

# Nuclear Waste Reduction Using Molecularly Imprinted Polymers

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**Abstract** Nuclear power accounts for just over twenty percent of America's electrical output and does not contribute to greenhouse gas emissions. Unfortunately, nuclear power does produce a deleterious by-product known as radioactive waste. One of the primary goals of nuclear power proponents is the development of methods that reduce the volume of radioactive waste, such as cobalt. Radioactive cobalt is usually accompanied by non-radioactive iron, making it more difficult to solely extract the harmful cobalt atoms. The application of molecularly imprinted polymers and chitosans increase the effectiveness of the removal of radioactive cobalt from cooling medium in order to reduce the overall volume of nuclear waste by having a high selectivity for the radioactive cobalt ions even in the presence of similar particles. This method's efficacy will be analyzed and compared to the current procedures for removing radioactive cobalt from cooling medium. A relevant explanation of a nuclear reactor's inner workings, radioactive waste formation, along with societal implications of cleaner nuclear power, and the benefits of its successful implementation, will also be discussed.

**Keywords:** half-life, molecular imprinting, nuclear power, nuclear waste, radiation

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## 1. Why Is Energy a Problem?

As the populations of developed countries rise, so do their standards of living. Such standards are only made possible through an abundant supply of energy [1]. Additionally, statistics show that the average life expectancy of people in nations with substantial energy availability is over seventy-five years, while those in underdeveloped countries have a life expectancy averaging a mere forty years [2]. The world's population is currently doubling every thirty five years, while its energy usage is doubling every fourteen years [2]. Due to the limited supply of fossil fuels, which comprise the majority of the world's energy producing sources, this increase in population, and living standards will not be indefinitely sustainable unless other viable energy sources are widely employed. The rate of oil production is expected to peak within the next few years, and although there is still a copious supply of coal to utilize, both types of fuel are major contributors of greenhouse gas emissions and overall climate change [2]. The burning of coal produces over five hundred pounds of airborne pollution per second in America alone, while the burning of oil contributes a similar amount of these harmful carbon pollutants [3]. The atmospheric waste produced by fossil fuels also leads to acid rain, which severely weakens surrounding vegetation, and can completely decimate aquatic life. Alternative fuel sources including solar, wind, and hydroelectric power simply do not produce enough

energy to make a significant contribution to worlds the overall energy needs, and are also limited by geographic location. It is this composite of increasing need with a diminishing supply that constitutes the energy crisis facing the world today [2]. This crisis can be met with the systematic integration of the large scale usage of nuclear power.

**Table 1. Annual Waste Produced by a 1000 Mw Plant [3]**

Type of Plant	Nuclear	Coal	Natural Gas	Petroleum (Oil)
Electricity produced (MWh)	7,971,600	6,683,880	998,640	1,173,840
Nuclear Used Fuel (tons)	27	0	0	0
Coal Ash (tons)	0	400,000	0	0
Sulfur Dioxide (tons)	0	20,000	2	2,248
Nitrogen Oxide (tons)	0	20,400	157	898
Carbon Dioxide (tons)	0	7,400,000	199,472	328,655
Small particulates (tons)	0	100	12	168
Carbon Monoxide (tons)	0	1,440	68	66
Total Annual Waste (tons)	27	7,841,940	199,711	332,036
Waste per kWh (lbs)	0.007	2,347	400	566

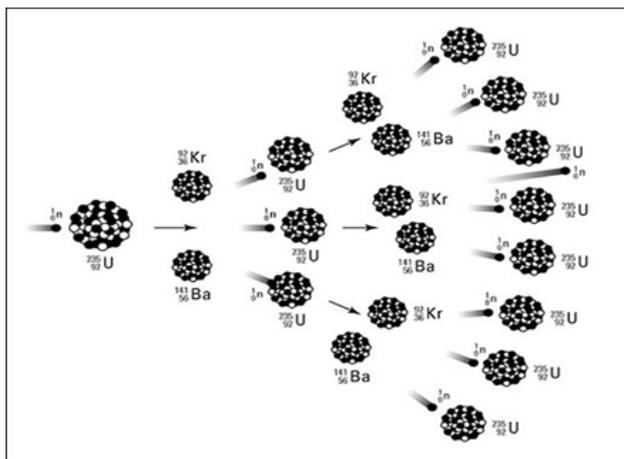
## 2. The Potential of Nuclear Power

Using nuclear power as a major source of electrical production for a country can alleviate many of the issues associated with the use of fossil fuels. Nuclear power uses only a minute amount of material to yield a massive energy output while releasing zero greenhouse gasses. As the fissionable material of choice, uranium is a better source for energy production compared to fossil fuels due to its high energy density. One kilogram of coal can keep a 100 watt light bulb lit for about four days, One kilogram of natural gas can only last for about six days, and One kilogram of uranium can keep the light bulb lit for over 140 years [3].

