

**Appendix D - UNIVERSITY HONORS PROGRAM
SENIOR PROJECT - APPROVAL**

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Purification of an Equipment Decontamination Stream

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Abstract

Industrial processes within the nuclear industry often result in equipment and facilities that are contaminated with radioactive and non-radioactive substances. This contamination hinders the reuse of the equipment and facilities and the recycle of the materials within the system. Cleaning and decontamination operations that remove impurities from a process and safely return the decontaminated solution to the public domain have challenged those in industry for years. The increased interest in the treatment and disposal of decontamination fluids from nuclear facilities leads to the research of a basic decontamination facility. A mobile facility, housed on two flatbed trucks, will be used to remove and properly dispose of contaminants, while recycling as much water as possible. The cleaning solution used to wash the industrial equipment contains detergent, ammonium oxalate, sodium citrate, hydrogen peroxide, and sodium hydroxide. After the solution has decontaminated the equipment, it also contains hydrocarbons (decane), trichloroethylene, cesium, uranium, plutonium, iron, and solid wastes.

In order to purify the contaminated stream, a detailed process must be utilized to ensure that all wastes are appropriately removed and properly handled. First, a simple filtration process removes the large solid particles. The radioactive elements must be removed in the next step in order to prevent further contamination of the equipment. Cesium is removed by a 3M Empore™ cartridge system while plutonium and uranium are simultaneously removed by co-precipitation with iron. The organic compounds, excluding trichloroethylene, can be destroyed using ultraviolet light, oxygen gas, and a titanium dioxide catalyst. Trichloroethylene is removed using a gas stripper, which produces a purified water stream, a water-saturated air stream, and a condensed trichloroethylene and water stream. A decanting process can separate the remaining trichloroethylene from the pure water, allowing the water to be recycled back to the gas stripper. Finally, the last traces of impurities are removed from the stream using an evaporator and an activated carbon bed.

The total capital investment for this project is estimated at \$923,000. This value includes the costs of purchasing and installing the major pieces of equipment, purchasing two flatbed trucks, and installing the controls and instrumentation, the piping, and the electrical wiring. The annual cost of the project is estimated at \$3,332,000. This value is determined by considering the annualized portion of the capital investment over the 15-year life of the plant and any annual operating costs such as utilities, labor, and maintenance. In order to achieve the desired 20% return on the initial investment, customers will be charged approximately \$359,000 per month, a reasonable amount when the sensitivity of the process is considered.

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Purification of an Equipment Decontamination Stream

Introduction and Background

Many industrial processes result in equipment and facilities that are contaminated with various organic, inorganic, and radioactive substances. This contamination hinders the reuse of the equipment and facilities and the recycle of materials within the system. Cleaning and decontamination operations of equipment and facilities have long been common practice, but efforts have been made in recent years to overcome the numerous environmental concerns initiated by the process. Past operations, which made use of organic solvents such as trichloroethylene or perchloroethylene, have given way to more environmentally friendly, water-based cleaning agents comprised of surfactants, or common detergents. Additional concerns have been raised regarding the conservation of clean water because many sites around the world already face a shortage of this natural resource.

Removal of the contaminants is only one part of the decontamination process. Once the contaminants have been removed from the equipment, the contaminated cleaning solution must be properly dealt with so as to ensure public safety. Several possibilities exist including complete disposal of the cleaning solution, recycle of the active decontamination agents, or disposal of only the decontamination agents. The safety of the public's water supply is the dominant factor when considering the alternatives.

The nuclear industry is one such industry that produces many harmful contaminants. Nuclear facilities, such as commercially and governmentally operated reactors, nuclear fuel fabricators and reprocessing plants, and health care establishments, all use radioactive and non-radioactive substances that must be handled properly so as to ensure safety. The equipment must first be cleaned to decrease the level of radiation so that workers may have direct contact for routine maintenance. Radiation exposure to the general public must be maintained at one percent from natural sources; however, workers are legally allowed radiation exposure several times greater. Regardless, the exposure must be suppressed to the lowest possible limits. Additionally, once the equipment has been cleaned, the waste and recycle solutions must be decontaminated so as to ensure that the public's water supply remains unharmed. Although there are limits on the contamination level entering the public water supply, the United States currently has no specification for the amount of radioactivity that is allowed to enter the commercial metal market. Naturally occurring radioactivity is present in most metals, and most European countries allow small percentages of radioactive material in their products.

Therefore, the United States has no control over the situation. This lack of regulation affects the procedure of recycling streams within industrial processes. The determination of appropriate levels of radioactivity is regulated on a case-by-case basis.

The recently increased interest in the treatment and disposal of decontamination fluids from nuclear facilities leads to the research of a proposed process. The system pertains to a generic decontamination facility from which a variety of contaminants are removed. Additionally, decontamination operations do not continue for long periods of time at one particular site. Therefore, a facility with a 15-year life span that can be easily moved from site to site via a flatbed truck is used. The decontamination solution is treated so that the contaminants are removed and disposed of properly, while recycling as much water and cleaning detergents as possible. The amount of solid waste generated will be minimized due to the high cost of disposal, approximately \$1,000 per cubic foot. This high cost is attributed to the TRU classification of the waste. TRU wastes contain more than 100 pCi/g of alpha radioactivity. Further complicating the process is the assumption that the equipment actually used in the mobile cleaning facility will also be contaminated after the decontamination process. It will need to be cleaned before reuse at another facility.

A typical decontamination solution used to clean the equipment contains:

- 200 ppm detergent
- 0.1 M ammonium oxalate
- 0.04 M sodium citrate
- 0.05 M hydrogen peroxide
- 0.2 M sodium hydroxide

The surfactant (detergent) is used to assist in the removal of oily materials and also to hold particles and inorganic contaminants. Additionally, the ligands are present to complex with the radioactive materials. Ammonium oxalate and sodium citrate are the ligands of choice because they are relatively inexpensive, non-toxic, and complex well with heavy metals. The hydrogen peroxide and sodium hydroxide are generally helpful in the decontamination of the equipment.

After the equipment is cleaned with the typical decontamination solution, the following concentrations of contaminants result:

- 200 ppm hydrocarbons (decane)
- 0.1 × saturation trichloroethylene
- 4 ppm cesium
- 200 ppm uranium
- 1 ppm plutonium
- 200 ppm iron
- 1000 ppm solids

The facility is capable of accepting one gallon per minute of the contaminated solution on a 24-hour basis as supplied by the customer. The client collects the material until it enters the facility for processing. All equipment designs for the facility are based on the processing of a 600-gallon batch of contaminated solution. The batches can enter the system in succession with little delay between batches. In other words, more than two 600-gallon batches can be run in a 24-hour day, allowing for maintenance and repairs between runs. The client also supplies a site that has adequate electrical, steam, and cooling water supplies. The decontamination facility operates 24 hours a day for 300 days a year, reserving the remaining days for relocation. Employees of the decontamination facility work 12-hour shifts for a total of two shifts per day. Ten hours of each shift are paid, with the remaining two hours set aside for meals and breaks. The employees work for four straight days with three days off for rest and relaxation. Overtime pay is based on the number of hours worked per week in excess of 40 hours.

The entire facility is placed on two flatbed trucks and will remove 99% of the contaminants before the solution can be reused in any manner. The following scheme allows for these and the previously mentioned specifications.

The solids and radioactive particles present in the stream must first be removed so as to simplify the remainder of the decontamination steps. A simple filtration process removes the larger solid particles. The radioactive particles, cesium, uranium, and plutonium are then eliminated so as not to contaminate the rest of the equipment. The cesium is removed using a 3M Empore™ filter cartridge. The cartridge not only eliminates more than 99% of the cesium from the stream, but it allows the entire cartridge containing the radioactive material to be disposed of as solid waste. Plutonium and uranium are removed by co-precipitation with iron(III) ions. The two radioactive elements are filtered simultaneously and form a solid cake that is removed as waste.

Any organic materials and trichloroethylene remaining in the stream must also be removed to ensure that the water is decontaminated. The surfactant, the organic compounds other than trichloroethylene, and the iron can be destroyed or complexed using ultraviolet light and hydrogen peroxide. Additions of air and titanium dioxide increase the speed of the reaction and drive it to completion. Carbon dioxide and nitrogen gases are the main byproducts of the reaction, and they are simply released into the atmosphere. The iron reacts with oxygen to form iron oxide compounds that are filtered out in the next step. The trichloroethylene is removed by a gas stripper, which produces a water-saturated air stream, a purified water stream, and a stream of condensed trichloroethylene and water. A decanting process can separate the trichloroethylene and water. The denser organic is removed from the bottom of the separation tank and the clean water is recycled into the gas stripper.

Finally, the water is further cleaned so as to ensure that the desired specifications are met. The remaining purified water from the gas stripping process is passed through an evaporator and a condenser. Before it is recycled, the water enters an activated carbon bed that removes most of the remaining contaminants. Only small traces of the original contaminants are present in the recycle waste stream. All wastes are disposed of properly, so as to affect the environment as little as possible. The entire decontamination process is shown as a schematic diagram in Figure 1.

