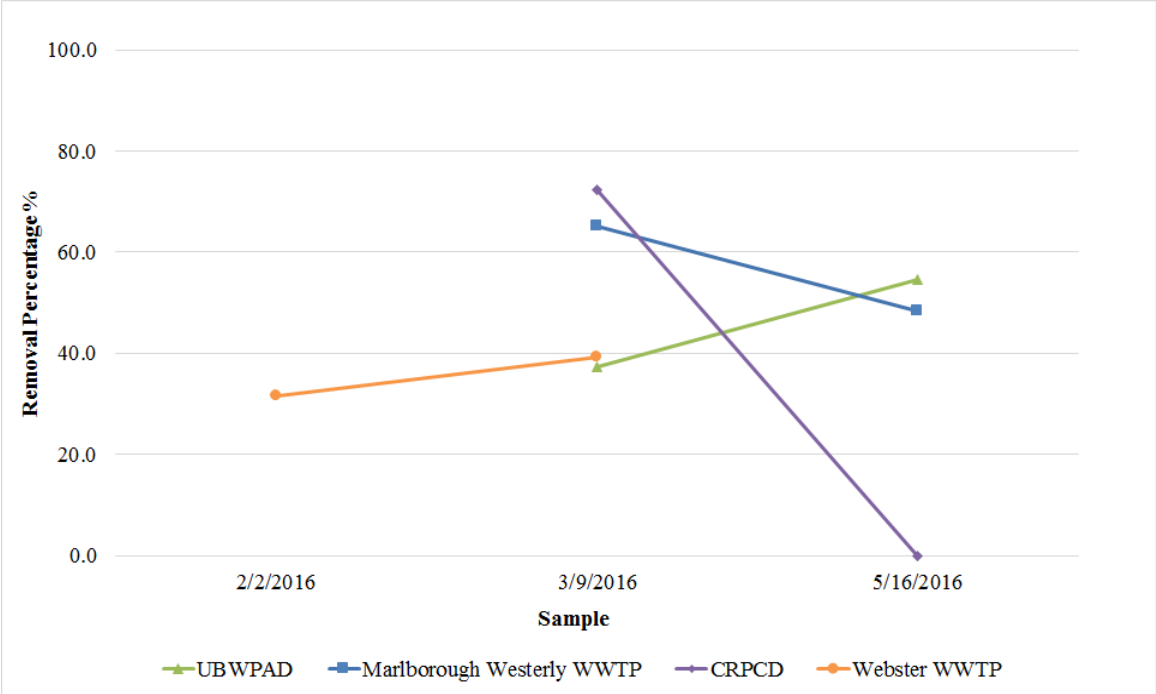

Figure 4-4: Removal Percentages of Ga-67.

Figure 4-5 shows the I-131 activities and the uncertainty in each sample. From the chart, the I-131 activities in the UBWPAD RAS were higher, and the uncertainties were lower. Compared to ICP-MS results, the existence of I-131 had greater variations. I-131 was only found in RAS samples. It is suggested that I-131 concentrations were lower than the detectable critical value of BEGe in the other samples. The results show that I-131 was concentrated in return activated sludge.

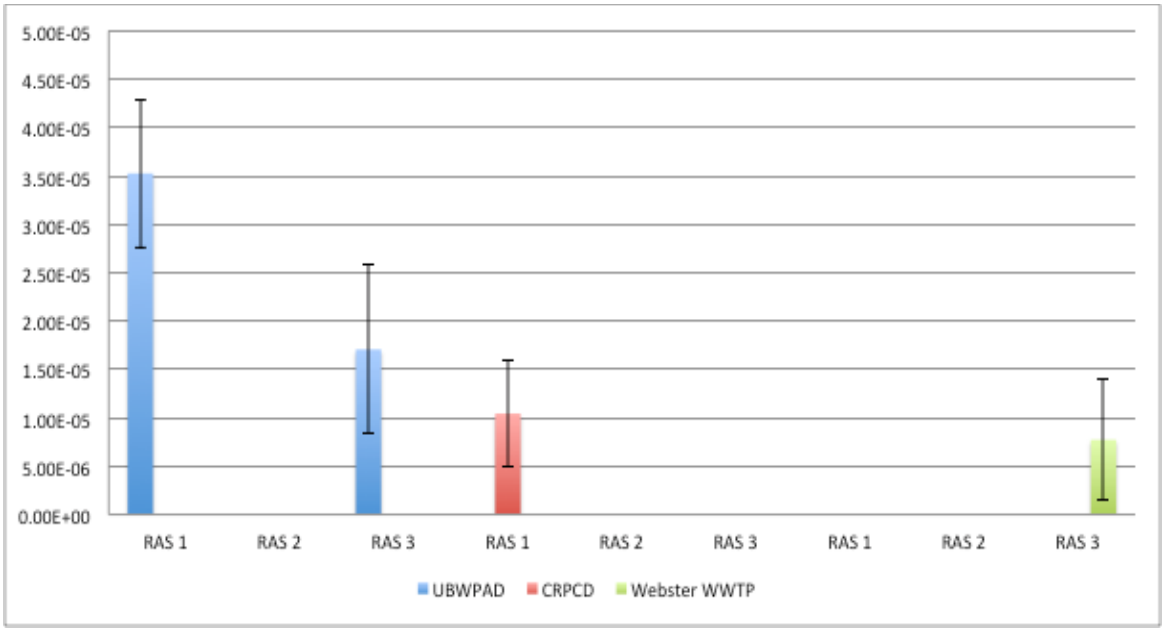

Figure 4-5: I-131 Activities of Different Samples.

According to the discussions above, I-131 was the only contaminant with measurable radioactivity; the rest of the target radionuclides had decayed into their corresponding stable products before they entered the WWTPs. This illustrates that the time the radionuclides spend in the collection systems, and time spent in the hospital decay tanks, is sufficiently long to allow effective decay of the radionuclides.

In addition, results show that all the contaminants were concentrated in return activated sludge. A common application of sewage sludge produced during wastewater treatment is using the biosolids (sludge) as fertilizer. After high temperature composting, the sewage sludge is utilized as fertilizer on woodland, grassland, urban greening, and mining dump vegetation restoration (Lin, 2006). Sewage sludge is rich in organic matter including nitrogen, phosphorus, potassium and other elements essential for plant growth. However, it also possibly contains pathogens, heavy metals and organic contaminants. High temperature composting is able to inactivate most of the pathogens and degrade organic contaminants. In this case, the decay products of In-111 and Tl-201 are Cd-111 and Hg-201 respectively, which are heavy metals. High temperature composting does not remove heavy metals, as well as radionuclides when the composting time is shorter than its half-life. In Massachusetts, sewage sludge can be purchased from treatment facilities,

and some facilities even provide free-composted sewage sludge for residents. However, the heavy metal contaminated or radionuclide-contaminated sludge can affect the environment, fertilized plants; and animals or humans if the sludge is applied on vegetables or fruits. Thus, additional treatment solutions should be considered to remove heavy metals and radionuclides.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

This section summarizes the conclusions of this research according to the discussions provided above. Furthermore, recommendations on further research are suggested.

5.1 Conclusions

Influent, return activated sludge and effluent samples were collected from February 2016 to May 2016 at four local Massachusetts facilities: UBWPAD, Marlborough Westerly WWTP, CRPCD and Webster WWTP. Each facility was sampled three different times.

Ga-67, Y-90, Tc-99m, In-111, I-131, Xe-133 and Tl-201 were the target radionuclides for ICP-MS testing. The results indicated that ICP-MS had a high sensitivity for Xe-133 and a low sensitivity for I-131 among all the target radionuclides. The results of ICP-MS testing varied little from facility to facility. Because of the low intensities of Tc-99m and Tl-201 in all the samples, the results for these two radioisotopes were not considered as reliable. The BEGe is able to detect Y-90, Tc-99m, I-131 and Xe-133. However, only I-131 was detected in the RAS samples. The results of ICP-MS and BEGe testing indicated no variation over sampling time.

Results from this research showed that Ga-67, Y-90, In-111, I-131, Xe-133 were discharged into the collection systems for the facilities, presumably from the medical groups in each service area. The decay tank system of each medical group produced good removal of the radioactive Ga-67, Y-90, In-111, and Xe-133. The final discharge of each radionuclide was its decay product. I-131 could be discharged from outpatients who had thyroid cancer treatment. The return activated sludge concentrated the decay products and I-131, which is a potential pollution source when it is used in land application.

5.2 Recommendations

After a review of the findings in this research, some recommendations for future work are revealed and listed below:

- In this study, each of the WWTP service areas had one or more medical groups involved with radioactive therapy and radioactive imaging. A control group with no radioactive influent component should be included in future studies.
- For the holistic approach to the use and discharge of radionuclides, the ultimate fate of the radionuclides (e.g. decay products) should be considered. More information of radionuclides before they are discharged into wastewater treatment facilities should be provided in further research.
- More samples should be collected over longer times to capture seasonal impacts.

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APPENDIX I: ICP-MS PARAMETER SETTINGS

Parameter Settings	
Nebulizer Gas Flow STD/KED [NEB]	1.04
Auxiliary Gas Flow	1.20
Plasma Gas Flow	18.00
Deflector Gas Flow	-12.00
ICP RF Power	1600.00
Analog Stage Voltage	-1675.00
Pulse Stage Voltage	900.00
Quadrupole Rod Offset STD[QRO]	0.00
Cell Rod Offset STD[CRO]	-7.00
Discriminator Threshold	12.00
Cell Entrance/Exit Voltage STD	-2.00
RPa	0.00
RPq	0.45
DRC Mode NEB	1.04
DRC Mode QRO	-7.00
DRC Mode CRO	-1.50
DRC Mode Cell Entrance /Exit Voltage	-5.00
Cell Gas A	0.65
Axial Field Voltage	200.00
KED Mode CRO	-13.50
KED Mode QRO	-12.00
KED Mode Cell Entrance Voltage	-10.00
KED Mode Cell Exit Voltage	-32.00
KED Cell Gas A	2.00
KED RPa	0.00
KED RPq	0.25
KED Mode Axial Field Voltage	475.00

APPENDIX II: Original Data from ICP-MS

UBWPAD 1/29/2016				UBWPAD 2/2/2016		
In Mean Intensity 68523.0				In Mean Intensity 56707.0		
Isotope	Mass	DI Water	RAS	DI Water	Influent	Effluent
		Intensity	Intensity	Intensity	Intensity	Intensity
Zn	66.0	945.1	2558645.8	902.2	178695.5	61601.5
Ga	67.0	147.7	374424.7	131.2	24573.8	8561.4
Y	90.0	289.1	260924.9	11.7	37224.4	1148.1
Tc	99.0	9.1	138.1	8.3	23.5	22.9
Ru	101.0	12.8	70.9	21.3	43.5	52.3
In	111.0	16.5	86170.7	14.1	1913.0	985.1
Cd	113.0	24.0	98694.8	12.8	2111.4	1190.2
I	129.0	10573.8	8533.9	9617.2	10261.5	8840.0
I	131.0	8757.1	6662.0	8082.1	8520.6	7222.9
Xe	132.0	11354.9	96334.8	10310.6	14050.2	10124.6
Xe	133.0	26.1	157496.3	14.9	46469.0	31875.8
Tl	201.0	15.5	2413.6	10.1	122.7	20.8