**Table 2. Energy Density for Various Materials [3]**

Fuel Type	Energy Density (kWh/kg)	Number of Times Denser than Coal
Nuclear Fission (100% U-235)	24513889	2715385
Natural Uranium (99.3% U-238, 0.7% U-235) in a fast breeder reactor	6666667	738462
Enriched Uranium (3.5% U-235) in a light water reactor	960000	106338
Natural Uranium (99.3% U-238, 0.7% U-235) in a light water reactor	123056	13631
LPG propane	14	2
LPG butane	14	2
Gasoline	13	1
Diesel fuel/Residential heating oil	13	1
Biodiesel oil	12	1
Anthracite Coal	9	1
Water at 100m dam height	0	N/A

The basic mechanics behind the production of electricity is the use of large generators. These generators produce electricity when relative motion is present between the conductors and magnets inside them. This motion is achieved by the use of steam driven, mechanical turbines. What differs from between the two types of power plants is the way in which this cooling water is heated to make the steam which drives the turbines. As opposed to continually burning incredibly large quantities of fossil fuels to generate the heat needed to boil the water, the heat produced from the process of nuclear fission is harnessed and used to our benefit.



**Figure 1. Nuclear Chain Reaction [4]**

The process of nuclear fission occurs when an atom's nucleus is bombarded with another particle, normally a neutron, and made to become so unstable that it breaks up into at least two smaller particles, some free neutrons, and releases gamma radiation. These free neutrons can go on to create a chain reaction that, with the use of proper materials, can be safe and controlled. After a fission event, these smaller particles move apart at high speeds, colliding with nearby molecules, increasing the overall kinetic energy in the system. The energy released is due to the small loss in mass of the products in the reaction. Einstein's famous equation  $E=mc^2$  allows us to see just why there is such a large release of energy [4]. Even when the mass is on the atomic scale, when multiplied by the speed of light squared, it will yield an enormous amount of energy. This increase in energy corresponds to a rise in temperature of the system that can be used to boil water, create steam, spin a turbine, and then generate electricity.

## 2.1. Further Comparisons For The Use Of Nuclear Power

A comparison of nuclear power to the use of fossil fuel for energy production should also include examining capacity, cost, reliability, and safety. Since the basic constructions of both types of power plants are similar, their capacities for energy production in either design are also similar at around 1000 megawatts [1]. Over 440 reactors are in operation around the world supplying more than a fifth of the energy used [1]. Due to the ample supply of uranium and other fissionable materials estimated to be available, there is no danger of extinguishing the supply for at least a century at today's current expenditure.

Cost per kilowatt produced in the different styles of power plant is difficult to truly evaluate. Government funding and tax incentives play a large role in the creation of a nuclear power plant; however, there are many other factors to consider related to cost. A nuclear plant requires fewer personnel to operate and maintain it compared to a coal plant. With higher standards and consistent operation, nuclear power plants experience less down time for unplanned maintenance reasons, operating at around 90% of the time for their almost fifty year life. They are also unaffected by an increase in the cost of the fissionable fuel chosen after construction is complete, unlike coal plants that are constantly purchasing and burning more fuel to create electricity. With the decline in supply of fossil fuels, the associated cost is sure to keep rising thereby keeping the cost of energy produced from coal on the rise. Considering these cost savings for the nuclear production of energy, researchers approximate the cost per unit of energy produced to be equivalent to or less than that of a similar quantity of energy produced by a coal plant.