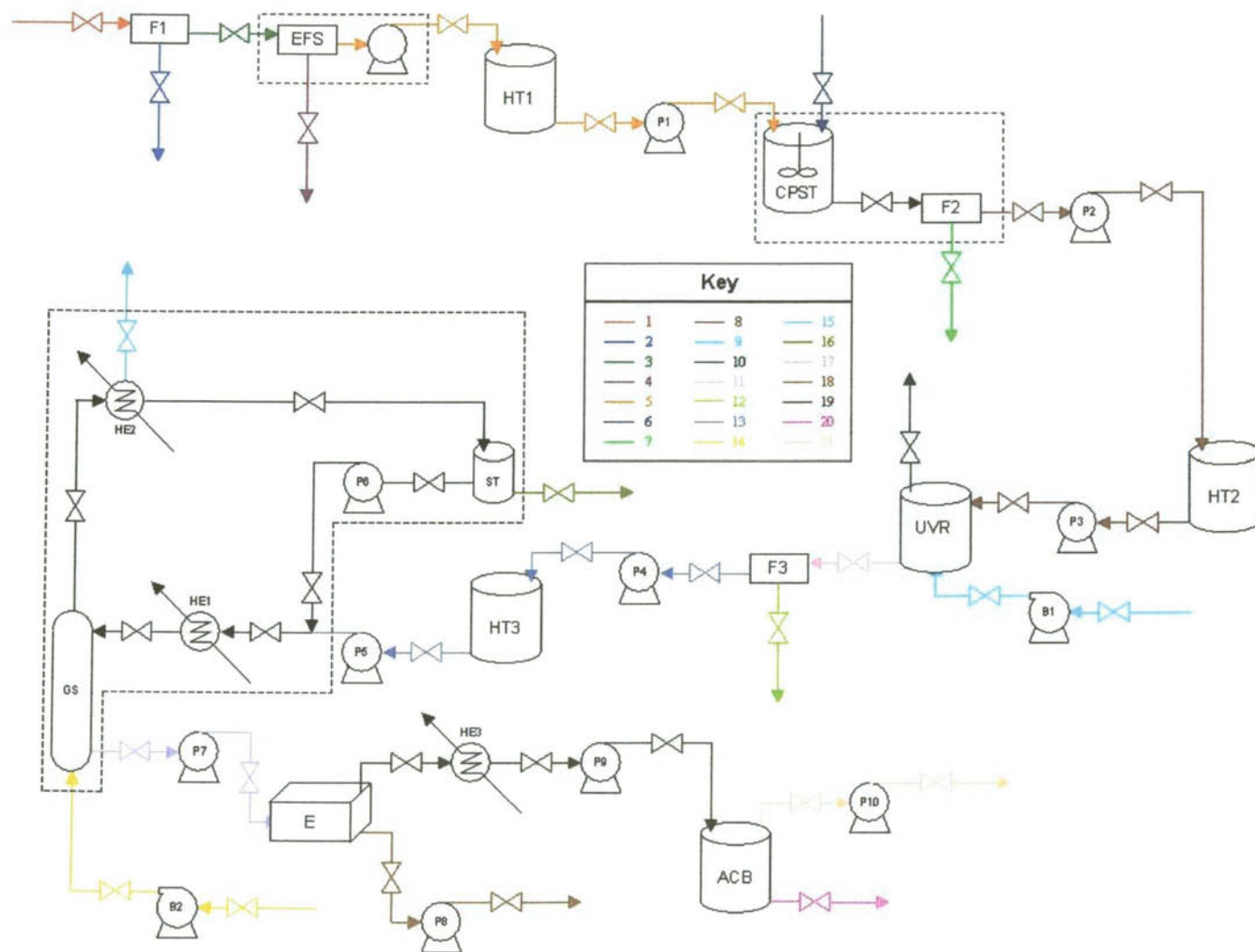


Figure 1. Process Schematic for the Purification of an Equipment Decontamination Stream

Process Description

Removal of the Solids

To begin the decontamination process, the contaminated stream passes through a \$28,556, 2-ft² filter that removes the majority of the solids (Peters, 1980). The solids exit the filter in the form of a cake comprised of 50-wt% solids and 50-wt% water. After this introductory step is complete, more complicated processes and more expensive pieces of equipment are needed to continue the decontamination of the stream.

Proposed Methods for the Removal of Radioactive Materials

As mentioned, the most dangerous contaminants from a nuclear plant are those that are radioactive. Cesium (Cs), uranium (U), and plutonium (Pu) are all radioactive elements that are present in the system, and they must be removed. Complete removal of these materials is extremely important due to the harmful effects that they can have upon humans. When choosing one of the alternatives that is available for complete removal of the radioactive materials, careful consideration must be given to the cost and time requirements of the process.

Several methods for removal of each of the three radioactive contaminants were studied before choosing the final method. A commonly used method for the removal of radioactive substances is ion exchange. However, ion exchange generates large waste volumes if there is a high concentration of the target ion, poor selectivity, or a poor regeneration procedure. Specifically, when ion exchange is used to remove radioactive materials, the sorbates quickly become saturated, thus generating a large amount of solid waste. Therefore, additional disposal costs are created.

For ion exchange to be effective in the removal of the radioactive elements, the correct ligand for complexing with each element must be found. Research in the past has pointed to crystalline silicotitanate (CST) for the removal of Cs. CST has been found to complex with Cs and has proven to be a useful resin in the ion exchange process. In this process, the average particle size for CST is $409 \pm 109 \mu\text{m}$, with an average moisture content of 14% for a dried pellet. The ion exchange capacity of Cs using CST is 0.8 meq/g per 50 g. Once the ion exchange has occurred, the complexed ligand can be easily removed by filtration. However, CST is an insoluble ligand and is most effective in packed beds, which are often extremely large and difficult to transport. Additionally, the CST cannot be recovered from the process, causing material to be purchased and vitrified each time the packed bed is loaded. Finally, an equilibrium mixing time of 100 hours is required, creating a bottleneck in the process. (Bostick, 1998)

Another ligand considered for ionic exchange was ammonium molybdophosphate (AMP). AMP is known to be an extremely selective sorbent for removing Cs from waste streams over wide ranges of acidity and salinity. It also has rapid loading kinetics. Cs can be eluted from AMP using an ammonium salt solution. However, AMP cannot be used in solutions with a pH greater than seven because it will decompose. The pH of a solution can be altered, but another problem encountered with AMP is that it is only selective for Cs. (Collins, 1998)

Zirconium monohydrogen phosphate (ZrHP) is also an effective sorbent for removing Cs, U(VI), and Pu(IV) from streams of low ionic concentrations. However, the solution in question contains Pu(VI). Therefore, in order to use ZrHP, the Pu(VI) must be neutralized and reduced to Pu(IV). If used, this process would create additional procedures, costs, and equipment. (Collins, 1998)

Another resin, 1,2-HOPO, has shown excellent sorption ability for Pu(IV) in nitric acid solutions. It has the ability to bind to Pu(IV) in the presence of competitive metal ions. Pu(IV) extraction using 1,2-HOPO is possible even in solutions with a 100,000-fold excess of iron(III), which is one of the most competitive ions with Pu(IV) sorption. Because such a large amount of iron(III) would need to be added to the process, this choice would not be economically feasible. (Romanovski, 1998)

Finally, diphonix was considered as a complexing agent because it is excellent for complexing with ions in acidic solutions. However, the presence of oxalate and citrate in the solution make the complexing of ions by any resin more difficult. Research has shown that few, if any, resins are able to complex with the ions from the oxalate. (Alexandratos, 2000)

The last option for the removal of radioactive substances that was explored and discarded is the removal of uranium by extraction through a filtration process with hydrogen peroxide (H_2O_2). Uranium can be filtered with H_2O_2 in acidic, alkaline, or neutral conditions when complexed with citrate, thus making it soluble. Neutral conditions with a pH of 4-5 at 25°C are the most economical situations. This process makes use of the least amount of H_2O_2 compared to the other discarded options; the ratio necessary for precipitation is 0.121 kg H_2O_2 / kg U_3O_8 . Once H_2O_2 is added, uranium peroxide (U_3O_8) forms and precipitates, and the excess H_2O_2 is released from the complex and remains in solution. Complete precipitation is obtained in a few hours using a normal batch filtration process with typical filter paper. The precipitate can be dried easily because it contains only 15% free water. Several problems, including lowering the current solution pH of 11.4 by the addition of an acid to reach the optimum operating conditions, would need to be addressed. Additionally, the several hours required for the reaction to occur would hinder the flow of the rest of the process. (Cahill, 1990)

Cesium removal by Species-Selective Filtration

After careful consideration and research, the Cs is removed using a 3M Empore™ filter cartridge. Empore™ cartridges are spiral wound filter cartridges that incorporate element selective particles to separate, collect, and concentrate target radioisotopes on the sturdy, porous membrane. The particles are tightly held together within an inert matrix of polytetrafluoroethylene (PTFE). A ratio of 90% sorbent to 10% PTFE is usually chosen. The effective sorption leads to high chemical recovery of the target radioisotope. During use in the field, with Cs-137 at levels of 0.09 mCi/L and 'cold' Cs concentrations of 0.15 ppm, individual cartridges processed in excess of 10,000 gallons of solution with no breakthrough of Cs. (Scanlon, 2000)

Counting efficiencies are also high with the Empore™ technology due to the large concentration of the target radioisotope in a shallow surface layer of the cartridge. Normally interfering substances simply pass through the process and remain in the filtrate. The captive-particle medium prevents channeling of liquids and insures uniform flow across the sorbing particle surface. Additionally, greater separation efficiencies can be realized at higher flowrates than in a normal column system. The cartridge installs easily, provides convenient replacement, and facilitates clean, simple disposal of reduced volume solids. (3M, 2000)

Studies have shown that separations using Empore™ technology are substantially less expensive than those using column or reverse osmosis systems. Tom Scanlon of 3M provided a rough estimate of cost and performance for a one to two gallon per minute portable cart-mounted system for Cs removal. The fully assembled capital equipment, including cart, pump, filter housings, valves, and gauges, costs a mere \$5,000. The three-inch by ten-inch cartridges can hold a capacity of 650 gallons of 4-ppm total Cs concentration to become fully saturated. Active Cesium Removal Cartridges cost \$1,000 per cartridge, which amounts to approximately \$1.54 per gallon of solution processed. To ensure that the capacity is not exceeded, only 600 gallons of solution will be passed through the cartridge before it is discarded. Also, because of the proven, outstanding performance of the cartridge, Cs is absorbed within the cartridge at 99.99%. For the purpose of material balance calculations, 100% absorption will be used. (Scanlon, 2000)

Removal of Plutonium and Uranium by Co-Precipitation with Fe(III)

Following the Cs removal, the remaining solution is held in a 734 gallon holding tank. The tank, five feet in height and five feet in diameter, costs approximately \$42,968 (Douglas, 1988). The solution is then pumped at two gallons per minute to a 734-gallon co-precipitation stirred tank (CPST) in order to remove the remaining radioactive elements. The pump costs \$10,470 (Peters, 1980), and the CPST costs an additional \$42,968 (Douglas, 1988).

The addition of iron (Fe) to alkaline solutions containing Pu and U is a known method of treatment for the removal of these radioactive elements in waste solutions. This method is commonly referred to as co-precipitation, the phenomenon whereby a metallic ion at low concentration is removed from solution by adsorption, occlusion, or inclusion with a freshly precipitated solid phase of a different metal. The species is removed from solution even though the solubility is not exceeded. This method is extremely fast and inexpensive. It also successfully achieves simultaneous removal of Pu and U. (Hobbs, 1999)

The amount of Fe(III) necessary to precipitate the Pu and U can be found by using a distribution coefficient. The distribution coefficient is the concentration on the solid (in g of Pu or U per g of Fe) divided by the concentration in the solution (in g of Pu or U per L of solution). The same distribution coefficient can be used for both the Pu and U and is assumed to be 100 L/g. An additional assumption is made that the available Fe consumes all of the citrate and surfactant to ensure that a suitable precipitate forms. This assumption allows the effects of the surfactant and citrate on the Fe precipitation to be ignored. (Watson, 2000)

Ferric nitrate (FeN_3O_9) is the source of Fe(III), and is sold at \$64 per 500 g (www.pfaltzandbauer.com, 2000). The addition of 3.896 pounds of ferric nitrate is needed to precipitate 90% of the 0.9988 pounds of U and the 0.004994 pounds of Pu. Therefore, each pass of 600 gallons of solution requires \$226 of ferric nitrate. A 2-ft² filter, priced at \$28,556, is used to perform the filtration (Peters, 1980).