Marlborough Westerly WWTP 2/15/2016					
In Mean Intensity 80021.7					
Isotope	Mass	DI Water	RAS	Influent	Effluent
		Intensity	Intensity	Intensity	Intensity
Zn	66.0	712.6	257655.2	81167.9	47740.7
Ga	67.0	105.1	353573.8	11294.5	6448.5
Y	90.0	6.1	4780292.4	62203.1	4377.7
Tc	99.0	3.5	122.4	16.5	15.7
Ru	101.0	5.1	61.6	12.5	14.4
In	111.0	8.0	9063.4	282.7	605.3
Cd	113.0	6.1	10210.8	276.5	482.1
I	129.0	18597.2	7639.7	18070.7	17319.4
I	131.0	15312.7	6013.1	14637.6	14186.7
Xe	132.0	20018.0	57289.5	20680.8	18653.0
Xe	133.0	16.3	19631.7	14593.0	14726.6
Tl	201.0	11.7	2381.6	77.1	32.3

CRPCD 2/19/2016					
In Mean Intensity 83184.5					
Isotope	Mass	DI Water	RAS	Influent	Effluent
		Intensity	Intensity	Intensity	Intensity
Zn	66.0	874.4	3235515.3	161312.7	58018.0
Ga	67.0	146.9	461901.3	23416.9	8034.0
Y	90.0	223.5	1929998.5	40809.2	4804.8
Tc	99.0	9.6	63.7	17.1	22.4
Ru	101.0	7.2	34.4	11.5	9.6
In	111.0	9.6	8820.6	635.5	282.7
Cd	113.0	13.3	9677.0	678.7	282.1
I	129.0	18413.9	7638.4	17810.8	18130.5
I	131.0	15085.2	6052.0	14878.2	14696.4
Xe	132.0	19750.3	196108.2	27436.5	20576.6
Xe	133.0	18.9	11160.8	5110.5	5472.5
Tl	201.0	13.3	1447.8	29.1	33.9

Webster WWTP 3/4/2016					
In Mean Intensity 68230.3					
Isotope	Mass	DI Water	RAS	Influent	Effluent
		Intensity	Intensity	Intensity	Intensity
Zn	66.0	861.4	5425874.6	31533.5	37893.0
Ga	67.0	133.1	852832.1	5409.0	6101.7
Y	90.0	95.7	396175.0	36565.4	1464.9
Tc	99.0	13.3	75.0	21.3	37.1
Ru	101.0	102.4	48.0	95.2	46.4
In	111.0	24.8	32330.7	209.1	208.0
Cd	113.0	459085.1	481148.3	468449.8	383720.9
I	129.0	20758.3	16683.2	21347.2	20951.5
I	131.0	17235.2	13413.2	17533.8	17079.8
Xe	132.0	22210.7	151356.1	24890.8	23160.4
Xe	133.0	38.7	78417.1	7216.5	6791.9
Tl	201.0	10.7	5186.8	33.1	17.3

UBWPAD 3/9/2016					
In Mean Intensity 66124.3					
Isotope	Mass	DI Water	RAS	Influent	Effluent
		Intensity	Intensity	Intensity	Intensity
Zn	66.0	429.6	4146651.1	77933.0	78045.8
Ga	67.0	69.1	649032.9	12480.6	12116.5
Y	90.0	488.8	378547.9	42200.8	1819.3
Tc	99.0	6.7	144.0	83.5	12.0
Ru	101.0	12.0	70.4	88.5	18.7
In	111.0	37.1	107522.6	2140.7	1218.2
Cd	113.0	472770.1	441428.9	490442.9	397566.9
I	129.0	13671.1	9134.7	12449.4	11825.8
I	131.0	11100.7	7154.0	10146.0	9575.1
Xe	132.0	14207.7	180068.5	15165.5	13421.7
Xe	133.0	27.7	353951.8	29278.8	33979.6
Tl	201.0	18.1	3812.4	108.5	28.3

Marlborough Westerly WWTP 3/17/2016					
In Mean Intensity 68230.3					
Isotope	Mass	DI Water	RAS	Influent	Effluent
		Intensity	Intensity	Intensity	Intensity
Zn	66.0	678.2	1024602.7	35361.5	19902.6
Ga	67.0	108.8	157873.1	6096.1	3244.7
Y	90.0	530.4	647190.3	21871.1	1082.2
Tc	99.0	4.8	138.9	68.5	30.4
Ru	101.0	50.9	89.6	70.1	19.7
In	111.0	51.5	5843.4	326.1	382.7
Cd	113.0	417443.7	261294.8	319215.2	320544.6
I	129.0	15186.6	11167.7	13768.5	13833.4
I	131.0	12643.7	8708.5	11144.0	11247.3
Xe	132.0	16411.8	47795.4	16551.3	14801.3
Xe	133.0	30.7	15186.4	12810.0	11177.9
Tl	201.0	14.1	1734.0	60.0	21.9

CRPCD 3/31/2016					
In Mean Intensity 70900.3					
Isotope	Mass	DI Water	RAS	Influent	Effluent
		Intensity	Intensity	Intensity	Intensity
Zn	66.0	1742.3	2285857.3	98499.5	55223.6
Ga	67.0	293.9	353330.6	16865.6	8807.5
Y	90.0	2848.7	3517342.5	74089.7	3336.8
Tc	99.0	6.9	131.2	179.2	177.3
Ru	101.0	6.7	51.7	117.1	67.5
In	111.0	128.0	7943.1	1561.2	304.8
Cd	113.0	1216914.4	246279.0	434716.9	439794.5
I	129.0	21782.9	10146.0	18984.7	19296.5
I	131.0	18110.2	7833.4	15551.4	16047.8
Xe	132.0	23652.4	183356.5	26143.5	22436.2
Xe	133.0	55.2	9555.6	4844.8	5163.6
Tl	201.0	18.9	744.6	29.3	20.0

Webster WWTP 4/7/2016					
In Mean Intensity 69785.9					
Isotope	Mass	DI Water	RAS	Influent	Effluent
		Intensity	Intensity	Intensity	Intensity
Zn	66.0	892.8	5157931.5	45873.7	38285.3
Ga	67.0	130.1	786140.2	7993.3	6387.7
Y	90.0	1573.2	219072.3	33883.6	781.4
Tc	99.0	5.9	87.5	67.7	53.1
Ru	101.0	6.7	47.7	222.9	129.6
In	111.0	21.6	30188.4	242.1	256.0
Cd	113.0	1070698.0	375492.8	416707.5	411888.8
I	129.0	22585.1	16331.5	21058.3	20613.2
I	131.0	18437.4	13187.0	17137.5	16868.0
Xe	132.0	23906.0	133820.4	24218.1	22958.4
Xe	133.0	50.9	58343.5	6595.0	6035.2
Tl	201.0	11.7	2893.2	21.1	6.7

Marlborough Westerly WWTP 4/22/2016					
In Mean Intensity 80021.7					
Isotope	Mass	DI Water	RAS	Influent	Effluent
		Intensity	Intensity	Intensity	Intensity
Zn	66.0	712.6	257655.2	81167.9	47740.7
Ga	67.0	105.1	353573.8	11294.5	6448.5
Y	90.0	6.1	4780292.4	62203.1	4377.7
Tc	99.0	3.5	122.4	16.5	15.7
Ru	101.0	5.1	61.6	12.5	14.4
In	111.0	8.0	9063.4	282.7	605.3
Cd	113.0	6.1	10210.8	276.5	482.1
I	129.0	18597.2	7639.7	18070.7	17319.4
I	131.0	15312.7	6013.1	14637.6	14186.7
Xe	132.0	20018.0	57289.5	20680.8	18653.0
Xe	133.0	16.3	19631.7	14593.0	14726.6
Tl	201.0	11.7	2381.6	77.1	32.3

CRPCD 4/29/2016					
In Mean Intensity 83184.5					
Isotope	Mass	DI Water	RAS	Influent	Effluent
		Intensity	Intensity	Intensity	Intensity
Zn	66.0	874.4	3235515.3	161312.7	58018.0
Ga	67.0	146.9	461901.3	23416.9	8034.0
Y	90.0	223.5	1929998.5	40809.2	4804.8
Tc	99.0	9.6	63.7	17.1	22.4
Ru	101.0	7.2	34.4	11.5	9.6
In	111.0	9.6	8820.6	635.5	282.7
Cd	113.0	13.3	9677.0	678.7	282.1
I	129.0	18413.9	7638.4	17810.8	18130.5
I	131.0	15085.2	6052.0	14878.2	14696.4
Xe	132.0	19750.3	196108.2	27436.5	20576.6
Xe	133.0	18.9	11160.8	5110.5	5472.5
Tl	201.0	13.3	1447.8	29.1	33.9

Webster WWTP 5/11/2016					
In Mean Intensity 68230.3					
Isotope	Mass	DI Water	RAS	Influent	Effluent
		Intensity	Intensity	Intensity	Intensity
Zn	66.0	861.4	5425874.6	31533.5	37893.0
Ga	67.0	133.1	852832.1	5409.0	6101.7
Y	90.0	95.7	396175.0	36565.4	1464.9
Tc	99.0	13.3	75.0	21.3	37.1
Ru	101.0	102.4	48.0	95.2	46.4
In	111.0	24.8	32330.7	209.1	208.0
Cd	113.0	459085.1	481148.3	468449.8	383720.9
I	129.0	20758.3	16683.2	21347.2	20951.5
I	131.0	17235.2	13413.2	17533.8	17079.8
Xe	132.0	22210.7	151356.1	24890.8	23160.4
Xe	133.0	38.7	78417.1	7216.5	6791.9
Tl	201.0	10.7	5186.8	33.1	17.3

UBWPAD 5/16/2016					
In Mean Intensity 56707.0					
Isotope	Mass	DI Water	RAS	Influent	Effluent
		Intensity	Intensity	Intensity	Intensity
Zn	66.0	945.1	2558645.8	178695.5	61601.5
Ga	67.0	147.7	374424.7	24573.8	8561.4
Y	90.0	289.1	260924.9	37224.4	1148.1
Tc	99.0	9.1	138.1	23.5	22.9
Ru	101.0	12.8	70.9	43.5	52.3
In	111.0	16.5	86170.7	1913.0	985.1
Cd	113.0	24.0	98694.8	2111.4	1190.2
I	129.0	10573.8	8533.9	10261.5	8840.0
I	131.0	8757.1	6662.0	8520.6	7222.9
Xe	132.0	11354.9	96334.8	14050.2	10124.6
Xe	133.0	26.1	157496.3	46469.0	31875.8
Tl	201.0	15.5	2413.6	122.7	20.8