The final area of significant concern with any nuclear reactor is safety. Safety is always a major consideration in the design of any nuclear power plant. The general public has a limited knowledge of the hazards associated with nuclear power, such as radiation and contamination. The media is able to take advantage of this knowledge deficit by exaggerating, as well as not giving a proper quantifiable analysis when comparing a nuclear issue to normal levels of radiation and contamination for the area. For instance, from the years 1969-1986 there were one

hundred eighty-seven mining disasters, three hundred thirty-four oil well fires, and nine dam bursts. Unless personally affected by these disasters, any given person is unlikely to remember them, but the one nuclear accident that happened, Chernobyl, is remembered by everyone [1]. The risks stemming from reactor accidents can be accurately estimated by probabilistic risk analysis. A fuel melt down can be expected to occur once in every twenty thousand years, accompanied by an average of 400 deaths per meltdown. Coal burning alone is estimated to cause 10,000 deaths per year, showing that the dangers associated with nuclear power are grossly exaggerated, and that nuclear power is actually much safer when compared to the burning of fossil fuels [5].

All potential energy sources have inherent risks associated with them. The unavoidable risks of nuclear power deal directly with the high energy byproducts produced from the process of fission itself. During fission, the release of high energy gamma rays can travel long distances through thick layers of material prior to slowing down enough to not pose as large a risk to our health. The irradiation of many different types of materials, within the reactor, causes them to become unstable and radioactive. These materials are known as nuclear waste, and can be especially detrimental to plant employees, the general public, as well as the environment if handled and disposed of improperly.

### 3. Nuclear Waste

The creation of nuclear waste is an unavoidable process in the production of electrical energy via nuclear power. When the materials used to create the reactor, such as iron, nickel, cobalt, and their alloys, absorb a neutron they may become an unstable radioactive isotope of that element. Many of these isotopes are of little concern as they have a half-life that is very short, however when cobalt-59 absorbs a neutron and becomes the highly radioactive cobalt-60 isotope there is concern. Cobalt-60 has a half-life around 5.27 years with a summed, peak gamma emission energy around 2.5 MeV [6]. A half-life is defined as the time that it takes for a given amount of a substance to decay, by the emission of smaller particles and energy, to half of its original amount. The mode of radioactive decay is the release of particles and energy of a substance in the attempt to become stable. The types of particles released are electrons, protons, positrons, neutrons, alpha particles, and high energy electromagnetic waves (gamma radiation) [7]. Each of these particles is a type of radiation that has varying degrees of detrimental effects on the human body.

The unit of measure that compares the amount of damage done to the human body, compared to that of one rad of gamma radiation, it is known as the "rem". The average person receives about 85 mrem worth of exposure a year from natural earthbound and cosmic sources of radiation. To give perspective to the low level of radiation emitted from the Three Mile Island accident for example, individuals in the surrounding area received around 1.2 mrem above their normal background level of approximately 60 mrem/year [8]. No negative effects have been found to occur at an increase in radiation exposure that is this small.

Source	Exposure
External Background Radiation	60 mrem/yr, US Average
Natural K-40 and Other Radioactivity in Body	40 mrem/yr
Air Travel Round Trip (NY-LA)	5 mrem
Chest X-Ray Effective Dose	10 mrem per film
Radon in the Home	200 mrem/yr (variable)
Man-Made (medical x rays, etc.)	60 mrem/yr (average)

Figure 2. Approximate yearly exposure from normal sources [8]

The high temperature cooling water that circulates within the reactor picks up corrosion particles, such as these radioactive isotopes, and carries them throughout the entire system. This causes an increase in the overall radiation levels within the reactor plant. Built-in purification systems, attached to the main cooling water system, function continuously with the cooling medium flowing through a bed of resin beads, filtering out mechanical particulate and removing certain ions from solution. These resin beds lack the selectivity to remove cobalt ions in the presence of ferrous ions due to their similar molecular structure. This leads to a larger amount of waste due to the presence of nonradioactive deposits along with the radioactive ones within this resin. Ion exchanger resin is difficult and very costly to replace. Radioactive waste levels could be significantly reduced if a resin with the ability to select what ions to bind to could be made. The utilization of molecularly imprinted polymers that readily accept cobaltous ions is the answer to this problem.