Removal of all Organic Compounds (excluding trichloroethylene)

Following the filtration process, the remaining solution will be pumped at two gallons per minute into another 734-gallon holding tank. Organic compounds remaining in the solution are the next set of compounds to be removed.

There are several ways to remove organic compounds from a wastewater stream. The most popular of these methods are to strip them from the stream according to their volatility, to adsorb the organics onto activated carbon, or to destroy the organics through oxidation. Due to the nature of the waste stream, boiling the organics out of the water is not an option. The waste stream contains a surfactant, which would foam in a distillation column, thus reducing or eliminating the ability to separate the organics from the wastewater stream.

Initially, adsorbing onto activated carbon seems to be the best option. The activated carbon would remove both the organic compounds as well as the surfactant. Also, it would remove any high valence uranium still in the stream. However, this process would make the activated carbon a radioactive waste by-product due to the build-up of these uranium ions. Most companies will not regenerate the material, so it would have to be disposed of it as hazardous

waste. Should a company be found that is willing to regenerate the carbon bed, the waste stream from the regeneration process would have to be disposed of as hazardous material. This added expense would be billed to the owner of the carbon bed as part of the regeneration costs. These considerations leave oxidizing the organic compounds as the only option for further consideration.

Research indicates that the surfactant as well as the organic compounds within the wastewater stream can be destroyed using a combination of H_2O_2 and ultraviolet (UV) light. The use of a catalyst such as titanium dioxide (TiO_2) improves the speed of the reaction. The UV light combined with the TiO_2 , or a similar catalyst, speeds the dissociation of the H_2O_2 molecules into hydroxyl radicals, which in turn react with the organic compounds and the surfactant. The hydroxyl radicals attack the organic compounds by breaking the bonds between carbons and between carbon and hydrogen atoms. Therefore, smaller carbon alcohols are created, which are further attacked by the hydroxyl radicals, eventually resulting in the formation of carbon dioxide (CO_2) and water (H_2O). The rate of this reaction is further increased through the use of air or oxygen gas, which will also drive the reaction to completion. It is assumed that the trichloroethylene (TCE) is not destroyed in the reaction. This assumption will be explained at a later time.

In the case of the surfactant, a phosphorus-based detergent, such as Tide[®], is assumed to be used. The carboxylic end of the surfactant chain will react with the hydroxyl radicals as detailed previously. The phosphorus atom has the possibility of reacting with hydroxyl radicals to form phosphorous acids. This formation is in minute quantities for several runs, and the affect on pH will be negligible due to the amount of sodium hydroxide (NaOH) present in the stream.

Correlations were made between the laboratory research found on UV reactions and the scale of an industrial process. Due to the great concentration of contaminants in the wastewater stream, it was determined that a larger wattage UV lamp system was necessary to completely destroy both the original organic compounds and the intermediate compounds. This increased power also helps keep the rate of reaction high. The use of air slows the reaction rate when compared to the use of pure oxygen gas. (Winterbottom, 1997)

In order to begin the hydrocarbon destruction with UV light, the solution is pumped at 20 gpm into the reactor. The five-feet by five-feet, 734 gallon reactor costs \$42,968 (Douglas, 1988), with an additional \$20,941 for the 20 gpm pump (Peters, 1980). The UV light requires large amounts of electricity. Processing 600 gallons of solution with a concentration of 23 g/L requires 5225.6 kW of electricity, resulting in an electrical cost of \$1,684 for one batch (Winterbottom, 1997). Additionally, a blower, at a cost of \$11,713, adds air at a flow rate of 231.8 ft^3/min into the system to complete the reaction (Peters, 1980). 2.492 lb (1130 g) of TiO_2 are also added at the cost of \$66.97 per 25 g, for a total

catalyst cost of \$3,028 per year (Alfa Aesar, 2000). It is assumed that the catalyst is replaced annually because of possible poisoning or deactivation.

Once the reaction has gone to completion, CO_2 and nitrogen gas escape from the unit. TCE, nitrate (NO_3^-), NaOH, iron oxide (Fe_2O_3), sodium ions, and ammonia (NH_4^+) continue through the process. After passing through a 1.5 ft², \$22,845 filter, the Fe_2O_3 is extracted from the solution (Peters, 1980). The remaining solution is then pumped at 20 gpm into a 734 gallon holding tank, before being pumped at one gallon per minute to the TCE-removal step.

Removal of Trichloroethylene by Gas Stripping

TCE is the compound that is used to remove grease from contaminated equipment. It is a toxic chemical and is not often used in industry at present. There are three main options to be considered for the removal and/or destruction of this material. The compound can be reduced and dechlorinated in solution, resulting in hydrochloric acid and alkanes. One of the compounds that is often formed in this process, however, is vinyl chloride, which is a potent human carcinogen. A second method for removing the TCE from a contaminated solution is through a gas stripper. TCE has a boiling point of 86.7°C, is only slightly soluble in water, and is more volatile than water; thus, it could be removed from the aqueous solution with air in a gas stripper. This method, however, is not often used in industry. The current trend is to remove TCE through bioprocessing. This method is too complicated and expensive to be used for the given circumstances (bioprocessing is only cost effective in extremely small, laboratory scale processes). Thus, stripping seems to be the best option until more research is completed.

(www.labmed.umn.edu/umbbd/tce/tce_map.html, 2000)

Several assumptions were made in the design of the gas stripper. Its placement in the general design of the process is after the UV reactor. In this process, it is assumed that all of the compounds with any organic components are destroyed in the reactor *except* for the TCE. This may seem like a gross assumption, but it was made with good intentions. If TCE is removed via stripping before the reactor, the detergent in the solution causes a terrible problem in the stripper. The detergent has a tendency to foam, thus making the separation nearly impossible. If the TCE is destroyed in the reactor, the hazardous vinyl chloride that was previously mentioned is created. This creation is to be avoided at all costs. Thus, the assumption is made that the TCE remains in solution following the UV reactor, and it can be removed by gas stripping in the next step.

The design of the stripping equipment was determined using the software program HYSYS. Such a program has limitations, but can easily provide an estimate for the design of the process. By assuming a system of only TCE, air, and water, a stripping tower was simulated. All other ions are considered to have

the properties of water since they are not stripped with the TCE into the air. Not only did HYSYS provide estimates for the material balances of the components, but it also provided design parameters such as the number of stages required in the stripper. By heating the entering stream to 150°F with 15-psig steam, the resulting stripping tower could remove over 98.7% of the TCE in solution in just two theoretical stages. Due to tray efficiencies and other such factors, three operating stages were chosen. To size the tower, a spacing of two feet was allotted for each the trays with an additional two feet being added for the end caps of the stripping tower, for a total height of eight feet. A diameter of two feet was chosen using an empirical correlation (Douglas, 1988). These were the only two dimensions necessary to find the installed cost of the tower. The installed cost of this major piece of equipment in the process was calculated to be \$23,585 (Douglas, 1988).

The gas stream that leaves the top of the tower is cooled/partially condensed to 75°F. Resulting is an air stream that is saturated with water and a liquid stream that contains TCE and water. The air stream is allowed to exit the system into the atmosphere. The liquid stream is fed into a small separation tank that acts as a decanter where the liquid separates into two components. This tank has a control scheme that allows the denser TCE to flow out of the bottom and to be taken to waste (with very little water accompanying it). The aqueous layer is siphoned off the top and recycled back to the stripper for further purification.

Purification of the Water

After the removal of the TCE, the remaining liquid solution from the bottom of the stripper is pumped through a \$9,519, one gallon per minute pump into a 375 gallon evaporator (Peters, 1980). The \$17,995 evaporator is 6.1 feet in length, 6.4 feet in height, and has a depth of 2.9 feet (www.equipmentmanufacturing.com, 2000). A photograph of the evaporator is included as Figure 2. Water is pumped out of the evaporator at 0.1 gpm. This small piece of equipment costs \$7,615 (Peters, 1980). The exiting vapor is then passed through a 65-ft² heat exchanger, priced at \$32,137 (Douglas, 1988). The final remaining solution is pumped at 0.9 gpm into a \$3,645 activated carbon bed (www.trorderonline2.thomasregister.com, 2000). The pump requires an expenditure of \$9,138 (Peters, 1980). The bed, 5.5 feet high and 4.5 feet in diameter, further removes any impurities that are left in the stream (www.trorderonline2.thomasregister.com, 2000). The activated carbon in this bed is \$14.20 per cubic foot and is replaced every 30 days (Douglas, 1988). Replacement more often is not necessary because of the small quantities of contaminants passing through the bed. Also, regeneration with steam is not a possibility because of the hazards associated with releasing even the smallest amounts of TCE into the environment. The pure water stream leaving the bed is then pumped at 0.9 gpm to the public water supply or to the plant of origin. The

solids that are collected as waste throughout the process are buried in concrete at the cost of \$1,000 per cubic foot.

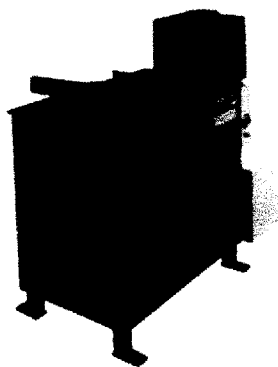


Figure 2. The WATER EATER Wastewater Evaporator Model 375G

Ground Transportation

In order to make the process mobile, all of the decontamination equipment will be placed on the trailers of two flatbed trucks. The equipment can remain on the beds throughout the process, allowing for ease of mobility to the next location. The placement of the equipment on the trucks can be seen in Figure 3. The price of a standard fleet tractor with a sleeper is approximately \$86,000. The tractors can range from approximately \$78,000 to \$110,000. The flat bed trailer has a standard length of 48 feet and a standard width of eight feet six inches. The thickness of the trailer bed is normally three to five inches, and it sits 48-52 inches off the ground. Standard trailer beds are made of steel and cost \$18,000; however, lighter aluminum beds can be purchased for \$22,000. Because aluminum trailers are lighter, they can carry 2,000 pounds more than steel trailers. Due to the extreme weight of the process under consideration, an aluminum bed is preferred. Additional accessories, such as a wire frame over the flatbed to apply a tarp, winches, and special fasteners can be added for a mere \$4,000. These additions are definitely needed for stability while moving the process to different sites. (Christian, 2000)

Specialty trailers for such uses as the hauling of bridge expansions that are extremely long can be purchased and would provide extra space for the process, but they require permits, escorts, and extra insurance. Therefore, two standard aluminum trailers will be adequate for the process. The total capital investment in the two tractors and corresponding trailers is \$224,000.