APPENDIX III: Interference Corrected Activity Reports

Interference Corrected Activity Report 1/30/2016

BLANK CONTROL GORUP 1

	Nuclide Name	Nuclide Id Confidence	Wt mean Activity (uCi/Unit)	Wt mean Activity Uncertainty
	NA-22	0.992	7.454196E-005	5.324582E-006
	K-40	0.984	7.497574E-002	3.663229E-003
	MN-54	0.952	8.854371E-005	4.749397E-006
	CO-57	0.816	2.581451E-005	4.762784E-006
	CO-60	0.985	1.381989E-004	8.978850E-006
	ZN-69M	0.999	5.526456E-005	1.022559E-005
	BA-133	0.992	8.768879E-005	4.478641E-006
X	XE-133	1.000		
	CS-137	0.996	4.704846E-004	1.263030E-005
	EU-152	0.777	3.081314E-006	4.338314E-006
	BI-211	0.402	2.479725E-003	1.185208E-004
	BI-212	0.999	1.792268E-003	8.618958E-005
	PB-212	0.986	2.559987E-004	2.000689E-005
	BI-214	0.993	3.219846E-003	4.648127E-005
	PB-214	0.999	7.795030E-004	2.890362E-005
	RA-226	0.987	2.122536E-003	1.772970E-004
	AC-228	0.849	2.120267E-003	3.442281E-005
	PA-234M	0.541	3.974842E-003	9.736746E-004
X	U-235	0.459		

? = nuclide is part of an undetermined solution
X = nuclide rejected by the interference analysis
@ = nuclide contains energy lines not used in Weighted Mean Activity

Errors quoted at 1.000 sigma

BLANK CONTROL GROUP 3

	Nuclide Name	Nuclide Id Confidence	Wt mean Activity (uCi/Unit)	Wt mean Activity Uncertainty
	NA-22	0.998	4.841360E-005	4.752093E-006
	K-40	0.993	7.545325E-002	3.692636E-003
	MN-54	0.875	5.970150E-005	4.303794E-006
	CO-60	0.997	7.258105E-005	8.064511E-006
	ZN-69M	0.988	3.940025E-005	8.519523E-006
	NB-95M	0.969	5.747518E-005	4.210034E-006
	ZR-97	0.718	8.124502E-005	1.528310E-005
	BA-133	0.904	8.849226E-005	4.396872E-006
X	XE-133	0.999		
	XE-133M	0.932	3.844754E-005	1.031040E-005
	CS-137	0.999	5.159748E-004	1.332408E-005
	XE-138	0.525	3.825064E-003	9.086474E-004
	BI-211	0.386	2.377573E-003	1.164700E-004
	BI-212	0.744	2.188817E-003	8.866045E-005
	PB-212	0.999	2.473789E-004	1.932398E-005
	BI-214	0.999	3.255037E-003	4.661391E-005
	PB-214	0.999	8.374869E-004	2.674336E-005
	RA-226	0.997	1.981852E-003	1.680528E-004
	AC-228	0.993	2.000636E-003	3.198353E-005
	PA-234M	0.543	4.779232E-003	9.403331E-004
X	U-235	0.526		

? = nuclide is part of an undetermined solution
X = nuclide rejected by the interference analysis
@ = nuclide contains energy lines not used in Weighted Mean Activity

Errors quoted at 1.000 sigma

BLANK CONTROL GROUP 2

	Nuclide Name	Nuclide Id Confidence	Wt mean Activity (uCi/Unit)	Wt mean Activity Uncertainty
	NA-22	0.998	5.860748E-005	5.015017E-006
	K-40	0.995	7.537819E-002	3.688565E-003
	MN-54	0.894	6.406078E-005	4.326647E-006
	CO-57	0.823	1.385449E-005	4.492380E-006
	CO-60	0.997	1.216644E-004	8.222466E-006
	ZN-69M	0.995	2.838281E-005	1.081610E-005
	I-126	0.983	2.991074E-005	1.707392E-005
	BA-133	0.914	1.129147E-004	5.117091E-006
X	XE-133	1.000		
	CS-137	0.999	4.164443E-004	1.079054E-005
	LA-140	0.619	1.358981E-005	1.205882E-005
	BI-211	0.388	2.454491E-003	1.166988E-004
	BI-212	0.746	1.957205E-003	9.263500E-005
	PB-212	0.986	2.394517E-004	1.996261E-005
	BI-214	0.999	3.197693E-003	4.575265E-005
	PB-214	1.000	7.715565E-004	2.893328E-005
X	RN-219	0.372		
	RA-226	0.994	1.968481E-003	1.674411E-004
	AC-228	0.991	2.098177E-003	3.365778E-005
	PA-234M	0.544	4.012064E-003	1.322415E-003
X	U-235	0.511		

? = nuclide is part of an undetermined solution
X = nuclide rejected by the interference analysis
@ = nuclide contains energy lines not used in Weighted Mean Activity

Errors quoted at 1.000 sigma

Interference Corrected Activity Report 1/28/2016

UBWPAD RAS 1/28/2016

	Nuclide Name	Nuclide Id Confidence	Wt mean Activity (uCi/Unit)	Wt mean Activity Uncertainty
	NA-22	0.980	7.730471E-005	5.451359E-006
	K-40	0.978	7.528161E-002	3.677274E-003
	MN-54	0.959	7.011012E-005	4.380825E-006
	CO-57	0.816	2.660604E-005	1.324362E-006
	CO-60	0.977	1.495091E-004	1.003113E-005
	ZN-69M	0.997	3.539745E-005	9.051430E-006
	SR-92	0.677	1.213756E-004	2.884810E-005
	NB-95M	0.987	3.736181E-005	9.751405E-006
	I-131	0.777	3.528700E-005	7.674841E-006
	BA-133	0.993	1.832773E-004	5.800680E-006
X	XE-133	1.000		
	CS-137	0.994	4.422904E-004	1.144494E-005
	BI-211	0.404	2.360670E-003	1.174807E-004
	BI-212	0.748	2.093243E-003	9.896098E-005
	PB-212	0.986	2.536279E-004	2.005094E-005
	BI-214	0.992	3.239801E-003	4.708761E-005
	PB-214	0.999	7.948754E-004	2.856511E-005
	RA-226	0.987	2.050596E-003	1.605028E-004
	AC-228	0.846	2.105225E-003	3.338729E-005
	PA-234M	0.535	3.106343E-003	9.275426E-004
X	U-235	0.459		

? = nuclide is part of an undetermined solution
X = nuclide rejected by the interference analysis
@ = nuclide contains energy lines not used in Weighted Mean Activity

Errors quoted at 1.000 sigma

UBWPAD INFLUENT 2/2/2016

	Nuclide Name	Nuclide Id Confidence	Wt mean Activity (uCi/Unit)	Wt mean Activity Uncertainty
	NA-22	0.998	6.574461E-005	5.224047E-006
	K-40	0.997	7.562749E-002	3.696964E-003
	MN-54	0.925	5.621457E-005	4.110660E-006
	CO-57	0.820	1.311733E-005	5.668065E-006
	CO-60	0.996	1.303329E-004	8.735103E-006
	ZN-69M	0.996	2.574132E-005	1.080719E-005
	ZR-97	0.687	3.605153E-005	5.544155E-006
	BA-133	0.993	1.525905E-004	5.310766E-006
X	XE-133	1.000		
	CS-137	0.999	4.532536E-004	1.144411E-005
	EU-152	0.777	1.138462E-005	4.655861E-006
	BI-211	0.398	2.525094E-003	1.202321E-004
	BI-212	0.999	1.911188E-003	8.697301E-005
	PB-212	0.986	2.731179E-004	2.031986E-005
	BI-214	0.998	3.340674E-003	4.695145E-005
	PB-214	1.000	8.167947E-004	2.932535E-005
	RA-226	0.990	1.999739E-003	1.682855E-004
	AC-228	0.982	2.012452E-003	3.022842E-005
?	TH-232	0.938	-1.153979E-004	1.712420E-003
	PA-234M	0.541	1.109121E-003	9.480093E-004
X	U-235	0.514		
?	AM-241	0.999	-6.040111E-007	8.963082E-006

? = nuclide is part of an undetermined solution
X = nuclide rejected by the interference analysis
@ = nuclide contains energy lines not used in Weighted Mean Activity

Errors quoted at 1.000 sigma

Interference Corrected Activity Report 2/5/2016

UBWPAD EFFLUENT 2/2/2016

	Nuclide Name	Nuclide Id Confidence	Wt mean Activity (uCi/Unit)	Wt mean Activity Uncertainty
	NA-22	0.986	6.944800E-005	5.325649E-006
	K-40	0.984	7.589555E-002	3.708037E-003
	MN-54	0.948	6.476901E-005	4.253725E-006
	CO-57	0.808	1.776818E-005	4.189412E-006
	CO-60	0.980	9.953939E-005	8.177724E-006
	ZN-69M	1.000	4.283990E-005	1.029635E-005
	NB-95M	0.992	3.368098E-005	9.957141E-006
	BA-133	0.905	1.276671E-004	4.889681E-006
X	XE-133	1.000		
	CS-137	0.997	4.722668E-004	1.181611E-005
	BI-211	0.402	2.356499E-003	1.174386E-004
	BI-212	0.748	1.878331E-003	8.104915E-005
	PB-212	1.000	2.087298E-004	2.019038E-005
	BI-214	0.993	3.181382E-003	4.586971E-005
	PB-214	0.999	8.056801E-004	2.913558E-005
	RA-226	0.989	1.927383E-003	1.594827E-004
	AC-228	0.850	2.062398E-003	3.423902E-005
	PA-234M	0.537	6.483219E-003	1.481581E-003
X	U-235	0.480		

? = nuclide is part of an undetermined solution
X = nuclide rejected by the interference analysis
@ = nuclide contains energy lines not used in Weighted Mean Activity