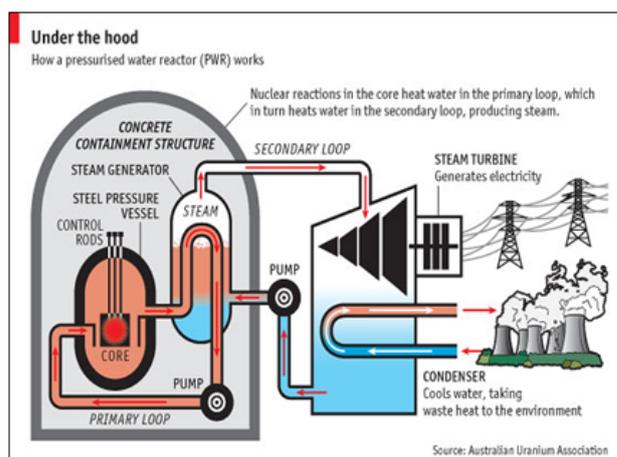


Figure 3. Basic Representation of a Nuclear Power Plant [9]

### 4. Molecular Imprinting

Molecular imprinting is a technique employed by chemists and chemical engineers in order to endow certain desired properties onto a chemical substance. This method is primarily used when attempting to induce selective adsorption characteristics onto a chemical filter and has been shown effective with various types of molecules and

metal ions. There are generally two standard processes used to facilitate molecular imprinting, one of which is a single step process while the other is a two-step process. The single step procedure consists of subjecting a functional monomer—which is a complex made of a polymer and a substance with a low molar mass—the metal salt—also referred to as the template molecule—with which you hope to instill absorption properties—and a cross link monomer are all subjected to polymerization within one container. The two step process differs in that the complex used is first isolated before being subjected to the polymerization process [9]. Before one can begin the polymerization process, the metal salt template and the functional monomer must also be chemically bound to form a complex of their own. The mechanism most commonly used to complete this task is that of relatively weak non-covalent bonding that typically consists of either hydrogen bonds, ionic interactions, or a combination of both. This bonding is controlled by an equilibrium reaction, necessitating a large amount of functional monomer in order to drive the reaction in the desired direction [10]. Once these bonds are in place the polymerization process is able to begin. The most common way of polymerization used to create molecularly imprinted polymers is the chain reaction method. This technique involves the chaining together of many separate molecules in order to create long molecules of high molecular mass, otherwise known as polymers [11]. Once the polymerization process has been completed, all of the components exist as one highly cross linked polymer in solution. The original metal salt template is then precisely extracted from the solution, thus leaving gaps in the forged polymer. These gaps closely resemble the size, shape, and general properties of the template molecule that preceded it. It is this similarity that allows the resulting gaps to act as binding sites for future substances that feature the very same characteristics, enabling the newly created chemical to selectively absorb and react to specific ions in a complicated solution.

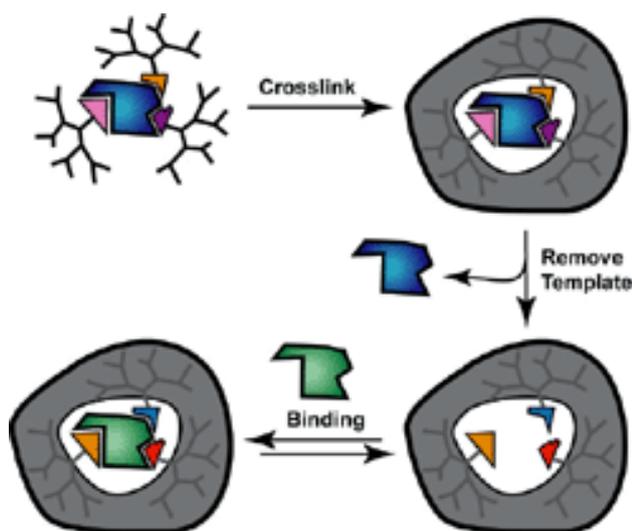


Figure 4. Diagram of the Molecular Imprinting Process [12]

This interaction mimics the method and efficiency of natural receptor interactions while providing further benefits. The process of creating such molecularly imprinted polymers is relatively cheap, allowing them to be a sustainable alternative to using natural receptor

interactions in most filtering processes. Polymers that are conceived in this fashion are also known for their strength and ability to hold together in extreme environments. The functionality of molecularly imprinted polymers has been shown to remain effective over a wide range of temperatures, pH values, and solvent attributes, which is particularly important when considering their application toward nuclear waste management [10].