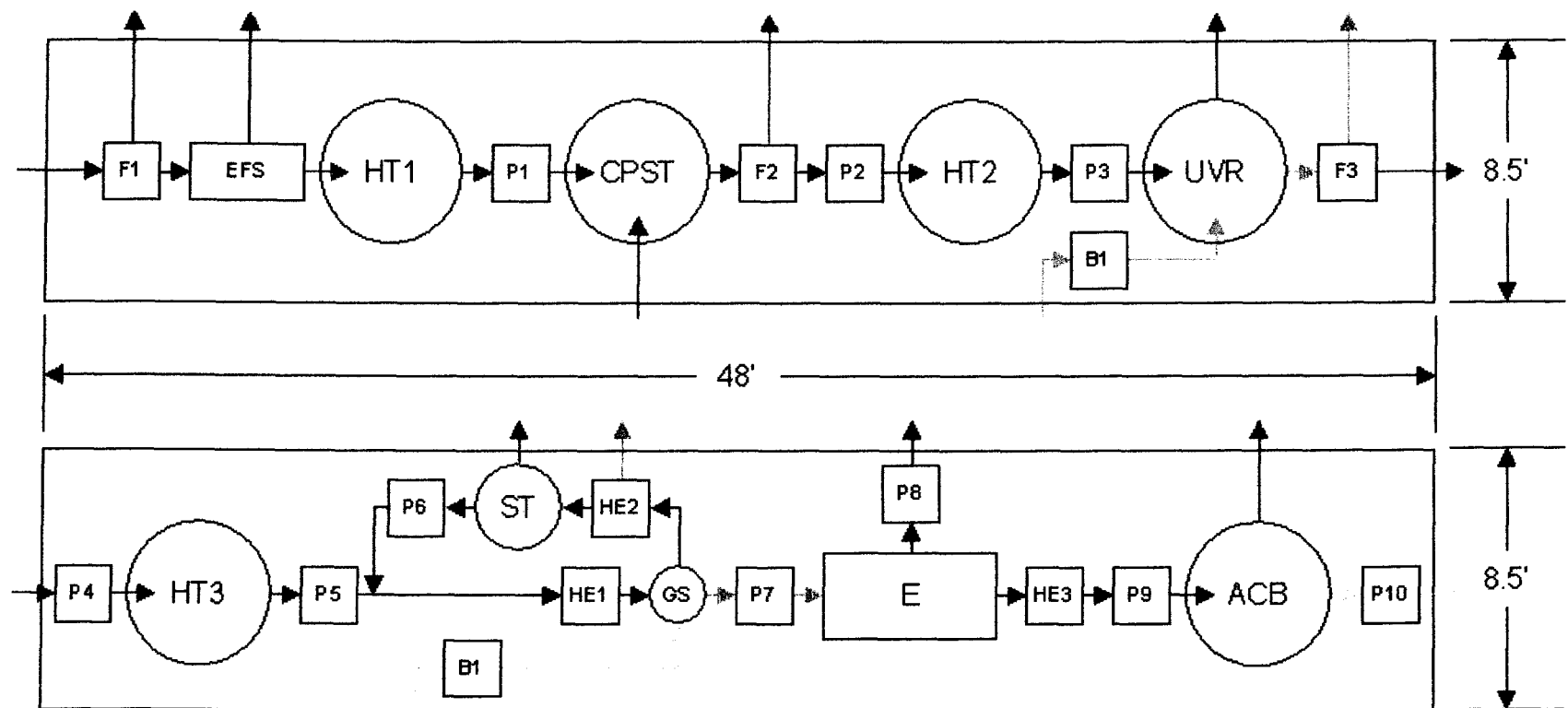


Figure 3. Position of Equipment for Ground Transportation

Cost Estimate Results

There are many ways to decontaminate a cleaning solution from a nuclear power plant. The feasibility of the design presented is based primarily upon the costs associated with achieving a 99% pure water stream. Also, the price charged by the company for rendering its services in order to make the desired return on its investment is an additional concern that must be considered.

The fixed capital investment is found by taking the sum of all of the purchased and installed costs of the various pieces of equipment. As described previously, each major piece of equipment, including the trucks required for transportation, was sized and the purchased and installed costs were determined. These sizes and costs are summarized in Appendix B, Table 4, and the sample calculations are found in Appendix C. In addition to the installed costs of the major pieces of equipment, the costs of the controls and instrumentation, the piping, and the electrical wiring were also included in order to find the total fixed capital investment. These costs were found using scaling factors from literature sources. The factors are percentages of the capital investment for the major pieces of equipment. The various factors are listed below in Table 1. The factors listed are the average values for the ranges given in the literature. These calculations can be found in Appendix B, Table 4 and Appendix C. The total fixed capital investment for this project was found to be \$923,000.

Table 1. Scaling Factors for Capital Investment Costs

Auxiliary Capital Costs	Factor
Piping	13.0%
Instrumentation and Control	4.75%
Electrical Equipment and Materials	5.75%

In order to determine the costs and revenues for the annual operation of the plant, the annualized cost of the capital investment was found. The capital recovery factor, at an interest rate of 10% over the 15-year project life, was used. The depreciation was calculated using the Sum-of-Years Digits (SYD) formula. It was assumed that the process equipment had a 9-year depreciable base because this is typical for most engineering process equipment. The calculation of depreciation was needed so that the tax benefit associated with it could later be calculated.

Besides the capital investment and depreciation, it is important to know the annual operating costs of the process. Included in the annual operating costs are the utility costs, waste disposal, maintenance, the cost of the material and replaceable equipment required by the process, and labor and salary expenses. The general utilities, maintenance, and supervisory costs were calculated using factors based on the revenue or the capital investment. These factors are listed in Table 2. The maintenance and supervisory salary factors are averages of the ranges given in the literature. The general utilities expense factor, however, was chosen from the low end of the range because it is anticipated that this process consumes far less utilities than most processes. Only the electricity cost required by the UV reactor is calculated separately from the other utilities costs because it is anticipated that this piece of equipment will have a substantial and consequential cost associated with its operation. The electricity requirement cost for this reactor was calculated from the design requirement and an average price of electricity from a national power supplier's web site. In choosing this price, it was assumed that the large permanent plant at each site consumes enough energy so that the charge for additional energy falls into the highest demand category.

Table 2. Scaling Factors for Operating Expenses

Expense	Factor
General Utilities	5.00%
Maintenance	4.00%
Supervisory Salaries	12.5%

Additional operating costs include the expenses of waste disposal, labor and overhead, and the materials used. The labor and overhead expense was calculated based on the premise that the plant uses twelve-hour shifts with two workers working each shift and with two shifts per day. The hourly wage for these workers was taken to be \$30, which includes both the base salary and any additional benefits such as insurance, vacations, and holidays. The labor expense is calculated based on year-round employment because of the start-up, shutdown, and transportation of the equipment that occurs in addition to the 300 days of operation per year. It is assumed that only one supervisor's salary will be required each year. This assumption means that either two supervisors from other areas of the plant can alternate the oversight of this project or that one supervisor can be solely responsible for the process. If the second option were used, one of the other workers would serve as a foreman in the absence of the salaried supervisor. The waste from the process is disposed of by an outside contractor at a cost of \$1,000 per cubic foot of waste material. It is assumed that the density of the material going to waste from this process is two grams per cubic centimeter. The operating materials costs were calculated based on

manufacturers costs for the TiO_2 (\$66.97 per 25 grams), the activated carbon (calculated from a correlation in Douglas), the ferric nitrate (\$64.00 per 500 grams), and the replacement Empore™ filters (\$1,000 per filter).

The total annual operating cost of the process is the sum of the utilities, maintenance, waste disposal, materials, labor, and salaries expenses. The total annual operating expense for the purification of an equipment decontamination stream is approximately \$3,211,000. This total, and all of its component costs, can be found in Appendix B, Table 5.

The price charged by the company for providing the equipment and service is the other important factor when choosing between competitive process designs. The price that the consumer is charge should create a 20% return for the company in this particular case. The value was found by taking the present value of the after tax cash flow (ATCF) at a rate of 20%. The ATCF is the gross revenue after taxes less the total expenses after taxes plus the tax benefits from depreciation. Since the revenue is a variable, a trial and error solution is used in order to make the total present worth of the ATCF over the 15-year life of the project, including the initial capital investment, equal to zero. The resulting annual revenue amount was determined to be \$3,589,000.

Discussion

The fixed capital investment for the purification of an equipment decontamination stream is approximately \$923,000. Additional operating costs totaling \$3,211,000 per year are incurred throughout the process. In order to achieve a minimum attractive rate of return of 20% on the initial capital investment, the customer is charged \$3,589,000 per year, or \$359,000 per month for the ten-month per year profitable duration of the project. Because decontamination operations are usually performed in unique situations, it is difficult to compare the monetary values associated with the process to examples from literature. Therefore, the price that a customer is charged must be considered reasonable unless information is presented that proves the opposite to be true. Nuclear clean-up operations are often multi-million dollar projects; however, the costs incurred often stretch into the billions of dollars. These high cost procedures can also result in illness and death if proper precautions are not taken. Because of the great dangers associated with such undertakings, the government levies numerous Environmental Protection Agency (EPA) regulations. If companies are found in violation of these regulations, the EPA can administer large fines and other serious consequences. Therefore, when the sensitivity of the process is considered, a charge of \$359,000 per month is considered a reasonable price to pay in order to ensure proper decontamination and disposal of hazardous materials.

The process described in this report successfully removes over 99% of the contaminants present; however, different approaches to the design do exist that could reduce the costs and increase the efficiency of the plant. For example, cesium is known to be the most dangerous and most difficult substance to remove from the solution. As expected, the removal of the cesium is one of the most costly procedures in the process. Other alternatives were explored that could have reduced the costs associated with cesium removal; however, all indications pointed to the 3M Empore™ filter as the most efficient and effective method for cesium removal. Other alternatives, such as ion exchange, would create higher capital equipment costs and would generate larger amounts of solid waste.

The greatest cost associated with the process is the destruction of the organic substances using ultraviolet light. Therefore, this step of the process should be explored in greater detail so as to determine ways to reduce the cost and/or increase the rate of the reaction. Because the pH of the solution has a direct effect on the rate of reaction, an acid could be added that would decrease the pH, speed the reaction, and lead to additional costs for the process. The costs of making such an addition should be weighed against the benefits associated with increasing the rate of the reaction. Also, it is debatable whether or not the ultraviolet light supplied to the reactor is sufficient to support the

reaction because the equipment requirements were scaled up from a laboratory procedure. The amount of electricity required for this operation is the largest operating expense of the process due to the results for the amount of ultraviolet light required. Finally, the capital cost of the reactor is determined using one of Guthrie's correlations that is found in Douglas. This estimate is not entirely accurate because the purchased and installed cost of the reactor should be greater than that of a general reactor. The ultraviolet reactor contains much advanced technology such as the lights, the agitator, and the method for adding the gaseous stream.