Errors quoted at 1.000 sigma

Interference Corrected Activity Report 2/15/2016

Marlborough Westerly WWTP RAS 2/12/2016

	Nuclide Name	Nuclide Id Confidence	Wt mean Activity (uCi/Unit)	Wt mean Activity Uncertainty
	NA-22	1.000	3.783836E-005	4.701589E-006
	K-40	0.995	7.534092E-002	3.682542E-003
	MN-54	0.945	5.743736E-005	4.116836E-006
	CO-57	0.821	2.084458E-005	5.439159E-006
	CO-60	0.993	1.163224E-004	8.497559E-006
	ZN-69M	0.999	3.731096E-005	1.314543E-005
	BA-133	0.991	1.357856E-004	5.491442E-006
X	XE-133	1.000		
	CS-137	0.999	4.464643E-004	1.145065E-005
?	BA-139	0.999	1.153885E-004	2.829091E-004
?	CE-139	0.999	2.027732E-006	4.919767E-006
	BI-211	0.400	2.421023E-003	1.181605E-004
	BI-212	0.749	1.827605E-003	8.636449E-005
	PB-212	0.986	2.475433E-004	2.041207E-005
	BI-214	0.997	3.256263E-003	4.674597E-005
	PB-214	0.999	7.849262E-004	2.962334E-005
	RA-226	0.990	2.116532E-003	1.524794E-004
	AC-228	0.855	2.067859E-003	3.183651E-005
	PA-234M	0.542	2.143899E-003	8.528556E-004
X	U-235	0.680		

? = nuclide is part of an undetermined solution
X = nuclide rejected by the interference analysis
@ = nuclide contains energy lines not used in Weighted Mean Activity

Errors quoted at 1.000 sigma

Interference Corrected Activity Report 2/16/2016

Marlborough Westerly WWTP INFLUENT 2/12/2016

	Nuclide Name	Nuclide Id Confidence	Wt mean Activity (uCi/Unit)	Wt mean Activity Uncertainty
	NA-22	0.996	6.138809E-005	5.140477E-006
	K-40	1.000	7.517603E-002	3.676336E-003
	MN-54	0.929	6.247708E-005	4.258816E-006
	CO-57	0.827	1.270139E-005	4.482630E-006
	CO-60	0.999	9.758474E-005	8.905298E-006
	ZN-69M	0.998	4.523997E-005	1.089116E-005
	NB-95M	0.981	3.775794E-005	9.862233E-006
	ZR-97	0.686	4.579816E-005	1.653635E-005
	BA-133	0.991	1.595307E-004	5.425732E-006
X	XE-133	1.000		
	CS-137	1.000	5.008744E-004	1.255459E-005
	LA-140	0.619	4.782991E-006	9.490897E-006
	BI-211	0.394	2.409241E-003	1.177638E-004
	BI-212	0.749	2.016512E-003	8.733630E-005
	PB-212	0.986	2.732328E-004	2.028539E-005
	BI-214	1.000	3.239525E-003	4.626814E-005
	PB-214	1.000	7.950385E-004	2.888283E-005
	RA-226	0.995	2.046487E-003	1.686437E-004
	AC-228	0.861	2.198561E-003	3.504200E-005
	PA-234M	0.542	4.355200E-003	8.965179E-004
X	U-235	0.676		

? = nuclide is part of an undetermined solution
X = nuclide rejected by the interference analysis
@ = nuclide contains energy lines not used in Weighted Mean Activity

Errors quoted at 1.000 sigma

Interference Corrected Activity Report 2/17/2016

Marlborough Westerly WWTP EFFLUENT 2/12/2016

	Nuclide Name	Nuclide Id Confidence	Wt mean Activity (uCi/Unit)	Wt mean Activity Uncertainty
	NA-22	0.999	5.372314E-005	4.967681E-006
	K-40	0.999	7.494123E-002	3.666104E-003
	MN-54	0.894	5.180560E-005	4.140385E-006
	CO-60	1.000	9.344504E-005	8.733367E-006
	ZN-69M	0.994	4.410278E-005	1.142993E-005
	BA-133	0.914	1.611171E-004	5.917384E-006
X	XE-133	1.000		
	XE-135M	0.896	3.562045E-005	3.811434E-004
	CS-137	1.000	4.927113E-004	1.242884E-005
	LA-140	0.616	3.347470E-006	9.959960E-006
	BI-211	0.391	2.461187E-003	1.189011E-004
	BI-212	0.747	2.079537E-003	8.571827E-005
	PB-212	0.986	2.831241E-004	2.027368E-005
	BI-214	1.000	3.249703E-003	4.656032E-005
	PB-214	1.000	7.945337E-004	2.909996E-005
	RA-226	0.993	2.112018E-003	1.609586E-004
	AC-228	0.864	1.813922E-003	2.951742E-005
	PA-234M	0.536	4.872213E-003	1.058017E-003
X	U-235	0.455		

? = nuclide is part of an undetermined solution
X = nuclide rejected by the interference analysis
@ = nuclide contains energy lines not used in Weighted Mean Activity

Errors quoted at 1.000 sigma

Interference Corrected Activity Report 2/19/2016

CRPCD RAS 2/19/2016

	Nuclide Name	Nuclide Id Confidence	Wt mean Activity (uCi/Unit)	Wt mean Activity Uncertainty
	NA-22	1.000	5.900837E-005	5.062505E-006
	K-40	0.999	7.555287E-002	3.695913E-003
	MN-54	0.884	7.823036E-005	4.474771E-006
	CO-57	0.819	1.456999E-005	2.512918E-006
	CO-60	1.000	1.092958E-004	9.060046E-006
	ZN-69M	0.991	3.931068E-005	1.258312E-005
	I-131	0.778	1.044421E-005	5.561571E-006
	BA-133	0.991	9.126069E-005	4.392431E-006
X	XE-133	1.000		
	CS-137	1.000	4.990825E-004	1.329911E-005
	BI-211	0.391	2.328409E-003	1.161299E-004
	BI-212	0.746	1.964509E-003	8.198131E-005
	PB-212	0.986	2.671711E-004	2.029001E-005
	BI-214	1.000	3.331423E-003	4.706520E-005
	PB-214	1.000	7.822167E-004	2.936553E-005
X	RN-219	0.367		
	RA-226	0.992	2.345570E-003	1.871644E-004
	AC-228	0.989	2.043724E-003	3.164326E-005
	PA-234M	0.540	1.834438E-003	6.861726E-004
X	U-235	0.513		

? = nuclide is part of an undetermined solution
X = nuclide rejected by the interference analysis
@ = nuclide contains energy lines not used in Weighted Mean Activity

Errors quoted at 1.000 sigma

Interference Corrected Activity Report 2/20/2016

CRPCD INFLUENT 2/19/2016

	Nuclide Name	Nuclide Id Confidence	Wt mean Activity (uCi/Unit)	Wt mean Activity Uncertainty
	NA-22	1.000	5.449029E-005	5.059587E-006
	K-40	0.998	7.481262E-002	3.660323E-003
	MN-54	0.916	7.555937E-005	4.457627E-006
	CO-60	1.000	9.720756E-005	9.069930E-006
	ZN-69M	0.989	3.600547E-005	9.061152E-006
	NB-95M	0.973	4.220630E-005	9.924369E-006
	ZR-97	0.683	4.107451E-005	1.360130E-005
	I-132	0.459	1.423084E-004	5.218513E-005
	BA-133	0.991	1.031638E-004	4.523063E-006
X	XE-133	0.999		
	CS-137	1.000	4.625210E-004	1.168900E-005
	BI-211	0.390	2.354586E-003	1.155528E-004
	BI-212	0.747	1.899198E-003	9.555687E-005
	PB-212	0.986	1.926896E-004	1.999619E-005
	BI-214	1.000	3.346458E-003	4.723549E-005
	PB-214	0.999	7.734721E-004	2.915826E-005
	RA-226	0.994	2.599395E-003	1.038613E-004
	AC-228	0.991	1.963090E-003	3.131076E-005
	PA-234M	0.544	2.500500E-003	1.067987E-003
X	U-235	0.534		

? = nuclide is part of an undetermined solution
X = nuclide rejected by the interference analysis
@ = nuclide contains energy lines not used in Weighted Mean Activity

Errors quoted at 1.000 sigma

Interference Corrected Activity Report 2/21/2016

CRPCD EFFLUENT 2/19/2016

	Nuclide Name	Nuclide Id Confidence	Wt mean Activity (uCi/Unit)	Wt mean Activity Uncertainty
	NA-22	1.000	5.532205E-005	5.033512E-006
	K-40	0.996	7.482554E-002	3.661471E-003
	MN-54	0.904	4.757107E-005	7.308138E-006
	CO-60	0.998	7.871002E-005	7.949265E-006
	ZN-69M	0.997	7.305131E-005	1.483360E-005
	ZR-97	0.751	5.966628E-005	1.581874E-005
	BA-133	0.906	6.882955E-005	4.014468E-006
X	XE-133	1.000		
	CS-137	0.999	5.224877E-004	1.333882E-005
	XE-138	0.351	5.116635E-003	1.114934E-003
	BI-211	0.387	2.246572E-003	1.142804E-004
	BI-212	0.745	1.999830E-003	8.682613E-005
	PB-212	0.986	2.395097E-004	2.012627E-005
	BI-214	0.999	3.209591E-003	4.669600E-005
	PB-214	0.999	7.769619E-004	2.913494E-005
X	RN-219	0.375		
	RA-226	0.994	2.429695E-003	1.876488E-004
	AC-228	0.866	2.081827E-003	3.362920E-005
	PA-234M	0.543	4.719348E-003	1.299701E-003
X	U-235	0.454		

? = nuclide is part of an undetermined solution
X = nuclide rejected by the interference analysis
@ = nuclide contains energy lines not used in Weighted Mean Activity

Errors quoted at 1.000 sigma

Interference Corrected Activity Report 3/3/2016

Webster WWTP RAS 3/3/2016

	Nuclide Name	Nuclide Id Confidence	Wt mean Activity (uCi/Unit)	Wt mean Activity Uncertainty
	NA-22	0.998	4.791011E-005	4.913490E-006
	K-40	0.995	7.500751E-002	3.670536E-003
	MN-54	0.885	7.011466E-005	4.401163E-006
	CO-60	0.999	1.150513E-004	8.926210E-006
	ZN-69M	0.995	2.979896E-005	1.085519E-005
	KR-87	0.756	4.396345E-004	1.548244E-004
	ZR-97	0.737	2.862401E-005	1.029402E-005
	RH-105	0.653	6.641105E-006	2.372690E-005
	BA-133	0.991	1.208873E-004	4.904912E-006
X	XE-133	1.000		
	CS-137	0.999	4.726178E-004	1.184613E-005
	LA-140	0.619	2.320886E-005	1.300180E-005
X	EU-152	0.492		
	AU-198	0.921	1.286747E-005	3.013920E-006
	BI-211	0.387	2.486764E-003	1.197172E-004
	BI-212	0.993	1.997339E-003	8.461644E-005
	PB-212	0.986	2.819317E-004	2.044298E-005
	BI-214	0.999	3.172437E-003	4.596270E-005
	PB-214	0.999	7.814656E-004	2.941913E-005
X	RN-219	0.910		
	RA-226	0.994	2.176809E-003	1.859464E-004
	AC-228	0.866	2.379993E-003	3.342856E-005
	PA-234M	0.543	4.596734E-003	1.103245E-003
X	U-235	0.454		