## 5. Polymer Applications to Nuclear Waste

The selectivity of a molecularly imprinted polymer in the context of chemical filtering specific ions in complicated solution is ideal for the reduction of radioactive waste volume through cobalt extraction and disposal. The most commonly used chemical filters in nuclear reactor decontamination lack a high selectivity toward radioactive cobalt ions. This, coupled with the fact that radioactive cobalt ions are nearly always found mixed with non-radioactive ferrous ions in solution, causes a problem when attempting to manage radioactive waste. The lack of selectivity will eventually lead to the generation of considerable quantities of radioactive ion exchange waste that is troublesome and expensive to dispose. Molecularly imprinted polymers created by the following method were able to show a large selectivity for radioactive cobalt ions, despite the presence of non-radioactive ferrous ions, and displayed adsorption properties efficient enough to reduce the overall volume of radioactive waste by 80-90% [10].

## 6. Template Complex Synthesis Techniques

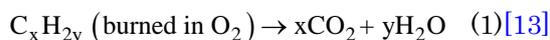
A two-step procedure was used in order to create the molecularly imprinted polymer, meaning that the metal template/cross link complex was synthesized prior to the polymerization process. In order to synthesize the polymer, pure crystals of the functional ligand d [N-(4-vinylbenzyl)imino]diacetic acid were used as the functional monomer in the imprinting process. The pure crystals of d [N-(4-vinylbenzyl)imino]diacetic acid were effectively produced by dissolving 3.99 grams of iminodiacetic acid (approximately 30 millimol) and 2.10 grams of sodium hydroxide (approximately 52.5 millimol), into a 60 milliliter mixture consisting of thirty milliliters of methanol and thirty milliliters of water. Then 4.30 grams of 4-Vinylbenzyl chloride (30 millimol), were added slowly to the solution from a dropping funnel over the course of 30 minutes. This was also done at a constant temperature of 30 degrees Celsius. A second 660 gram amount of NaOH was then added to the solution and was allowed to react for 45 minutes at a constant temperature of 60 degrees Celsius. The solution was then vacuum evaporated to one half of its original volume, and underwent diethyl ether extractions a total of four times. The solution was then diluted to twice the current volume with deionized water, and the pH was decreased to 1.0 by the addition of concentrated hydrochloric acid. The solution was then placed in a refrigerator where the d [N-(4-vinylbenzyl)imino]diacetic acid crystals developed over a twenty-four hour period. Once the crystals were formed they were first filtered, and then washed with ether.

This was all done in an effort to eliminate any potential impurities that may negatively affect the bonding of the monomer to the metal ion template or the polymerization process [10].

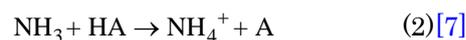
In order to chemically bond the pure d [N-(4-vinylbenzyl)imino]diacetic acid crystals to the radioactive cobalt ion template, two and a half grams of the pure crystals were first suspended in fifty milliliters of water. The pH. of the water was increased to 9.0 through the addition of 1 molar NaOH solution, which allowed the pure crystals to dissolve. A mixture of 1.45 grams of cobalt(II) Nitrate hexahydrate dissolved in one hundred and fifty milliliters of deionized water was added to the mixture of pure crystals and water from a dropping funnel. As the two solutions were being mixed, they underwent a constant stirring process to ensure an equal distribution of the solvent. After the mixing was complete the resultant solution was filtered in order to remove any remaining insoluble pieces. The filtered solution is then freeze dried in an effort to remove any excess water. The resultant substance is mixed with methanol, filtered, and evaporated. The solid obtained is sent through the same process once more, thus forming the complex used in the polymerization process. This intricate reaction procedure is necessary to limit the contaminants in the complex. Contaminants present in your metal template/monomer complex will result in unwanted gaps being formed in the end result. These unwanted gaps decrease the effectiveness of the polymer's selectivity and adsorption abilities, thus every measure is taken to ensure the most pure product is being formed [6].

## 6.1. Elemental Analysis

Elemental analysis is a technique employed by chemists and chemical engineers in order to analyze the elemental composition of an unknown or synthesized substance. The most common way of performing an elemental analysis is the CHN method, which is most useful when dealing with organic compounds such as the molecularly imprinted polymer. An elemental analysis will tell you ratio of present elements in your chemical compound in its simplest form, also known as the empirical formula. For example, The empirical formula for Octane is  $C_4H_9$ , although Octane only exists as  $C_8H_{18}$ . The ratio with which the elements actually exist is known as the molecular formula. The molecular formula is always a multiple of the empirical formula, thus you can determine the molecular formula based on the substance's empirical formula and molecular/molar mass. However, to find the empirical formula of a substance the mass percentages of the elements in that substance must first be determined. When dealing with organic compounds, such as our molecularly imprinted polymer, a sample of the substance is burned to react all of the present carbon with oxygen, forming carbon dioxide ( $CO_2$ ), and all of the present hydrogen to  $H_2O$  by the following reaction:



The mass percentage of Nitrogen is determined by converting it to ammonia. The ammonia can then be titrated with a strongly acidic substance in order to find the amount of ammonia present, and thus the amount of nitrogen present by the following chemical reaction:



The elemental analysis for the polymer showed the following empirical ratios: C, 30.87; H, 3.19; N, 8.05 [6,13].