The most grandiose assumption made in the design is that the trichloroethylene is not destroyed in the ultraviolet reactor. This assumption was made so that the possibility of the trichloroethylene forming vinyl chloride in the ultraviolet reactor would not have to be addressed. Vinyl chloride has been proven to cause cancer in humans. However, if there were some method in place to monitor and contain the amount of vinyl chloride produced, the entire gas stripping operation could be eliminated from the process, thus decreasing the total costs associated with the plant. Removal of the trichloroethylene prior to the ultraviolet reactor was also considered as a viable option; however, detergent is present in the system that would prevent the use of columns or beds because of the possibility of foaming.

The evaporator that is used to further purify the water stream requires a slow flowrate or a batch process and is powered by natural gas. A faster flowrate would allow the section of the process after the last holding tank to be idle for a period of the day, thus decreasing the power requirements for the plant. Further investigation could lead to an evaporator that is able to process water at a faster flowrate using an alternative power supply. Such a change could lead to a decrease in the costs associated with this operation.

Many assumptions were made when costing the capital equipment and operating expenses that could have lead to different results. The transportation equipment comprises the largest portion of the initial capital expenditure; therefore, the equipment that is used to actually purify the decontamination stream is relatively inexpensive and more than likely priced below the actual costs. Also, scaling factors were used to account for the piping, the instrumentation and controls, the electrical equipment and materials, the general utilities, the maintenance expense, and the salaries expense. These estimates result in costs that are not completely accurate. Actual calculations, especially for the general utilities, the piping, and the salaries, would have yielded a more accurate estimate of the total costs associated with the project.

One of the major expenses of the process is the disposal of the solid wastes that are generated. An external company will charge approximately \$1,000 per cubic foot to dispose of the wastes in an appropriate manner. The waste disposal expense is \$101,000 per year, or 3% of the total costs associated

with the project. This estimate does not include the small mass of the Empore™ filters that must also be properly discarded. Even though the filters weight only a few ounces each, omission of the disposal costs result in a lower total cost for the process. Additionally, all other filters that are used in the process are assumed to last the entire life of the project, which is a reasonable assumption when the operation of the filters is considered. The disposal of the solids that are initially present in the system accounts for the largest percentage of the waste disposal costs. The disposal of these solids, including the water that is discarded with them, accounts for 57% of the total waste disposal costs, or \$58,000 per year. The initial concentration of solids is assumed equal for each batch; therefore, there is no way to reduce the costs associated with this step.

In the end, an appropriate design was created for the purification of an equipment decontamination stream that achieved the desired objectives at a reasonable cost. A large amount of information was collected in order to complete the design of the plant in the most effective manner within the given time constraints. The entire design process may be considered a rewarding experience when considering the final product in light of the cooperation, research, and many hours of work that are included in the conclusive result.

Conclusions

Cleaning and decontamination operations are commonly needed to remove the radiation from processes within the nuclear industry. However, once the equipment has been properly cleaned, a contaminated solution remains that must be purified so as to return clean water to the public domain. A generic facility is studied in order to gain an understanding and further insight into this typical problem of decontaminating cleaning solutions used on nuclear equipment. The following conclusions are made from this study:

- Solids in the initial stream account for more than half of the total waste that is removed from the system.
- The contaminants are removed in an orderly process so as to ensure complete removal at the fastest and least expensive rate. A simple filtration process removes the large solid particles first. Cesium is then eliminated using a 3M Empore™ filter cartridge, followed by the plutonium and uranium, which are removed simultaneously by co-precipitation with iron. The surfactant and the remaining organic compounds, except trichloroethylene, are destroyed using ultraviolet light and hydrogen peroxide in the presence of titanium dioxide. Trichloroethylene is removed by gas stripping in combination with a decanting process. The water then passes through an evaporator and a condenser before entering an activated carbon bed that further removes any remaining contaminants. This final step allows the purified water stream to be safely recycled through the system or returned to the public domain. All solids removed as waste are properly buried in concrete.
- The assumption that trichloroethylene is not destroyed in the ultraviolet reactor is not a feasible possibility. However, the assumption is made due to the safety concerns associated with harmful byproducts that can be created in the ultraviolet reactor.
- More than 99% of the contaminants present in the decontamination stream are removed via a mobile facility. All of the equipment is contained on the beds of two flatbed trucks. Of the original solution, 83% is considered clean enough to be returned to the public water supply.
- The total capital investment for this project is found to be \$923,000. The largest percentage of the capital costs come from the transportation equipment, directly followed by the piping. All of the other capital costs are comparatively small, but there are a large number of these costs present.

- The cost of electricity for the ultraviolet reactor constitutes the largest operating expense at approximately \$1,212,000 per year. This expense stems from the reactor's nine hours of operation per batch, which results in an immense electricity requirement for the unit.
- The annual cost of the project is \$3,332,000. This figure assumes a 15-year plant life, an interest rate of 10%, nine-year sum-of-years digits depreciation, and a 40% tax base.
- Customers are charged \$359,000 per month in order to decontaminate one gallon per minute of solution. This figure covers all of the annual costs as well as a 20% rate of return on the initial investment.

Nomenclature

Concentrations

[Cs]	Concentration of cesium, ppm
[C ₂ H ₈ N ₂ O ₄]	Concentration of ammonium oxalate, <u>M</u>
[C ₂ HCl ₃]	Concentration of trichloroethylene, ppm
[C ₆ H ₅ Na ₃ O ₇]	Concentration of sodium citrate, <u>M</u>
[C ₁₀ H ₂₂]	Concentration of hydrocarbons, ppm
[Fe]	Concentration of iron, ppm
[H ₂ O ₂]	Concentration of hydrogen peroxide, <u>M</u>
[NaOH]	Concentration of sodium hydroxide, <u>M</u>
[Pu]	Concentration of plutonium, ppm
[Solids]	Concentration of solids, ppm
[U]	Concentration of uranium, ppm

Greek

Δ	Change
π	Pi, unitless
ρ	Density of water, lb/ft ³
Σ	Summation

Roman

A	Area, ft ²
ACB	Activated carbon bed

ATCF	After tax cash flow, \$
B1	Blower 1
B2	Blower 2
C	Installed cost, \$
C_p	Heat capacity, Btu / lb-mol °R
CPST	Co-precipitation stirred tank
D	Diameter, ft
E	Evaporator
EEM	Electrical equipment and materials
EFS	Empore filter system
F	Guthrie's Correlation correction factor, unitless Volumetric flow rate, gal/min
F1	Filter 1
F2	Filter 2
F3	Filter 3
GS	Gas stripper
H	Height, ft
HE1	Heat exchanger 1
HE2	Heat exchanger 2
HE3	Heat exchanger 3
HT1	Holding tank 1
HT2	Holding tank 2
HT3	Holding tank 3
i	Interest rate, %

IC	Instrumentation and controls
L	Length, ft
m	Mass, lb, g
MARR	Minimum attractive rate of return, %
M&S	Marshall & Swift cost index, unitless
MW	Molecular weight, lb/lb-mol
n	Project life, yr
P	Pressure, atm Piping
P1	Pump 1
P2	Pump 2
P3	Pump 3
P4	Pump 4
P5	Pump 5
P6	Pump 6
P7	Pump 7
P8	Pump 8
P9	Pump 9
P10	Pump 10
Q	Volumetric flow rate, ft ³
R	Ideal gas constant, atm ft ³ / lb-mol °R
S	Solubility in water, g/mL
ST	Separation tank

t	Time, min
T	Temperature, °F, °R
TE	Transportation equipment
U	Overall heat transfer coefficient, Btu / h ft ² °R
UVR	Ultraviolet reactor
V	Volume, gal
W	Width, ft

Subscripts

1	Stream 1
2	Stream 2
3	Stream 3
4	Stream 4
5	Stream 5
6	Stream 6
7	Stream 7
8	Stream 8
9	Stream 9
10	Stream 10
11	Stream 11
12	Stream 12
13	Stream 13
14	Stream 14
15	Stream 15

16	Stream 16
17	Stream 17
18	Stream 18
19	Stream 19
20	Stream 20
21	Stream 21
1980	1980
1999	1999
ACB	Activated carbon bed
AIR	Air
B	Batch
B1	Blower 1
B2	Blower 2
c	Cost
C1	Cold fluid inlet
C2	Cold fluid outlet
$C_2H_8N_2O_4$	Ammonium oxalate
C_2HCl_3	Trichloroethylene
$C_6H_5Na_3O_7$	Sodium citrate
$C_{10}H_{22}$	Hydrocarbons
CO_2	Carbon dioxide
CPST	Co-precipitation Stirred Tank
Cs	Cesium

d	design
EEM	Electrical Equipment and Materials
F1	Filter 1
F2	Filter 2
F3	Filter 3
Fe	Iron
FeN_3O_9	Ferric nitrate
Fe_2O_3	Ferric oxide
GS	Gas stripper
H	HYSYS estimate
H1	Hot fluid inlet
H2	Hot fluid outlet
H_2O	Water
H_2O_2	Hydrogen peroxide
HE1	Heat exchanger 1
HE2	Heat exchanger 2
HE3	Heat exchanger 3
HT1	Holding tank 1
HT2	Holding tank 2
HT3	Holding tank 3
IC	Instrumentation and controls
m	Log mean Material

N ₂	Nitrogen
Na ⁺	Sodium ion
NaOH	Sodium hydroxide
NH ₄ ⁺	Ammonium ion
NO ₃ ⁻	Nitrate ion
O ₂	Oxygen
P	Pressure Piping
P1	Pump 1
P2	Pump 2
P3	Pump 3
P4	Pump 4
P5	Pump 5
P6	Pump 6
P7	Pump 7
P8	Pump 8
P9	Pump 9
P10	Pump 10
Pu	Plutonium
Solids	Solid particles
ST	Separation tank
T	Total
TCE	Trichloroethylene
U	Uranium

UVR	Ultraviolet reactor
X	Capital costs excluding P, IC, EEM, and TE
Z	Operating expenses excluding the general utilities expense

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Appendix A. Material Balances

Table 3. Material Balances

Component	Initial Concentrations			MW	1		2	
	(M)	(ppm)	% saturation)	(lb/lb-mol)	(lb)	(wt%)	(lb)	(wt%)
C ₂ H ₈ N ₂ O ₄	0.1			124.0962	62.14	1.24%	0.00	0.00%
C ₆ H ₅ Na ₃ O ₇	0.04			258.07061	51.69	1.04%	0.00	0.00%
H ₂ O ₂	0.05			34.0146	8.516	0.171%	0.00	0.00%
NaOH	0.2			39.99707	40.06	0.802%	0.00	0.00%
C ₁₀ H ₂₂		200		142.2838	0.9988	0.0200%	0.00	0.00%
C ₂ HCl ₃		110.3	10%	131.3889	0.5508	0.0110%	0.00	0.00%
Cs		4		132.9054	0.01998	0.000400%	0.00	0.00%
U		200		238.029	0.9988	0.0200%	0.00	0.00%
Pu		1		244	0.004994	0.000100%	0.00	0.00%
Fe		200		55.845	0.9988	0.0200%	0.00	0.00%
Solids		1000			4.994	0.100%	4.994	50.0%
H ₂ O				18.01528	4823	96.6%	4.994	50.0%
FeN ₃ O ₉				241.8597	0.00	0.00%	0.00	0.00%
NO ₃ ⁻				62.0049	0.00	0.00%	0.00	0.00%
O ₂				31.9988	0.00	0.00%	0.00	0.00%
N ₂				28.0134	0.00	0.00%	0.00	0.00%
CO ₂				44.0098	0.00	0.00%	0.00	0.00%
Fe ₂ O ₃				159.6882	0.00	0.00%	0.00	0.00%
Na ⁺				22.98977	0.00	0.00%	0.00	0.00%
NH ₄ ⁺				18.03846	0.00	0.00%	0.00	0.00%
Total					4994	100%	9.988	100%