? = nuclide is part of an undetermined solution
X = nuclide rejected by the interference analysis
@ = nuclide contains energy lines not used in Weighted Mean Activity

Errors quoted at 1.000 sigma

Interference Corrected Activity Report 3/4/2016

Webster WWTP Effluent 3/3/2016

	Nuclide Name	Nuclide Id Confidence	Wt mean Activity (uCi/Unit)	Wt mean Activity Uncertainty
	NA-22	1.000	4.306254E-005	4.880339E-006
	K-40	0.996	7.523592E-002	3.681447E-003
	MN-54	0.888	6.396187E-005	4.320506E-006
	CO-57	0.821	1.435022E-005	4.507410E-006
	CO-60	1.000	9.931307E-005	7.976466E-006
	ZN-69M	0.991	5.143700E-005	1.207380E-005
	I-126	0.965	2.814700E-005	1.604420E-005
	BA-133	0.829	1.334199E-004	5.442806E-006
X	XE-133	1.000		
	CS-137	0.999	4.831399E-004	1.257193E-005
	BI-211	0.649	6.612352E-004	5.475329E-005
	BI-212	0.745	1.974648E-003	8.495018E-005
	PB-212	0.986	1.785533E-004	1.975103E-005
	BI-214	0.999	3.157431E-003	4.628057E-005
	PB-214	1.000	9.236282E-004	2.796524E-005
	RA-226	0.997	2.637376E-003	1.815123E-004
	AC-228	0.991	1.788789E-003	2.647842E-005
?	TH-232	0.935	3.556441E-003	1.478856E-003
	PA-234M	0.539	3.602950E-003	1.027628E-003
X	U-235	0.507		
?	AM-241	0.998	1.861498E-005	7.740571E-006

? = nuclide is part of an undetermined solution
X = nuclide rejected by the interference analysis
@ = nuclide contains energy lines not used in Weighted Mean Activity

Errors quoted at 1.000 sigma

Interference Corrected Activity Report 3/5/2016

Webster WWTP INFLUENT 3/3/2016

	Nuclide Name	Nuclide Id Confidence	Wt mean Activity (uCi/Unit)	Wt mean Activity Uncertainty
	NA-22	0.993	4.184605E-005	4.718235E-006
	K-40	0.996	7.543144E-002	3.691019E-003
	MN-54	0.899	6.386868E-005	4.194653E-006
	CO-60	0.999	9.811921E-005	7.748085E-006
	ZN-69M	0.987	6.013783E-005	1.374993E-005
	ZR-97	0.692	4.407849E-005	1.367331E-005
	BA-133	0.991	1.233817E-004	4.822639E-006
X	XE-133	0.999		
	CS-137	0.999	4.680272E-004	1.231905E-005
?	BA-139	0.907	8.547896E-005	2.829950E-004
?	CE-139	0.907	1.501987E-006	4.944267E-006
	AU-198	0.930	1.396186E-005	3.293790E-006
	BI-211	0.389	2.209919E-003	1.150499E-004
	BI-212	0.745	1.784978E-003	9.314677E-005
	PB-212	0.986	2.328696E-004	2.007716E-005
	BI-214	1.000	3.314889E-003	4.678364E-005
	PB-214	1.000	7.880474E-004	2.895172E-005
X	RN-219	0.374		
	RA-226	0.993	2.231803E-003	1.865693E-004
	AC-228	0.991	2.013324E-003	3.262059E-005
?	TH-232	0.936	4.099313E-003	1.487307E-003
	PA-234M	0.537	3.660891E-003	8.921813E-004
X	U-235	0.512		
?	AM-241	0.998	2.145646E-005	7.784804E-006

? = nuclide is part of an undetermined solution
X = nuclide rejected by the interference analysis
@ = nuclide contains energy lines not used in Weighted Mean Activity

Errors quoted at 1.000 sigma

Interference Corrected Activity Report 3/11/2016

UBWPAD RAS 3/9/2016

	Nuclide Name	Nuclide Id Confidence	Wt mean Activity (uCi/Unit)	Wt mean Activity Uncertainty
	NA-22	0.956	5.174985E-005	4.829097E-006
	K-40	0.963	7.478914E-002	3.663702E-003
	CO-57	0.819	1.580135E-005	5.062306E-006
	CO-60	0.981	1.046594E-004	9.041212E-006
	ZN-69M	0.961	3.743880E-005	1.253820E-005
	ZR-97	0.757	3.708384E-005	1.366301E-005
	I-126	0.985	1.670713E-005	1.466590E-005
	BA-133	0.990	1.108452E-004	4.678497E-006
X	XE-133	0.999		
	CS-137	0.994	4.615527E-004	1.168643E-005
	EU-152	0.771	5.861719E-006	4.675173E-006
	BI-211	0.376	2.455790E-003	1.171011E-004
	BI-212	0.986	1.756014E-003	9.506229E-005
	PB-212	0.985	2.405455E-004	1.993334E-005
	BI-214	0.991	3.172633E-003	4.590260E-005
	PB-214	0.998	7.451114E-004	2.875130E-005
X	RN-219	0.368		
	RA-226	0.996	2.456984E-003	1.797715E-004
	AC-228	0.993	2.005346E-003	3.151142E-005
	PA-234M	0.512	2.941053E-003	8.939476E-004
X	U-235	0.749		

? = nuclide is part of an undetermined solution
X = nuclide rejected by the interference analysis
@ = nuclide contains energy lines not used in Weighted Mean Activity

Errors quoted at 1.000 sigma

Interference Corrected Activity Report 3/12/2016

UBWPAD INFLUENT 3/9/2016

	Nuclide Name	Nuclide Id Confidence	Wt mean Activity (uCi/Unit)	Wt mean Activity Uncertainty
	NA-22	0.963	5.536664E-005	4.972822E-006
	K-40	0.966	7.504931E-002	3.676134E-003
	CO-57	0.823	1.734492E-005	4.506049E-006
	CO-60	0.982	1.258831E-004	8.845580E-006
	ZN-69M	0.991	4.230142E-005	1.080799E-005
	BA-133	0.827	1.067747E-004	4.996752E-006
X	XE-133	0.998		
	CS-137	0.994	4.167259E-004	1.148752E-005
	XE-138	0.518	2.538984E-003	1.052431E-003
X	EU-152	0.772		
	BI-211	0.377	2.425661E-003	1.171719E-004
	BI-212	0.988	1.608740E-003	8.230981E-005
	PB-212	0.985	2.542901E-004	2.001029E-005
	BI-214	0.991	3.225042E-003	4.585502E-005
	PB-214	0.998	7.473693E-004	2.884067E-005
	RN-219	0.378	2.577961E-005	6.924294E-005
	RA-226	0.997	2.061307E-003	1.689361E-004
	AC-228	0.992	1.677860E-003	2.949624E-005
?	TH-232	0.944	1.622161E-003	1.356882E-003
	PA-234M	0.539	4.430792E-003	1.151790E-003
X	U-235	0.506		
?	AM-241	0.999	8.490652E-006	7.102138E-006

? = nuclide is part of an undetermined solution
X = nuclide rejected by the interference analysis
@ = nuclide contains energy lines not used in Weighted Mean Activity

Errors quoted at 1.000 sigma

Interference Corrected Activity Report 3/13/2016

UBWPAD EFFLUENT 3/9/2016

	Nuclide Name	Nuclide Id Confidence	Wt mean Activity (uCi/Unit)	Wt mean Activity Uncertainty
	NA-22	0.978	6.834632E-005	5.172482E-006
	K-40	0.972	7.514582E-002	3.680320E-003
	CO-57	0.817	1.467019E-005	4.822389E-006
	CO-60	0.981	1.274197E-004	9.002075E-006
	ZN-69M	0.984	5.921676E-005	1.376899E-005
	ZR-97	0.796	2.603418E-005	1.256085E-005
	BA-133	0.827	1.057801E-004	4.748143E-006
X	XE-133	0.999		
	CS-137	0.996	4.379570E-004	1.159765E-005
X	EU-152	0.768		
	BI-211	0.378	2.422426E-003	1.165067E-004
	BI-212	0.985	1.985710E-003	8.527914E-005
	PB-212	0.985	2.435691E-004	1.985539E-005
	BI-214	0.992	3.234673E-003	4.605461E-005
	PB-214	0.999	7.614066E-004	2.871677E-005
X	RN-219	0.380		
	RA-226	0.994	2.346896E-003	1.790695E-004
	AC-228	0.994	2.099501E-003	3.221631E-005
	PA-234M	0.536	6.957189E-003	1.230549E-003
X	U-235	0.734		

? = nuclide is part of an undetermined solution
X = nuclide rejected by the interference analysis
@ = nuclide contains energy lines not used in Weighted Mean Activity

Errors quoted at 1.000 sigma

Interference Corrected Activity Report 3/18/2016

Marlborough Westerly WWTP RAS 3/17/2016

	Nuclide Name	Nuclide Id Confidence	Wt mean Activity (uCi/Unit)	Wt mean Activity Uncertainty
	NA-22	0.984	4.860576E-005	4.894675E-006
	K-40	0.988	7.473528E-002	3.658684E-003
?	CR-51	0.908	3.937846E-005	4.362182E-005
	MN-54	0.879	7.204525E-005	4.402468E-006
	CO-57	0.813	1.435004E-005	5.015323E-006
	CO-60	0.996	1.098885E-004	9.186252E-006
	ZN-69M	0.995	5.359278E-005	1.306821E-005
	NB-95M	0.952	4.624481E-005	9.946727E-006
	ZR-97	0.766	2.735626E-005	9.562532E-006
?	RH-105	0.636	2.498504E-005	2.767510E-005
	I-126	0.970	4.016076E-005	2.025374E-005
	BA-133	0.905	7.241702E-005	3.542690E-006
X	XE-133	1.000		
	CS-137	0.998	4.310528E-004	1.148004E-005
	EU-152	0.765	1.710607E-005	4.276134E-006
	BI-211	0.384	2.537432E-003	1.197602E-004
	BI-212	0.992	1.901823E-003	8.814837E-005
	PB-212	0.986	2.605940E-004	2.017957E-005
	BI-214	0.997	3.234552E-003	4.647108E-005
	PB-214	0.999	7.820604E-004	2.894914E-005
X	RN-219	0.378		
	RA-226	0.995	1.965313E-003	1.597342E-004
	AC-228	0.868	2.035374E-003	3.063051E-005
	PA-234M	0.540	5.898191E-003	1.267760E-003
X	U-235	0.475		

? = nuclide is part of an undetermined solution
X = nuclide rejected by the interference analysis
@ = nuclide contains energy lines not used in Weighted Mean Activity