## 6.2. Determination of Cobalt and Present Impurities

The amount of cobalt present is able to be determined through a procedure known as atomic absorption spectroscopy, or AAS. AAS uses a hollow cathode lamp in order to send a narrow band light source, such as a laser, through molecules or atoms in the gas phase. These atoms or molecules absorb the energy from the light, and are thus excited to higher energy levels. The concentration of the element being measured can then be determined from the amount of energy absorbed [14]. The amount of cobalt present in the sample was determined to be 5.66% [6].

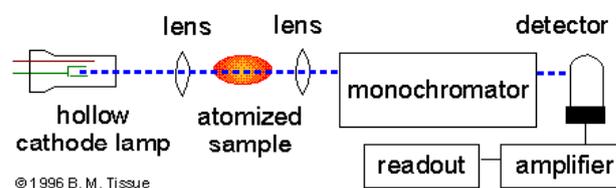


Figure 5. Diagram of Aas Analysis [14]

In order to determine the amount of sodium impurities present a technique known as flame atomic emission spectroscopy, or flame photometry, was performed. In flame photometry, a flame is used to sublimate and atomize the metal in which you are trying to measure; in this case it is sodium present in our polymer. The flame is also able to excite some of sodium's valence electrons to a higher level energy state. As the sodium atoms cool, their valence electrons will return to their original ground energy states, emitting light in the process. A quantitative analysis of the amount of sodium atoms present is possible by measuring the intensity of this measured light. The intensity of the light given off is related to the amount of sodium present by the following equation:

$$I = K * C \quad (3)[15]$$

Where  $I$  represents the measured intensity of light,  $K$  represents a proportionality constant,  $C$  represents the concentration of the metal that is analyzed. The amount of sodium impurities present in the sample was determined to be 13.60%. These results show that the metal template/functional monomer complex was successfully formed; however, there are a significant amount of sodium impurities present [10,15].

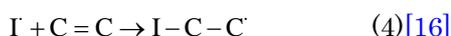
## 7. Polymer Synthesis Techniques

With the metal template/functional monomer complex created, the polymerization process is able to begin. Polymerization is essentially the chemical reaction by which single molecules or monomers are combined to form long chains of the molecules/monomers linked together, otherwise known as a polymer. For the molecularly imprinted polymer the metal template/cross link complex is linked together using the chain reaction

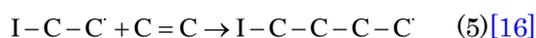
method. The chain reaction method of polymerization requires a certain chemical, referred to as an initiator, to trigger the chemical process. For the molecularly imprinted polymer the initiator used was AIBN. A cross link in reference to a polymer is a bond formed between individual chains of the polymer separate from the bonds holding the polymer chain together. Cross linking bonds are generally not as strong as the bonds linking the individual chains together, but they do play an important role in determining the resulting polymers properties. Generally, a high degree of cross linking grants the polymer rigidity and strength when faced with stressful conditions. This is particularly important to consider when crafting a polymer for use in nuclear waste reduction. The cross linking reagent used in this polymerization reaction is EDMA [6,12].

### 7.1. Polymerization Procedure

180 Milligrams of Bis(vinylbenzyliminodiacetato) cobaltate(II), Which is our metal template/functional monomer complex, is added to a container along with 1.25 grams of EDMA and 15 milligrams of AIBN. The resultant mixture was subjected to three Freeze-Thaw cycles, and then allowed to polymerize at sixty two degrees Celsius for 24 hours. The AIBN initiator is highly reactive, and will quickly react with the Bis (vinylbenzyliminodiacetato) cobaltate(II) to form a new area on the chain that is also reactive. This can be seen by the following general reaction:



The resultant reactive complex will continue to react with neighboring metal template/functional monomer complexes, thus growing in length and forming polymer chains. This can be seen by the following general reactions:



After the 24 hour period was complete, the polymer was cured at seventy-five degrees Celsius for an additional twenty-four hours. The resultant substance was smashed, and then cleaned with methanol in an effort to rid any monomers that had remained unreacted. The resultant substance is then treated with hydrochloric acid in order to extract the cobalt metal ions from the polymer, effectively completing the molecular imprinting process and leaving cobalt shaped gaps in the polymer. These cobalt shaped gaps are then able to recognize and bind to radioactive cobalt ions in solution. The gaps also enable the polymer to display a high selectivity towards radioactive cobalt ions, allowing them to be extracted while the non-radioactive ferrous ions that normally coexist with cobalt are ignored [16,6].

## 8. Radioactive Cobalt Ion Retrieval Analysis

As mentioned previously, the flame photometry study of the metal template/functional monomer complex indicated the amount of sodium impurities to be 13.60%. This is a noteworthy amount of impurity that was factored into the polymerization reaction; however, as shown by

the following analysis, the impurities did not adversely affect the polymers capabilities.

In order to test the polymers ability to filter out cobalt ions in a complex solution in a realistic environment, studies were conducted in the presence of nitrilotriacetic acid (1.4 millimol), ascorbic acid (1.7 millimol), and citric acid (2.4 millimol). The preceding three acids are commonly used complexants during nuclear reactor cleanup, and are thus relevant to the polymer's application. Along with the three acid complexants, the solutions also contained a large excess of ferrous ions (4 millimol), a smaller amount of radioactive cobalt ions (an activity of .8 mCi/l, bringing the total cobalt activity of the solution to 2 $\mu$ Ci). These conditions accurately simulate a typical solution used during nuclear reactor cleanup, and this give an accurate assessment of the polymers capabilities in real world situations. Twenty-five grams of the polymer were then added to this solution and aloud to react until chemical equilibrium was reached. The results of the study showed that the molecularly imprinted polymer was able to extract cobalt ions while completely disregarding any circulating ferrous ion. Using AAs, The total active cobalt extracted from the solution was determined to be 44.0  $\mu$ Ci/g, thus reducing the solution's radioactivity by 55%. For the polymers primary application in nuclear waste disposal, its ability to specifically recognize and absorb cobalt over ferrous iron is more important than its actual capacity for cobalt ion uptake. These results signify that the polymer is capable of selectively extracting radioactive cobalt ions in the presence of a common solution occurring with nuclear reactor cleanup [6].

Once the radioactive cobalt was successfully extracted, the cobalt ions were then removed from the polymer using hydrochloric acid. The desorption process was able to fully remove all bound cobalt ions, and also finished quickly with both .1 molar HCl and .5 molar HCl. The resultant polymers then underwent the same test in order to determine their selectivity for cobalt ions, and their uptake capacity for cobalt ions. Despite being reused for five trials, no appreciable reduction in selectivity or extraction capacity was noted. This adds extra sustainability to the polymer, as it is also reusable [6].

### 8.1. Comparison to Currently Available Filtering Agents

Amberlite-IRC-718 is a commercially available resin with a similar functional monomer to the molecularly imprinted polymer. In order to assess the Amberlites capacity to extract radioactive cobalt ion from solution in comparison the molecularly imprinted polymers capabilities, both substances were subjugated to the same tests. A solution of cobalt ion, ferrous ion, copper ion, nickel ion, and a citrate buffer (used to keep the pH of the solution at 4.8) was prepared. The commercially available resin and the molecularly imprinted polymer were then separately reacted with this solution. The amberlite was able to extract 485  $\mu$ mol/g of cobalt, although it extracted 125  $\mu$ mol/g of ferrous ion as well. The molecularly imprinted polymer, on the other hand, was able to extract roughly 60  $\mu$ mol/g of cobalt ion while completely excluding ferrous ions in solution. Although the commercially available resin was able to extract a significantly larger amount of cobalt than the molecularly

imprinted polymer, the amberlite's level of specificity toward cobalt was not great enough to be of use in nuclear reactor decontamination. This is further exacerbated due to the fact that non-radioactive ferrous ion is present in great excess in comparison to the amounts of radioactive cobalt found during nuclear reactor decontamination. It is this specificity that is absolutely key for making a noteworthy reduction in the volume of radioactive waste [6].