Table 3. Material Balances (continued)

Component	3		4		5		6	
	(lb)	(wt%)	(lb)	(wt%)	(lb)	(wt%)	(lb)	(wt%)
C ₂ H ₈ N ₂ O ₄	62.14	1.25%	0.00	0.00%	62.14	1.25%	0.00	0.00%
C ₆ H ₅ Na ₃ O ₇	51.69	1.04%	0.00	0.00%	51.69	1.04%	0.00	0.00%
H ₂ O ₂	8.516	0.171%	0.00	0.00%	8.516	0.171%	0.00	0.00%
NaOH	40.06	0.804%	0.00	0.00%	40.06	0.804%	0.00	0.00%
C ₁₀ H ₂₂	0.9988	0.0200%	0.00	0.00%	0.9988	0.0200%	0.00	0.00%
C ₂ HCl ₃	0.5508	0.0111%	0.00	0.00%	0.5508	0.0111%	0.00	0.00%
Cs	0.01998	0.000401%	0.01998	100%	0.00	0.00%	0.00	0.00%
U	0.9988	0.0200%	0.00	0.00%	0.9988	0.0200%	0.00	0.00%
Pu	0.004994	0.000100%	0.00	0.00%	0.004994	0.000100%	0.00	0.00%
Fe	0.9988	0.0200%	0.00	0.00%	0.9988	0.0200%	0.00	0.00%
Solids	0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00	0.00%
H ₂ O	4818	96.7%	0.00	0.00%	4818	96.7%	0.00	0.00%
FeN ₃ O ₉	0.00	0.00%	0.00	0.00%	0.00	0.00%	3.896	100%
NO ₃ ⁻	0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00	0.00%
O ₂	0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00	0.00%
N ₂	0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00	0.00%
CO ₂	0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00	0.00%
Fe ₂ O ₃	0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00	0.00%
Na ⁺	0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00	0.00%
NH ₄ ⁺	0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00	0.00%
Total	4984	100%	0.01998	100%	4984	100%	3.896	100%

Table 3. Material Balances (continued)

Component	7		8		9		10	
	(lb)	(wt%)	(lb)	(wt%)	(lb)	(wt%)	(lb)	(wt%)
$C_2H_8N_2O_4$	0.00	0.00%	62.14	1.25%	0.00	0.00%	0.00	0.00%
$C_6H_5Na_3O_7$	0.00	0.00%	51.69	1.04%	0.00	0.00%	0.00	0.00%
H_2O_2	0.00	0.00%	8.516	0.171%	0.00	0.00%	0.00	0.00%
NaOH	0.00	0.00%	40.06	0.804%	0.00	0.00%	0.00	0.00%
$C_{10}H_{22}$	0.00	0.00%	0.9988	0.0200%	0.00	0.00%	0.00	0.00%
C_2HCl_3	0.00	0.00%	0.5508	0.0111%	0.00	0.00%	0.00	0.00%
Cs	0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00	0.00%
U	0.8989	24.9%	0.09988	0.00200%	0.00	0.00%	0.00	0.00%
Pu	0.004494	0.125%	0.0004994	0.0000100%	0.00	0.00%	0.00	0.00%
Fe	0.8995	24.9%	0.9988	0.02004%	0.00	0.00%	0.00	0.00%
Solids	0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00	0.00%
H_2O	1.803	50.0%	4816	96.6%	0.00	0.00%	0.00	0.00%
FeN_3O_9	0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00	0.00%
NO_3^-	0.00	0.00%	2.996	0.06%	0.00	0.00%	0.00	0.00%
O_2	0.00	0.00%	0.00	0.00%	23.94	23.3%	0.00	0.00%
N_2	0.00	0.00%	0.00	0.00%	78.84	76.7%	78.84	44.1%
CO_2	0.00	0.00%	0.00	0.00%	0.00	0.00%	100.1	55.9%
Fe_2O_3	0.00	0.00%	0.00	0.00%	0.00	0.0%	0.00	0.0%
Na^+	0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00	0.00%
NH_4^+	0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00	0.00%
Total	3.606	100%	4984	100%	102.8	100%	178.9	100%

Table 3. Material Balances (continued)

Component	11		12		13		14	
	(lb)	(wt%)	(lb)	(wt%)	(lb)	(wt%)	(lb)	(wt%)
C ₂ H ₈ N ₂ O ₄	0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00	0.00%
C ₆ H ₅ Na ₃ O ₇	0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00	0.00%
H ₂ O ₂	0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00	0.00%
NaOH	40.06	0.816%	0.00	0.00%	40.06	0.817%	0.00	0.00%
C ₁₀ H ₂₂	0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00	0.00%
C ₂ HCl ₃	0.5508	0.0112%	0.00	0.00%	0.5508	0.0112%	0.00	0.00%
Cs	0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00	0.00%
U	0.09988	0.00203%	0.00	0.00%	0.09988	0.00204%	0.00	0.00%
Pu	0.0004994	0.0000102%	0.00	0.00%	0.0004994	0.0000102%	0.00	0.00%
Fe	0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00	0.00%
Solids	0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00	0.00%
H ₂ O	4831	98.4%	1.428	50.0%	4830	98.5%	0.00	0.00%
FeN ₃ O ₉	0.00	0.00%	0.00	0.00%	0.00	0.0%	0.00	0.00%
NO ₃ ⁻	2.996	0.0610%	0.00	0.00%	2.996	0.0611%	0.00	0.00%
O ₂	0.00	0.00%	0.00	0.00%	0.00	0.00%	2329	23.3%
N ₂	0.00	0.00%	0.00	0.00%	0.00	0.00%	7671	76.7%
CO ₂	0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00	0.00%
Fe ₂ O ₃	1.428	0.0291%	1.428	50.0%	0.00	0.00%	0.00	0.00%
Na ⁺	13.81	0.281%	0.00	0.00%	13.81	0.282%	0.00	0.00%
NH ₄ ⁺	18.06	0.368%	0.00	0.00%	18.06	0.368%	0.00	0.00%
Total	4908	100%	2.856	100%	4905	100.00%	10000	100%

Table 3. Material Balances (continued)

Component	15		16		17		18	
	(lb)	(wt%)	(lb)	(wt%)	(lb)	(wt%)	(lb)	(wt%)
C ₂ H ₈ N ₂ O ₄	0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00	0.00%
C ₆ H ₅ Na ₃ O ₇	0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00	0.00%
H ₂ O ₂	0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00	0.00%
NaOH	0.00	0.00%	0.00	0.00%	40.06	0.853%	40.06	7.45%
C ₁₀ H ₂₂	0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00	0.00%
C ₂ HCl ₃	0.00	0.00%	0.5501	50.0%	0.0007300	0.0000155%	0.00	0.00%
Cs	0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00	0.00%
U	0.00	0.00%	0.00	0.00%	0.09988	0.00213%	0.09988	0.0186%
Pu	0.00	0.00%	0.00	0.00%	0.0004994	0.0000106%	0.0004994	0.0000929%
Fe	0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00	0.00%
Solids	0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00	0.00%
H ₂ O	205.7	2.02%	0.5501	50.0%	4623	98.4%	462.3	86.0%
FeN ₃ O ₉	0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00	0.00%
NO ₃ ⁻	0.00	0.00%	0.00	0.00%	2.996	0.0638%	2.996	0.558%
O ₂	2329	22.8%	0.00	0.00%	0.00	0.00%	0.00	0.00%
N ₂	7671	75.2%	0.00	0.00%	0.00	0.00%	0.00	0.00%
CO ₂	0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00	0.00%
Fe ₂ O ₃	0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00	0.00%
Na ⁺	0.00	0.00%	0.00	0.00%	13.81	0.294%	13.81	2.57%
NH ₄ ⁺	0.00	0.00%	0.00	0.00%	18.06	0.384%	18.06	3.36%
Total	10206	100%	1.100	100%	4698	100%	537.4	100%

Table 3. Material Balances (continued)

Component	19		20		21	
	(lb)	(wt%)	(lb)	(wt%)	(lb)	(wt%)
C ₂ H ₈ N ₂ O ₄	0.00	0.00%	0.00	0.00%	0.00	0.00%
C ₆ H ₅ Na ₃ O ₇	0.00	0.00%	0.00	0.00%	0.00	0.00%
H ₂ O ₂	0.00	0.00%	0.00	0.00%	0.00	0.00%
NaOH	0.00	0.00%	0.00	0.00%	0.00	0.00%
C ₁₀ H ₂₂	0.00	0.00%	0.00	0.00%	0.00	0.00%
C ₂ HCl ₃	0.0007300	0.0000175%	0.0007300	50.0%	0.00	0.00%
Cs	0.00	0.00%	0.00	0.00%	0.00	0.00%
U	0.00	0.00%	0.00	0.00%	0.00	0.00%
Pu	0.00	0.00%	0.00	0.00%	0.00	0.00%
Fe	0.00	0.00%	0.00	0.00%	0.00	0.00%
Solids	0.00	0.00%	0.00	0.00%	0.00	0.00%
H ₂ O	4161	100%	0.0007300	50.0%	4161	100%
FeN ₃ O ₉	0.00	0.00%	0.00	0.00%	0.00	0.00%
NO ₃ ⁻	0.00	0.00%	0.00	0.00%	0.00	0.00%
O ₂	0.00	0.00%	0.00	0.00%	0.00	0.00%
N ₂	0.00	0.00%	0.00	0.00%	0.00	0.00%
CO ₂	0.00	0.00%	0.00	0.00%	0.00	0.00%
Fe ₂ O ₃	0.00	0.00%	0.00	0.00%	0.00	0.00%
Na ⁺	0.00	0.00%	0.00	0.00%	0.00	0.00%
NH ₄ ⁺	0.00	0.00%	0.00	0.00%	0.00	0.00%
Total	4161	100%	0.001460	100%	4161	100%