Errors quoted at 1.000 sigma

Interference Corrected Activity Report 3/19/2016

Marlborough Westerly WWTP INFLUENT 3/17/2016

	Nuclide Name	Nuclide Id Confidence	Wt mean Activity (uCi/Unit)	Wt mean Activity Uncertainty
	NA-22	0.993	5.155949E-005	5.055734E-006
	K-40	0.985	7.492734E-002	3.668491E-003
	MN-54	0.890	6.486814E-005	4.315740E-006
	CO-57	0.824	1.404606E-005	4.534170E-006
	CO-60	0.991	1.323377E-004	5.704400E-006
	ZN-69M	0.983	5.817634E-005	1.320152E-005
	BA-133	0.828	7.556898E-005	3.887187E-006
X	XE-133	0.999		
	CS-137	0.997	4.547888E-004	1.183796E-005
	XE-138	0.348	2.458430E-003	7.884704E-004
	BI-211	0.383	2.470421E-003	1.169210E-004
	BI-212	0.741	2.091402E-003	8.657522E-005
	PB-212	0.986	2.560531E-004	2.021519E-005
	BI-214	0.997	3.201697E-003	4.604460E-005
	PB-214	0.999	7.580088E-004	2.933396E-005
X	RN-219	0.370		
	RA-226	0.992	2.015275E-003	1.696615E-004
	AC-228	0.868	2.141784E-003	3.254333E-005
	PA-234M	0.534	3.379332E-003	9.091932E-004
X	U-235	0.490		

? = nuclide is part of an undetermined solution
X = nuclide rejected by the interference analysis
@ = nuclide contains energy lines not used in Weighted Mean Activity

Errors quoted at 1.000 sigma

Marlborough Westerly WWTP EFFLUENT 3/17/2016

	Nuclide Name	Nuclide Id Confidence	Wt mean Activity (uCi/Unit)	Wt mean Activity Uncertainty
	NA-22	0.998	3.611696E-005	4.653048E-006
	K-40	0.990	7.489571E-002	3.666067E-003
	MN-54	0.869	5.814667E-005	4.233248E-006
	CO-57	0.820	1.294153E-005	5.614945E-006
	CO-60	0.996	1.143295E-004	8.647253E-006
	ZN-69M	0.993	2.290700E-005	1.028847E-005
	ZR-97	0.731	2.530871E-005	1.255306E-005
	I-126	0.969	2.066344E-005	1.810612E-005
	BA-133	0.991	8.878679E-005	4.370447E-006
X	XE-133	1.000		
	CS-137	0.998	4.384693E-004	1.148873E-005
	XE-138	0.352	3.009909E-003	7.278820E-004
	EU-152	0.718	1.164541E-005	4.063682E-006
	BI-211	0.385	2.446820E-003	1.177992E-004
	BI-212	0.991	1.597413E-003	8.451764E-005
	PB-212	0.986	2.743578E-004	2.018797E-005
	BI-214	0.998	3.202517E-003	4.613362E-005
	PB-214	0.999	7.548973E-004	2.897736E-005
	RA-226	0.993	2.298339E-003	1.869202E-004
	AC-228	0.867	2.092598E-003	3.081504E-005
	PA-234M	0.531	4.491606E-003	1.061659E-003
X	U-235	0.455		

? = nuclide is part of an undetermined solution
X = nuclide rejected by the interference analysis
@ = nuclide contains energy lines not used in Weighted Mean Activity

Errors quoted at 1.000 sigma

Interference Corrected Activity Report 3/31/2016

CRPCD RAS 3/30/2016

	Nuclide Name	Nuclide Id Confidence	Wt mean Activity (uCi/Unit)	Wt mean Activity Uncertainty
	BE-7	0.900	6.595485E-005	2.063841E-005
	NA-22	0.954	5.659227E-005	5.013952E-006
	K-40	0.957	7.593959E-002	3.720140E-003
	CO-57	0.822	1.475514E-005	4.706857E-006
	CO-60	0.976	1.218525E-004	9.101953E-006
	ZN-69M	0.982	3.599704E-005	9.136664E-006
	NB-95M	0.967	3.272169E-005	9.787717E-006
	ZR-97	0.749	3.688138E-005	1.149637E-005
	BA-133	0.913	1.395438E-004	5.190366E-006
X	XE-133	0.999		
	CS-137	0.992	4.695678E-004	1.239419E-005
	EU-152	0.782	3.189165E-005	3.811476E-006
	AU-198	0.919	1.778324E-005	3.047439E-006
	BI-211	0.374	2.732957E-003	1.232184E-004
	BI-212	0.980	1.594565E-003	9.236634E-005
	PB-212	0.985	3.182764E-004	2.048569E-005
	BI-214	0.988	3.353738E-003	4.747655E-005
	PB-214	0.998	7.744979E-004	2.940002E-005
X	RN-219	0.374		
	RA-226	0.998	2.379652E-003	1.795801E-004
	AC-228	0.993	1.903725E-003	2.771501E-005
	PA-234M	0.525	3.614844E-003	9.757672E-004
X	U-235	0.506		

? = nuclide is part of an undetermined solution
X = nuclide rejected by the interference analysis
@ = nuclide contains energy lines not used in Weighted Mean Activity

Errors quoted at 1.000 sigma

Interference Corrected Activity Report 4/1/2016

CRPCD INFLUENT 3/30/2016

	Nuclide Name	Nuclide Id Confidence	Wt mean Activity (uCi/Unit)	Wt mean Activity Uncertainty
	NA-22	0.949	5.344611E-005	4.885608E-006
	K-40	0.931	7.511515E-002	3.681749E-003
	CO-57	0.827	2.315935E-005	4.782555E-006
	CO-60	0.960	1.112501E-004	2.761808E-006
	ZN-69M	0.979	4.968341E-005	1.087724E-005
	RB-89	0.626	9.664466E-004	3.379203E-004
	ZR-97	0.766	5.704440E-005	1.593895E-005
	BA-133	0.826	1.308956E-004	5.064973E-006
X	XE-133	0.999		
	CS-137	0.988	4.652514E-004	1.230413E-005
X	CS-138	0.422		
	EU-152	0.819	4.087590E-006	4.578956E-006
	BI-211	0.502	1.805110E-003	8.385500E-005
	BI-212	0.977	1.841217E-003	7.898306E-005
	PB-212	0.984	2.036855E-004	1.976291E-005
	BI-214	0.981	3.236613E-003	4.628453E-005
	PB-214	0.997	8.521642E-004	2.815533E-005
X	RN-219	0.374		
	RA-226	0.997	2.043264E-003	1.686759E-004
	AC-228	0.865	2.075074E-003	3.231903E-005
	PA-234M	0.524	2.355285E-003	1.074317E-003
X	U-235	0.449		

? = nuclide is part of an undetermined solution
X = nuclide rejected by the interference analysis
@ = nuclide contains energy lines not used in Weighted Mean Activity

Errors quoted at 1.000 sigma

Interference Corrected Activity Report 4/2/2016

CRPCD EFFLUENT 3/30/2016

	Nuclide Name	Nuclide Id Confidence	Wt mean Activity (uCi/Unit)	Wt mean Activity Uncertainty
	NA-22	0.980	6.172546E-005	5.297487E-006
	K-40	0.947	7.484913E-002	3.668554E-003
	CO-57	0.825	2.520602E-005	4.944271E-006
	CO-60	0.961	1.132537E-004	9.853578E-006
	ZN-69M	0.985	6.284130E-005	1.265256E-005
	KR-87	0.761	1.496278E-004	1.330857E-004
	ZR-97	0.776	5.457150E-006	1.038552E-005
	BA-133	0.912	1.084029E-004	4.073403E-006
X	XE-133	0.999		
	CS-137	0.990	4.572987E-004	1.228010E-005
	EU-152	0.831	1.053980E-005	4.778718E-006
	YB-169	0.303	1.981272E-006	1.569012E-006
	BI-211	0.490	1.843296E-003	1.041407E-004
	BI-212	0.982	1.837574E-003	1.010717E-004
	PB-212	0.985	2.428363E-004	2.016401E-005
	BI-214	0.986	3.231147E-003	4.740627E-005
	PB-214	0.997	8.241789E-004	2.884611E-005
X	RN-219	0.920		
	RA-226	0.996	2.705056E-003	1.867283E-004
	AC-228	0.991	2.116932E-003	3.374867E-005
	PA-234M	0.525	2.428813E-003	9.673646E-004
X	U-235	0.507		

? = nuclide is part of an undetermined solution
X = nuclide rejected by the interference analysis
@ = nuclide contains energy lines not used in Weighted Mean Activity

Errors quoted at 1.000 sigma

Webster WWTP RAS 4/5/2016

	Nuclide Name	Nuclide Id Confidence	Wt mean Activity (uCi/Unit)	Wt mean Activity Uncertainty
	NA-22	0.967	4.975505E-005	4.860870E-006
	K-40	0.952	7.536813E-002	3.692294E-003
	CO-57	0.825	2.240033E-005	5.083301E-006
	CO-60	0.966	1.253430E-004	9.506895E-006
	ZN-69M	0.980	4.640432E-005	8.533480E-006
	ZR-97	0.772	1.424773E-005	1.147186E-005
	I-126	0.950	1.579375E-005	1.890245E-005
	BA-133	0.913	1.226892E-004	4.859652E-006
X	XE-133	1.000		
	CS-137	0.991	4.786366E-004	1.259030E-005
X	LA-140	0.620		
	BI-211	0.507	1.355826E-003	8.040779E-005
	BI-212	0.730	1.905001E-003	8.557832E-005
	PB-212	0.985	2.130617E-004	1.987173E-005
	BI-214	0.987	3.269677E-003	4.640660E-005
	PB-214	0.998	8.778615E-004	2.809612E-005
	RN-219	0.383	2.676474E-005	6.918950E-005
	RA-226	0.997	2.277653E-003	1.683097E-004
	AC-228	0.868	1.945393E-003	3.124892E-005
	PA-234M	0.530	3.975102E-003	1.048188E-003
X	U-235	0.450		

? = nuclide is part of an undetermined solution
X = nuclide rejected by the interference analysis
@ = nuclide contains energy lines not used in Weighted Mean Activity