## 9. Potential of Polymer to Reduce Radioactive Waste

During a common nuclear reactor decontamination campaign about 13 Ci of radioactive cobalt activity is removed. The Ci system is a method of measuring the radioactivity present in a given system [8]. A single Ci is a staggeringly large amount of radioactivity, and decontamination of 13 Ci of radioactive cobalt produces a similarly large amount of radioactive waste. Nearly 3500kg of commercial resin is currently required to successfully remove the radioactive cobalt. The cobalt binds to these resins, thus creating 3500kg of solid radioactive waste that still needs to be disposed of. The molecularly imprinted polymer is able to extract 1.1  $\mu$ Ci of radioactive cobalt for every 25mg used. Simple stoichiometry reveals that the amount of molecularly imprinted polymer needed to successfully extract the 13 Ci of radioactive cobalt would be 325kg. Taking into account that the radioactive cobalt ions are a high level radioactive waste, this is a significant decrease. Using the molecularly imprinted polymer, the material that extracts and thus contains the radioactive cobalt could be reduced by 90%. A 90% reduction would result in a much easier storing process, and an overall easier to manage load of radioactive waste [6].

### 9.1. Overview of Sustainability

Sustainability is a broadly defined term that often takes on different meanings depending on the context with which it's used. Sustainability here refers to nuclear power's potential as an alternative energy source and to the molecularly imprinted polymers' potential to alleviate some of the problems concerning nuclear energy. As stated previously, the molecularly imprinted polymer is able to cause a 90% reduction in the mass of high level radioactive waste. Not only does this increase the sustainability of nuclear power, as the waste output is considerably reduced, it is also a cheaper alternative to the commercially available resins currently in use. To capture and extract the same amount of radioactive cobalt only 325 kg of the molecularly imprinted polymer must be used, whereas 3500 kg of a commonly used commercial resin must be used [17]. This decrease in the amount of filtering material needed to extract radioactive cobalt can decrease costs dramatically.

The application of the molecularly imprinted polymer also has the potential to eliminate radioactive ion-exchange waste. Radioactive Ion-exchange waste is formed when commercially available resins are used to filter radioactive particles in solution. Since the resins lack any kind of special selectivity toward the radioactive ions, both radioactive ions and normal ions are absorbed into

the resin. This necessitates a more costly and elaborate disposal procedure that would otherwise not be needed. The molecularly imprinted polymer's selectivity toward radioactive cobalt ions could solve this problem, as it would drastically decrease the amount of radioactive ion-exchange waste. Additionally, the polymer is able to be reused up to five times without any significant decrease in its ability to extract cobalt ions. The polymer can also be cheaply manufactured, making it a viable option for industrial applications [17].

## 10. The Societal Implications of Cleaner Nuclear Power

A survey recently conducted in Europe asked people who live near nuclear reactors if they were either supportive or against the utilization of nuclear power. The study was evenly divided, with 44% of the participants being in favor of nuclear energy, and 45% of them being against it. Of the 45% who were against nuclear energy, 39% of them claimed that if a permanent and safe solution for managing radioactive waste could be found then they would change their minds. In a separate study, people surveyed were found to be more worried by the management of radioactive waste than by the chance of a nuclear reactor accident [18].

The public's perception is an important thing to factor in when designing and implementing new technology. When a large majority of the public's opinion is negative, it can be difficult to perpetuate new technology or solutions despite of their efficiency. Such is the case for nuclear power, whose inherent danger is grossly overstated, and is thus not widely implemented despite of its enormous potential for energy.

Many leading scientists and engineers agree that nuclear power is a relatively safe and reliable means of providing energy for the world. The widespread utilization of nuclear power could not only help bring an end to the energy crisis, but it could also alleviate the negative effects that fossil fuel dependence has placed on the environment. Despite these assertions, the public still remains skeptical of the inherent risks in managing radioactive waste, which thus makes it difficult to increase the widespread usage of nuclear reactors [19]. The molecularly imprinted polymer has the capacity to reduce the amount of high level radioactive cobalt waste by 90 percent of its original amount. A decrease in waste levels of this extent may bear an impact on the public's perception of radioactive waste. If dramatically less waste were to be formed, then the inherent dangers in managing that waste would also decrease, and public perception may become more favorable. The utilization of the polymer to achieve such an outcome would be the first step taken towards mitigating the public perception of nuclear waste management, and possibly the public perception of nuclear power as a whole, thus paving the way for nuclear power to become more widely utilized.

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