Appendix B. Cost Information

Table 4. Fixed Capital and Equipment Information

Equipment	Abbreviation	L (ft)	W (ft)	A (ft ²)	V (gal)	H (ft)	D (ft)	Head (gpm)	Q (ft ³ /min)	ΔT_m (°F)	Cost	Source of Cost Information
Filter	F1	2	2	4							\$28,556	Peters & Timmerhaus (587)
Empore Filter System	EFS										\$5,000	3M
Holding Tank	HT1				734	5	5				\$42,968	Douglas (574)
Pump	P1							2			\$10,470	Peters & Timmerhaus (555)
Co-Precipitation Stirred Tank	CPST				734	5	5				\$42,968	Douglas (574)
Filter	F2	2	2	4							\$28,556	Peters & Timmerhaus (587)
Pump	P2							2			\$10,470	Peters & Timmerhaus (555)
Holding Tank	HT2				734	5	5				\$42,968	Douglas (574)
Pump	P3							20			\$20,941	Peters & Timmerhaus (555)
UV Reactor	UVR				734	5	5				\$42,968	Douglas (574)
Blower	B1								231.8		\$11,713	Douglas (577)
Filter	F3	1.5	1.5	2.25							\$22,845	Peters & Timmerhaus (587)
Pump	P4							20			\$20,941	Peters & Timmerhaus (555)
Holding Tank	HT3				735	5	5				\$42,968	Douglas (574)
Pump	P5							1			\$9,519	Peters & Timmerhaus (555)
Heat Exchanger	HE1			9.42						79.49	\$9,155	Douglas (572)
Gas Stripper	GS				188	8	2				\$23,585	Douglas (574)
Heat Exchanger	HE2			38.4						32.46	\$22,841	Douglas (572)
Separation Tank	ST				159	3	3				\$16,547	Douglas (574)
Pump	P6							1			\$9,519	Peters & Timmerhaus (555)
Blower	B2								225.5		\$11,543	Douglas (577)
Pump	P7							1			\$9,519	Peters & Timmerhaus (555)
Evaporator	E	6.1	2.9		375	6.4					\$17,995	Equipment Manufacturing Corporation
Pump	P8							0.1			\$7,615	Peters & Timmerhaus (555)
Heat Exchanger	HE3			65.0						51.05	\$32,137	Douglas (572)
Pump	P9							0.9			\$9,138	Peters & Timmerhaus (555)
Activated Carbon Bed	ACB					5.5	4.5				\$3,645	Envirotrol, Inc.
Pump	P10							0.9			\$9,138	Peters & Timmerhaus (555)
Piping	P										\$73,609	Peters & Timmerhaus (171)
Instrumentation and Controls	IC										\$26,896	Douglas (38)
Electrical Equipment and Materials	EEM										\$32,558	Douglas (38)
Transportation Equipment	TE										\$224,000	Eastman Chemical
Total											\$923,289	

Table 5. Project Cost Summary

Year	Fixed Capital Investment	Annualized Fixed Capital	Depreciation	Utilities Expense		Maintenance Expense	Waste Disposal Expense	Materials Expense			
				General	UVR			Iron Nitrate	Titanium Dioxide	Activated Carbon	Empore Filters
0	\$923,289										
1		\$121,388	\$184,658	\$321,094	\$1,212,256	\$36,932	\$101,331	\$162,864	\$3,028	\$12,421	\$720,000
2		\$121,388	\$164,140	\$321,094	\$1,212,256	\$36,932	\$101,331	\$162,864	\$3,028	\$12,421	\$720,000
3		\$121,388	\$143,623	\$321,094	\$1,212,256	\$36,932	\$101,331	\$162,864	\$3,028	\$12,421	\$720,000
4		\$121,388	\$123,105	\$321,094	\$1,212,256	\$36,932	\$101,331	\$162,864	\$3,028	\$12,421	\$720,000
5		\$121,388	\$102,588	\$321,094	\$1,212,256	\$36,932	\$101,331	\$162,864	\$3,028	\$12,421	\$720,000
6		\$121,388	\$82,070	\$321,094	\$1,212,256	\$36,932	\$101,331	\$162,864	\$3,028	\$12,421	\$720,000
7		\$121,388	\$61,553	\$321,094	\$1,212,256	\$36,932	\$101,331	\$162,864	\$3,028	\$12,421	\$720,000
8		\$121,388	\$41,035	\$321,094	\$1,212,256	\$36,932	\$101,331	\$162,864	\$3,028	\$12,421	\$720,000
9		\$121,388	\$20,518	\$321,094	\$1,212,256	\$36,932	\$101,331	\$162,864	\$3,028	\$12,421	\$720,000
10		\$121,388	\$0	\$321,094	\$1,212,256	\$36,932	\$101,331	\$162,864	\$3,028	\$12,421	\$720,000
11		\$121,388	\$0	\$321,094	\$1,212,256	\$36,932	\$101,331	\$162,864	\$3,028	\$12,421	\$720,000
12		\$121,388	\$0	\$321,094	\$1,212,256	\$36,932	\$101,331	\$162,864	\$3,028	\$12,421	\$720,000
13		\$121,388	\$0	\$321,094	\$1,212,256	\$36,932	\$101,331	\$162,864	\$3,028	\$12,421	\$720,000
14		\$121,388	\$0	\$321,094	\$1,212,256	\$36,932	\$101,331	\$162,864	\$3,028	\$12,421	\$720,000
15		\$121,388	\$0	\$321,094	\$1,212,256	\$36,932	\$101,331	\$162,864	\$3,028	\$12,421	\$720,000

Table 5. Project Cost Summary (continued)

Year	Labor and Overhead Expense	Salaries Expense	Total Operating Expenses	Total Cost	Gross Revenue	After Tax Cash Flow	Present Value of the After Tax Cash Flow
0						-\$923,289	-\$923,289
1	\$525,600	\$115,411	\$3,210,936	\$3,332,325	\$3,588,764	\$227,727	\$189,772
2	\$525,600	\$115,411	\$3,210,936	\$3,332,325	\$3,588,764	\$219,520	\$152,444
3	\$525,600	\$115,411	\$3,210,936	\$3,332,325	\$3,588,764	\$211,313	\$122,287
4	\$525,600	\$115,411	\$3,210,936	\$3,332,325	\$3,588,764	\$203,106	\$97,948
5	\$525,600	\$115,411	\$3,210,936	\$3,332,325	\$3,588,764	\$194,899	\$78,325
6	\$525,600	\$115,411	\$3,210,936	\$3,332,325	\$3,588,764	\$186,692	\$62,523
7	\$525,600	\$115,411	\$3,210,936	\$3,332,325	\$3,588,764	\$178,485	\$49,812
8	\$525,600	\$115,411	\$3,210,936	\$3,332,325	\$3,588,764	\$170,278	\$39,601
9	\$525,600	\$115,411	\$3,210,936	\$3,332,325	\$3,588,764	\$162,071	\$31,410
10	\$525,600	\$115,411	\$3,210,936	\$3,332,325	\$3,588,764	\$153,863	\$24,850
11	\$525,600	\$115,411	\$3,210,936	\$3,332,325	\$3,588,764	\$153,863	\$20,708
12	\$525,600	\$115,411	\$3,210,936	\$3,332,325	\$3,588,764	\$153,863	\$17,257
13	\$525,600	\$115,411	\$3,210,936	\$3,332,325	\$3,588,764	\$153,863	\$14,381
14	\$525,600	\$115,411	\$3,210,936	\$3,332,325	\$3,588,764	\$153,863	\$11,984
15	\$525,600	\$115,411	\$3,210,936	\$3,332,325	\$3,588,764	\$153,863	\$9,987

Appendix C. Sample Calculations

Initial Concentrations

$$[C_2HCl_3] = \frac{(0.1)S_{TCE}}{\rho} = \frac{(0.1)(0.0011 \frac{g}{mL})(28317 \frac{mL}{ft^3})(10^6 \text{ ppm})}{(62.261 \frac{lb}{ft^3})(453.59 \frac{g}{lb})} = 110.3 \text{ ppm}$$

Stream 1

$$m_{C_2H_8N_2O_4,1} = V_B [C_2H_8N_2O_4] MW_{C_2H_8N_2O_4} = \frac{(600 \text{ gal})(0.1M)(124.0962 \frac{lb}{lb-mol})(3.7854 \frac{L}{gal})}{453.59 \frac{g-mol}{lb-mol}} = 62.14 \text{ lb}$$

$$m_{C_6H_5Na_3O_7,1} = V_B [C_6H_5Na_3O_7] MW_{C_6H_5Na_3O_7} = \frac{(600 \text{ gal})(0.04M)(258.07061 \frac{lb}{lb-mol})(3.7854 \frac{L}{gal})}{453.59 \frac{g-mol}{lb-mol}} = 51.69 \text{ lb}$$

$$m_{H_2O_2,1} = V_B [H_2O_2] MW_{H_2O_2} = \frac{(600 \text{ gal})(0.05 M)(34.0146 \frac{lb}{lb-mol})(3.7854 \frac{L}{gal})}{453.59 \frac{g-mol}{lb-mol}} = 8.516 \text{ lb}$$

$$m_{NaOH,1} = V_B [NaOH] MW_{NaOH} = \frac{(600 \text{ gal})(0.2M)(39.99707 \frac{lb}{lb-mol})(3.7854 \frac{L}{gal})}{453.59 \frac{g-mol}{lb-mol}} = 40.06 \text{ lb}$$

$$m_{T,1} = V_B \rho = \frac{(600 \text{ gal})(62.261 \frac{lb}{ft^3})}{7.4805 \frac{gal}{ft^3}} = 4994 \text{ lb}$$

$$m_{C_{10}H_{22},1} = [C_{10}H_{22}] m_{T,1} = \frac{(200 \text{ ppm})(4994 \text{ lb})}{10^6 \text{ ppm}} = 0.9988 \text{ lb}$$

$$m_{C_2HCl_3,1} = [C_2HCl_3] m_{T,1} = \frac{(110.3 \text{ ppm})(4994 \text{ lb})}{10^6 \text{ ppm}} = 0.5508 \text{ lb}$$

$$m_{Cs,1} = [Cs] m_{T,1} = \frac{(4 \text{ ppm})(4994 \text{ lb})}{10^6 \text{ ppm}} = 0.01998 \text{ lb}$$

$$m_{U,1} = [U] m_{T,1} = \frac{(200 \text{ ppm})(4994 \text{ lb})}{10^6 \text{ ppm}} = 0.9988 \text{ lb}$$

$$m_{Pu,1} = [Pu] m_{T,1} = \frac{(1 \text{ ppm})(4994 \text{ lb})}{10^6 \text{ ppm}} = 0.004994 \text{ lb}$$

$$m_{Fe,1} = [Fe] m_{T,1} = \frac{(200 \text{ ppm})(4994 \text{ lb})}{10^6 \text{ ppm}} = 0.9988 \text{ lb}$$

$$m_{\text{Solids},1} = [\text{Solids}]m_{T,1} = \frac{(1000 \text{ ppm})(4994 \text{ lb})}{10^6 \text{ ppm}} = 4.994 \text{ lb}$$

$$\begin{aligned} m_{\text{H}_2\text{O},1} &= m_{T,1} - (m_{\text{C}_2\text{H}_8\text{N}_2\text{O}_4,1} + m_{\text{C}_6\text{H}_5\text{Na}_3\text{O}_7,1} + m_{\text{H}_2\text{O}_2,1} + m_{\text{NaOH},1} + m_{\text{C}_{10}\text{H}_{22},1} + m_{\text{C}_2\text{HCl}_3,1} + m_{\text{Cs},1} + m_{\text{U},1} + m_{\text{Pu},1} + m_{\text{Fe},1} + m_{\text{Solids},1}) \\ &= 4994 \text{ lb} - (62.14 \text{ lb} + 51.69 \text{ lb} + 8.516 \text{ lb} + 40.06 \text{ lb} + 0.9988 \text{ lb} + 0.5508 \text{ lb} + 0.01998 \text{ lb} + 0.9988 \text{ lb} + 0.004994 \text{ lb}) \\ &= 4823 \text{ lb} \end{aligned}$$