Errors quoted at 1.000 sigma

Interference Corrected Activity Report 4/9/2016

Webster WWTP INFLUENT 4/5/2016

	Nuclide Name	Nuclide Id Confidence	Wt mean Activity (uCi/Unit)	Wt mean Activity Uncertainty
	NA-22	0.980	6.317367E-005	5.133124E-006
	K-40	0.968	7.505714E-002	3.676545E-003
	CO-57	0.821	1.728079E-005	5.714296E-006
	CO-60	0.977	1.291285E-004	9.197935E-006
	ZN-69M	0.987	4.439379E-005	1.437734E-005
	KR-87	0.771	2.463924E-004	1.276837E-004
	NB-95M	0.973	1.920012E-005	9.786301E-006
	BA-133	0.913	1.209198E-004	5.264079E-006
X	XE-133	1.000		
	CS-137	0.995	4.871273E-004	1.263438E-005
	XE-138	0.546	4.730740E-003	1.044741E-003
	EU-152	0.732	9.030421E-006	4.753598E-006
	BI-211	0.377	2.415453E-003	1.185581E-004
	BI-212	0.987	1.933407E-003	8.233567E-005
	PB-212	0.985	2.805121E-004	2.039706E-005
	BI-214	0.993	3.262914E-003	4.643404E-005
	PB-214	0.998	7.749692E-004	2.946965E-005
X	RN-219	0.916		
	RA-226	0.996	2.023645E-003	1.616571E-004
	AC-228	0.868	2.251457E-003	3.597354E-005
?	TH-232	0.960	1.500835E-003	1.596323E-003
	PA-234M	0.524	4.502942E-003	1.278207E-003
X	U-235	0.537		
?	AM-241	1.000	7.855609E-006	8.355407E-006

? = nuclide is part of an undetermined solution
X = nuclide rejected by the interference analysis
@ = nuclide contains energy lines not used in Weighted Mean Activity

Errors quoted at 1.000 sigma

Interference Corrected Activity Report 4/10/2016

Webster WWTP Effluent 4/5/2016

	Nuclide Name	Nuclide Id Confidence	Wt mean Activity (uCi/Unit)	Wt mean Activity Uncertainty
	NA-22	0.991	6.007572E-005	5.076611E-006
	K-40	0.972	7.579315E-002	3.709408E-003
	CO-57	0.824	2.231547E-005	5.952339E-006
	CO-60	0.981	1.133563E-004	8.354846E-006
	ZN-69M	0.976	6.916386E-005	1.382674E-005
	Y-91M	0.990	5.096219E-005	5.069338E-005
	NB-95M	0.970	2.360453E-005	9.793668E-006
	ZR-97	0.767	4.601034E-005	1.256782E-005
	BA-133	0.914	1.055051E-004	4.637103E-006
X	XE-133	1.000		
	CS-137	0.995	5.042283E-004	1.290797E-005
	LA-140	0.619	6.785739E-006	1.468815E-005
	EU-152	0.748	2.270813E-005	4.104317E-006
	BI-211	0.379	2.497870E-003	1.189546E-004
	BI-212	0.986	1.964750E-003	8.018790E-005
	PB-212	0.985	2.732243E-004	2.032711E-005
	BI-214	0.993	3.202285E-003	4.630715E-005
	PB-214	0.999	7.980175E-004	2.908949E-005
X	RN-219	0.373		
	RA-226	0.997	2.218890E-003	1.703627E-004
	AC-228	0.868	2.167923E-003	3.193743E-005
	PA-234M	0.534	4.282507E-003	1.110529E-003
X	U-235	0.450		

? = nuclide is part of an undetermined solution
X = nuclide rejected by the interference analysis
@ = nuclide contains energy lines not used in Weighted Mean Activity

Errors quoted at 1.000 sigma

Marlborough Westerly WWTP RAS 4/22/2016

	Nuclide Name	Nuclide Id Confidence	Wt mean Activity (uCi/Unit)	Wt mean Activity Uncertainty
	NA-22	0.895	4.156432E-005	4.791919E-006
	K-40	0.892	7.612170E-002	3.733064E-003
	CO-57	0.823	2.277257E-005	4.521195E-006
	CO-60	0.924	1.231992E-004	9.005421E-006
	ZN-69M	0.978	5.557240E-005	1.428983E-005
	NB-95M	0.972	5.122133E-005	9.902645E-006
	ZR-97	0.767	1.579325E-005	1.151366E-005
	BA-133	0.823	1.216525E-004	4.886785E-006
X	XE-133	0.998		
	CS-137	0.979	2.818037E-004	8.163508E-006
	BI-212	0.715	1.969537E-003	9.958123E-005
	PB-212	0.983	1.525088E-004	1.971727E-005
	BI-214	0.968	3.258089E-003	4.535998E-005
	PB-214	0.994	1.001499E-003	2.750891E-005
	RN-219	0.388	6.349802E-005	6.441805E-005
	RA-226	0.998	2.531409E-003	1.811630E-004
	AC-228	0.986	1.814230E-003	3.127258E-005
	PA-234M	0.526	4.590601E-003	1.312485E-003
X	U-235	0.506		

? = nuclide is part of an undetermined solution
X = nuclide rejected by the interference analysis
@ = nuclide contains energy lines not used in Weighted Mean Activity

Errors quoted at 1.000 sigma

Marlborough Westerly WWTP INFLUENT 4/22/2016

	Nuclide Name	Nuclide Id Confidence	Wt mean Activity (uCi/Unit)	Wt mean Activity Uncertainty
	NA-22	0.930	3.658615E-005	4.594458E-006
	K-40	0.890	7.526752E-002	3.691416E-003
	CO-57	0.827	2.037920E-005	5.386140E-006
	CO-60	0.917	1.124597E-004	8.396056E-006
	ZN-69M	0.969	4.851249E-005	1.022632E-005
	BA-133	0.909	1.228600E-004	5.198053E-006
X	XE-133	0.999		
	CS-137	0.977	2.784539E-004	8.137970E-006
	LA-140	0.623	8.746439E-006	1.035255E-005
	EU-152	0.690	9.939995E-007	4.680196E-006
	BI-212	0.963	1.897705E-003	7.878274E-005
	PB-212	0.983	1.421091E-004	1.942821E-005
	BI-214	0.968	3.272902E-003	4.155223E-005
	PB-214	0.995	9.639582E-004	2.719212E-005
X	RN-219	0.380		
	RA-226	0.998	2.118517E-003	1.693590E-004
	AC-228	0.985	1.763544E-003	2.996528E-005
	PA-234M	0.494	3.093365E-003	1.025633E-003
X	U-235	0.505		

? = nuclide is part of an undetermined solution
X = nuclide rejected by the interference analysis
@ = nuclide contains energy lines not used in Weighted Mean Activity

Errors quoted at 1.000 sigma

Marlborough Westerly WWTP EFFLUENT 4/22/2016

	Nuclide Name	Nuclide Id Confidence	Wt mean Activity (uCi/Unit)	Wt mean Activity Uncertainty
	NA-22	0.955	5.529495E-005	4.957850E-006
	K-40	0.911	7.486437E-002	3.670642E-003
	K-42	0.894	-4.348818E-005	5.802261E-005
	CO-57	0.823	3.074945E-005	5.165981E-006
	CO-60	0.929	1.196309E-004	8.274453E-006
	ZN-69M	0.972	4.932360E-005	1.142116E-005
	BA-133	0.910	1.051051E-004	4.423182E-006
X	XE-133	0.999		
	CS-137	0.985	2.816587E-004	8.251464E-006
	XE-138	0.515	3.306414E-003	9.741628E-004
	BI-212	0.722	1.977288E-003	9.914309E-005
	PB-212	0.984	1.380240E-004	1.934942E-005
	BI-214	0.976	3.279028E-003	4.607000E-005
	PB-214	0.996	9.692506E-004	2.715005E-005
X	RN-219	0.389		
	RA-226	0.998	2.318087E-003	1.624931E-004
	AC-228	0.988	2.092940E-003	3.108359E-005
	PA-234M	0.524	4.799146E-003	1.242282E-003
X	U-235	0.506		

? = nuclide is part of an undetermined solution
X = nuclide rejected by the interference analysis
@ = nuclide contains energy lines not used in Weighted Mean Activity

Errors quoted at 1.000 sigma

CRPCD RAS 4/29/2016

	Nuclide Name	Nuclide Id Confidence	Wt mean Activity (uCi/Unit)	Wt mean Activity Uncertainty
	NA-22	0.965	4.431422E-005	4.770106E-006
	K-40	0.923	7.451516E-002	3.653133E-003
	CO-57	0.820	1.091069E-005	5.430794E-006
	CO-60	0.948	1.183421E-004	5.031993E-006
	ZN-69M	0.981	6.307584E-005	1.189933E-005
	NB-95M	0.974	5.023049E-005	1.000940E-005
	I-126	0.962	1.574686E-005	1.787894E-005
	BA-133	0.826	1.074832E-004	4.972989E-006
X	XE-133	0.998		
	CS-137	0.985	2.827023E-004	8.255433E-006
	BI-212	0.722	1.749869E-003	8.668925E-005
	PB-212	0.984	1.469680E-004	1.912781E-005
	BI-214	0.979	3.168757E-003	4.579976E-005
	PB-214	0.996	1.042953E-003	2.615458E-005
X	RN-219	0.387		
	RA-226	0.998	2.124128E-003	1.527838E-004
	AC-228	0.865	2.211890E-003	3.432297E-005
	PA-234M	0.521	5.659804E-003	1.140077E-003
X	U-235	0.693		

? = nuclide is part of an undetermined solution
X = nuclide rejected by the interference analysis
@ = nuclide contains energy lines not used in Weighted Mean Activity

Errors quoted at 1.000 sigma

Interference Corrected Activity Report 4/30/2016

CRPCD INFLUENT 4/29/2016

	Nuclide Name	Nuclide Id Confidence	Wt mean Activity (uCi/Unit)	Wt mean Activity Uncertainty
	NA-22	0.916	2.393336E-005	4.692385E-006
	K-40	0.924	7.492880E-002	3.673241E-003
	CO-60	0.949	1.348606E-004	9.652994E-006
	ZN-69M	0.974	4.279959E-005	9.683881E-006
	NB-97	0.986	5.616408E-005	4.248714E-005
	ZR-97	0.755	1.720912E-005	1.033769E-005
	I-126	0.962	1.295447E-005	1.456101E-005
	SB-126	0.699	5.562380E-005	3.548289E-006
	BA-133	0.912	1.267520E-004	4.903795E-006
X	XE-133	0.999		
	CS-137	0.986	2.936499E-004	8.430004E-006
	LA-140	0.622	1.244017E-005	4.184855E-006
	BI-211	0.369	2.565014E-003	1.195227E-004
	BI-212	0.726	2.143671E-003	6.912891E-005
	PB-212	0.984	2.581814E-004	2.020110E-005
	BI-214	0.979	3.218048E-003	4.625932E-005
	PB-214	0.996	7.657745E-004	2.924169E-005
X	RN-219	0.377		
	RA-226	0.998	2.226648E-003	1.784890E-004
	AC-228	0.990	2.091987E-003	3.243679E-005
	PA-234M	0.518	4.350674E-003	1.188700E-003
X	U-235	0.506		

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@ = nuclide contains energy lines not used in Weighted Mean Activity

Errors quoted at 1.000 sigma

Interference Corrected Activity Report 5/1/2016

CRPCD EFFLUENT 4/29/2016

	Nuclide Name	Nuclide Id Confidence	Wt mean Activity (uCi/Unit)	Wt mean Activity Uncertainty
	NA-22	0.937	4.266188E-005	4.923284E-006
	K-40	0.925	7.491683E-002	3.672452E-003
	CO-57	0.823	1.193021E-005	4.486029E-006
	CO-60	0.952	1.260081E-004	9.312029E-006
	ZN-69M	0.976	4.261118E-005	1.252282E-005
	ZR-97	0.767	3.209087E-005	1.078466E-005
	BA-133	0.912	1.245334E-004	4.849834E-006
X	XE-133	0.999		
	CS-137	0.987	2.789915E-004	8.153374E-006
	BI-211	0.503	1.703066E-003	8.227656E-005
	BI-212	0.724	1.934914E-003	8.916047E-005
	PB-212	0.984	2.120792E-004	1.985022E-005
	BI-214	0.979	3.192754E-003	4.565278E-005
	PB-214	0.997	8.290781E-004	2.832675E-005
X	RN-219	0.385		
	RA-226	0.996	2.360560E-003	1.790133E-004
	AC-228	0.989	1.811296E-003	2.975625E-005
	PA-234M	0.531	2.365842E-003	1.024466E-003
X	U-235	0.508		

? = nuclide is part of an undetermined solution
X = nuclide rejected by the interference analysis
@ = nuclide contains energy lines not used in Weighted Mean Activity

Errors quoted at 1.000 sigma

Interference Corrected Activity Report 5/12/2016

Webster WWTP RAS 5/11/2016

	Nuclide Name	Nuclide Id Confidence	Wt mean Activity (uCi/Unit)	Wt mean Activity Uncertainty
	NA-22	0.966	4.823607E-005	4.843941E-006
	K-40	0.919	7.557410E-002	3.704776E-003
?	CR-51	0.971	4.489922E-005	4.035900E-005
	CO-57	0.824	3.546740E-005	5.806387E-006
	CO-60	0.945	1.338241E-004	9.247812E-006
	ZN-69M	0.973	3.362191E-005	1.192912E-005
	KR-87	0.782	1.472331E-004	1.111708E-004
?	RH-105	0.587	2.848787E-005	2.560395E-005
	I-131	0.772	7.740859E-006	6.324266E-006
	BA-133	0.910	1.087256E-004	4.522357E-006
X	XE-133	0.999		
	CS-137	0.985	3.182705E-004	8.621370E-006
	BI-212	0.722	1.815696E-003	9.310857E-005
	PB-212	0.984	1.754907E-004	1.975990E-005
	BI-214	0.978	3.185821E-003	4.626092E-005
	PB-214	0.996	9.830702E-004	2.753908E-005
X	RN-219	0.918		
	RA-226	0.998	2.568569E-003	1.808308E-004
	AC-228	0.865	2.095496E-003	3.125241E-005
	PA-234M	0.521	3.141274E-003	1.071034E-003
X	U-235	0.671		

? = nuclide is part of an undetermined solution
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Errors quoted at 1.000 sigma

Interference Corrected Activity Report 5/13/2016

Webster WWTP INFLUENT 5/11/2016

	Nuclide Name	Nuclide Id Confidence	Wt mean Activity (uCi/Unit)	Wt mean Activity Uncertainty
	NA-22	0.922	4.431529E-005	4.759489E-006
	K-40	0.895	7.535617E-002	3.695413E-003
	CO-57	0.825	1.626048E-005	4.455004E-006
	CO-60	0.922	1.318089E-004	9.282975E-006
	ZN-69M	0.971	4.784291E-005	1.136653E-005
	NB-95M	0.968	3.929184E-005	9.835757E-006
	ZR-97	0.778	3.778604E-005	1.378932E-005
	BA-133	0.824	1.277270E-004	5.041526E-006
X	XE-133	0.999		
	CS-137	0.981	3.051955E-004	8.396883E-006
	XE-138	0.533	4.380918E-003	1.146920E-003
	EU-152	0.660	1.450467E-005	4.357433E-006
	BI-212	0.967	1.733908E-003	9.702666E-005
	PB-212	0.983	1.894074E-004	1.976979E-005
	BI-214	0.970	3.130623E-003	4.551400E-005
	PB-214	0.995	1.003988E-003	2.746574E-005
	RN-219	0.387	5.677482E-005	7.063981E-005
	RA-226	0.998	2.466330E-003	1.722881E-004
	AC-228	0.986	2.111643E-003	3.123735E-005
	PA-234M	0.534	4.379104E-003	9.746780E-004
X	U-235	0.506		

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Errors quoted at 1.000 sigma

Interference Corrected Activity Report 5/15/2016

Webster WWTP Effluent 5/11/2016

	Nuclide Name	Nuclide Id Confidence	Wt mean Activity (uCi/Unit)	Wt mean Activity Uncertainty
	NA-22	0.942	4.250425E-005	4.747475E-006
	K-40	0.944	7.542833E-002	3.696251E-003
	CO-57	0.821	1.374200E-005	5.654078E-006
	CO-60	0.960	1.208924E-004	8.862358E-006
	ZN-69M	0.982	3.947814E-005	9.658208E-006
	BA-133	0.911	1.191464E-004	5.181183E-006
X	XE-133	0.999		
	CS-137	0.991	3.247863E-004	8.721544E-006
	XE-138	0.340	1.256190E-003	7.929071E-004
	LA-140	0.780	1.049260E-005	1.104050E-005
	EU-152	0.767	2.757447E-005	4.190382E-006
	BI-211	0.372	2.751356E-003	1.225924E-004
	BI-212	0.979	1.767490E-003	9.079235E-005
	PB-212	0.984	3.044282E-004	2.050772E-005
	BI-214	0.985	3.231791E-003	4.632626E-005
	PB-214	0.997	7.577200E-004	2.949565E-005
X	RN-219	0.380		
	RA-226	0.997	2.039440E-003	1.605989E-004
	AC-228	0.992	2.012255E-003	3.149099E-005
	PA-234M	0.531	2.262861E-003	9.887357E-004
X	U-235	0.730		

? = nuclide is part of an undetermined solution
X = nuclide rejected by the interference analysis
@ = nuclide contains energy lines not used in Weighted Mean Activity

Errors quoted at 1.000 sigma

Interference Corrected Activity Report 5/17/2016

UBWPAD RAS 5/16/2016

	Nuclide Name	Nuclide Id Confidence	Wt mean Activity (uCi/Unit)	Wt mean Activity Uncertainty
	NA-22	0.976	3.795449E-005	4.617276E-006
	K-40	0.960	7.496878E-002	3.672698E-003
	CO-57	0.824	1.551199E-005	5.452616E-006
	CO-60	0.973	9.764986E-005	9.037597E-006
	ZN-69M	0.977	5.869845E-005	1.623003E-005
	KR-87	0.792	9.372227E-005	1.403755E-004
	I-131	0.777	1.708027E-005	8.732461E-006
	BA-133	0.904	1.087391E-004	5.050765E-006
X	XE-133	1.000		
	CS-137	0.986	3.104965E-004	3.591458E-005
	EU-152	0.705	1.302902E-005	4.540614E-006
	BI-211	0.506	1.646008E-003	8.744932E-005
	BI-212	0.982	1.800969E-003	9.234075E-005
	PB-212	0.998	2.695367E-004	2.038944E-005
	BI-214	0.990	3.251011E-003	4.675694E-005
	PB-214	0.998	8.317521E-004	2.877509E-005
X	RN-219	0.925		
	RA-226	0.992	2.383992E-003	1.828112E-004
	AC-228	0.992	1.813896E-003	2.938576E-005
	PA-234M	0.528	4.893244E-003	1.025040E-003
X	U-235	0.512		

? = nuclide is part of an undetermined solution
X = nuclide rejected by the interference analysis
@ = nuclide contains energy lines not used in Weighted Mean Activity

Errors quoted at 1.000 sigma

Interference Corrected Activity Report 5/18/2016

UBWPAD INFLUENT 5/16/2016

	Nuclide Name	Nuclide Id Confidence	Wt mean Activity (uCi/Unit)	Wt mean Activity Uncertainty
	NA-22	0.945	2.894819E-005	4.294640E-006
	K-40	0.944	7.470638E-002	3.660965E-003
	ZN-69M	0.969	4.400318E-005	1.187497E-005
	NB-95M	0.976	3.799704E-005	9.750928E-006
	ZR-97	0.738	3.898764E-005	1.366959E-005
	BA-133	0.826	1.242433E-004	4.978916E-006
X	XE-133	0.999		
	CS-137	0.990	2.927734E-004	8.413014E-006
	CE-141	0.984	1.115430E-005	3.389701E-006
	BI-211	0.372	2.753551E-003	1.216952E-004
	BI-212	0.727	1.942197E-003	8.800082E-005
	PB-212	0.984	2.803162E-004	2.013763E-005
	BI-214	0.983	3.193964E-003	4.645513E-005
	PB-214	0.997	7.439220E-004	2.898164E-005
	RN-219	0.384	6.343845E-005	6.914886E-005
	RA-226	0.997	2.428103E-003	1.786639E-004
	AC-228	0.992	1.762873E-003	2.866001E-005
	PA-234M	0.524	4.058952E-003	1.134651E-003
X	U-235	0.729		

? = nuclide is part of an undetermined solution
X = nuclide rejected by the interference analysis
@ = nuclide contains energy lines not used in Weighted Mean Activity

Errors quoted at 1.000 sigma

Interference Corrected Activity Report 5/19/2016

UBWPAD EFFLUENT 5/16/2016

	Nuclide Name	Nuclide Id Confidence	Wt mean Activity (uCi/Unit)	Wt mean Activity Uncertainty
	NA-22	0.939	5.191551E-005	4.942559E-006
	K-40	0.914	7.489119E-002	3.671601E-003
	CO-60	0.954	3.973184E-005	6.522415E-006
	ZN-69M	0.976	3.041738E-005	9.050628E-006
	NB-95M	0.965	9.158647E-006	6.542705E-006
	ZR-97	0.761	4.661659E-005	1.821289E-005
	I-126	0.932	2.901416E-005	1.687183E-005
	BA-133	0.909	1.165231E-004	4.747185E-006
X	XE-133	0.999		
	CS-137	0.984	2.997963E-004	8.582867E-006
	BI-212	0.718	2.012324E-003	9.156398E-005
	PB-212	0.984	1.528990E-004	1.897573E-005
	BI-214	0.975	3.141046E-003	4.551929E-005
	PB-214	0.996	1.021943E-003	2.592069E-005
X	RN-219	0.382		
	RA-226	0.995	2.128434E-003	1.602152E-004
	AC-228	0.989	2.090696E-003	3.361234E-005
	PA-234M	0.518	3.633242E-003	8.909714E-004
X	U-235	0.509		

? = nuclide is part of an undetermined solution
X = nuclide rejected by the interference analysis
@ = nuclide contains energy lines not used in Weighted Mean Activity

Errors quoted at 1.000 sigma