Stream 2

$$m_{\text{Solids},2} = m_{\text{Solids},1} = 4.994 \text{ lb}$$

$$m_{\text{H}_2\text{O},2} = m_{\text{Solids},2} = 4.994 \text{ lb}$$

$$m_{T,2} = m_{\text{Solids},2} + m_{\text{H}_2\text{O},2} = 9.988 \text{ lb}$$

Stream 3

$$m_{\text{C}_2\text{H}_8\text{N}_2\text{O}_4,3} = m_{\text{C}_2\text{H}_8\text{N}_2\text{O}_4,1} = 62.14 \text{ lb}$$

$$m_{\text{C}_6\text{H}_5\text{Na}_3\text{O}_7,3} = m_{\text{C}_6\text{H}_5\text{Na}_3\text{O}_7,1} = 51.69 \text{ lb}$$

$$m_{\text{H}_2\text{O}_2,3} = m_{\text{H}_2\text{O}_2,1} = 8.516 \text{ lb}$$

$$m_{\text{NaOH},3} = m_{\text{NaOH},1} = 40.06 \text{ lb}$$

$$m_{\text{C}_{10}\text{H}_{22},3} = m_{\text{C}_{10}\text{H}_{22},1} = 0.9988 \text{ lb}$$

$$m_{\text{C}_2\text{HCl}_3,3} = m_{\text{C}_2\text{HCl}_3,1} = 0.5508 \text{ lb}$$

$$m_{\text{Cs},3} = m_{\text{Cs},1} = 0.01998 \text{ lb}$$

$$m_{\text{U},3} = m_{\text{U},1} = 0.9988 \text{ lb}$$

$$m_{\text{Pu},3} = m_{\text{Pu},1} = 0.004994 \text{ lb}$$

$$m_{\text{Fe},3} = m_{\text{Fe},1} = 0.9988 \text{ lb}$$

$$m_{\text{Solids},3} = m_{\text{Solids},1} - m_{\text{Solids},2} = 4.994 \text{ lb} - 4.994 \text{ lb} = 0.00 \text{ lb}$$

$$m_{\text{H}_2\text{O},3} = m_{\text{H}_2\text{O},1} - m_{\text{H}_2\text{O},2} = 4823 \text{ lb} - 4.994 \text{ lb} = 4818 \text{ lb}$$

$$m_{T,3} = m_{T,1} - m_{T,2} = 4994 \text{ lb} - 9.988 \text{ lb} = 4984 \text{ lb}$$

Stream 4

$$m_{Cs,4} = m_{Cs,3} = 0.01998 \text{ lb}$$

$$m_{T,4} = m_{Cs,4} = 0.01998 \text{ lb}$$

Stream 5

$$m_{C_2H_8N_2O_4,5} = m_{C_2H_8N_2O_4,3} = 62.14 \text{ lb}$$

$$m_{C_6H_5Na_3O_7,5} = m_{C_6H_5Na_3O_7,3} = 51.69 \text{ lb}$$

$$m_{H_2O,5} = m_{H_2O,3} = 8.516 \text{ lb}$$

$$m_{NaOH,5} = m_{NaOH,3} = 40.06 \text{ lb}$$

$$m_{C_{10}H_{22},5} = m_{C_{10}H_{22},3} = 0.9988 \text{ lb}$$

$$m_{C_2HCl_3,5} = m_{C_2HCl_3,3} = 0.5508 \text{ lb}$$

$$m_{Cs,5} = m_{Cs,3} - m_{Cs,4} = 0.01998 \text{ lb} - 0.01998 \text{ lb} = 0.00 \text{ lb}$$

$$m_{U,5} = m_{U,3} = 0.9988 \text{ lb}$$

$$m_{Pu,5} = m_{Pu,3} = 0.004994 \text{ lb}$$

$$m_{Fe,5} = m_{Fe,3} = 0.9988 \text{ lb}$$

$$m_{Solids,5} = m_{Solids,3} = 0.00 \text{ lb}$$

$$m_{H_2O,5} = m_{H_2O,3} = 4818 \text{ lb}$$

$$m_{T,5} = m_{T,3} - m_{T,4} = 4984 \text{ lb} - 0.01998 \text{ lb} = 4984 \text{ lb}$$

Stream 6

$$m_{\text{FeN}_3\text{O}_9,6} = \frac{(0.18 \text{ g/L})m_{\text{T},5}\text{MW}_{\text{FeN}_3\text{O}_9}}{\rho\text{MW}_{\text{Fe}}} = \frac{(0.18 \text{ g/L})(4984 \text{ lb})(241.8597 \text{ lb/lb-mol})(28.317 \text{ L/m}^3)}{(62.261 \text{ lb/m}^3)(55.845 \text{ lb/lb-mol})(453.59 \text{ g/lb})} = 3.896 \text{ lb}$$

$$m_{\text{T},6} = m_{\text{FeN}_3\text{O}_9,6} = 3.896 \text{ lb}$$

Stream 7

$$m_{\text{U},7} = (0.9)m_{\text{U},5} = (0.9)(0.9988 \text{ lb}) = 0.8989 \text{ lb}$$

$$m_{\text{Pu},7} = (0.9)m_{\text{Pu},5} = (0.9)(0.004994 \text{ lb}) = 0.004494 \text{ lb}$$

$$m_{\text{Fe},7} = \frac{m_{\text{FeN}_3\text{O}_9,6}\text{MW}_{\text{Fe}}}{\text{MW}_{\text{FeN}_3\text{O}_9}} = \frac{(3.896 \text{ lb})(55.845 \text{ lb})}{241.8597 \text{ lb}} = 0.8995 \text{ lb}$$

$$m_{\text{H}_2\text{O},7} = m_{\text{U},7} + m_{\text{Pu},7} + m_{\text{FeN}_3\text{O}_9,7} = 0.8989 \text{ lb} + 0.004495 \text{ lb} + 0.8996 \text{ lb} = 1.803 \text{ lb}$$

$$m_{\text{T},7} = m_{\text{U},7} + m_{\text{Pu},7} + m_{\text{FeN}_3\text{O}_9,7} + m_{\text{H}_2\text{O},7} = 0.8989 \text{ lb} + 0.004495 \text{ lb} + 0.8996 \text{ lb} + 1.803 \text{ lb} = 3.606 \text{ lb}$$

Stream 8

$$m_{\text{C}_2\text{H}_8\text{N}_2\text{O}_4,8} = m_{\text{C}_2\text{H}_8\text{N}_2\text{O}_4,5} = 62.14 \text{ lb}$$

$$m_{\text{C}_6\text{H}_5\text{Na}_3\text{O}_7,8} = m_{\text{C}_6\text{H}_5\text{Na}_3\text{O}_7,5} = 51.69 \text{ lb}$$

$$m_{\text{H}_2\text{O}_2,8} = m_{\text{H}_2\text{O}_2,5} = 8.516 \text{ lb}$$

$$m_{\text{NaOH},8} = m_{\text{NaOH},5} = 40.06 \text{ lb}$$

$$m_{\text{C}_{10}\text{H}_{22},8} = m_{\text{C}_{10}\text{H}_{22},5} = 0.9988 \text{ lb}$$

$$m_{\text{C}_2\text{HCl}_3,8} = m_{\text{C}_2\text{HCl}_3,5} = 0.5508 \text{ lb}$$

$$m_{\text{Cs},8} = m_{\text{Cs},5} = 0.00 \text{ lb}$$

$$m_{\text{U},8} = (0.1)m_{\text{U},5} = (0.1)(0.9988 \text{ lb}) = 0.09988 \text{ lb}$$

$$m_{\text{Pu},8} = (0.1)m_{\text{Pu},5} = (0.1)(0.004994 \text{ lb}) = 0.0004994 \text{ lb}$$

$$m_{\text{Fe},8} = m_{\text{Fe},5} = 0.9988 \text{ lb}$$

$$m_{\text{Solids},8} = m_{\text{Solids},5} = 0.00 \text{ lb}$$

$$m_{\text{H}_2\text{O},8} = m_{\text{H}_2\text{O},5} - m_{\text{H}_2\text{O},7} = 4818 \text{ lb} - 1.803 \text{ lb} = 4816 \text{ lb}$$

$$m_{\text{FeN}_3\text{O}_9,8} = m_{\text{FeN}_3\text{O}_9,6} - \frac{m_{\text{Fe},7} \text{MW}_{\text{FeN}_3\text{O}_9}}{\text{MW}_{\text{Fe}}} = 3.896 \text{ lb} - \frac{(0.8995 \text{ lb})(241.8597 \text{ lb/lb-mol})}{55.845 \text{ lb/lb-mol}} = 0.00 \text{ lb}$$

$$m_{\text{NO}_3^-,8} = \frac{(3)m_{\text{FeN}_3\text{O}_9,6} \text{MW}_{\text{NO}_3^-}}{\text{MW}_{\text{FeN}_3\text{O}_9}} = \frac{(3)(3.896 \text{ lb})(62.0049 \text{ lb/lb-mol})}{(241.8597 \text{ lb/lb-mol})} = 2.996 \text{ lb}$$

$$m_{\text{T},8} = m_{\text{T},5} + m_{\text{T},6} - m_{\text{T},7} = 4984 \text{ lb} + 3.896 \text{ lb} - 3.606 \text{ lb} = 4984 \text{ lb}$$

Stream 9

$$\begin{aligned} m_{\text{O}_2,9} &= \left[\frac{(2)m_{\text{CO}_2,10}}{\text{MW}_{\text{CO}_2}} + \frac{m_{\text{H}_2\text{O},11} - m_{\text{H}_2\text{O},8}}{\text{MW}_{\text{H}_2\text{O}}} + \frac{(3)m_{\text{Fe}_2\text{O}_3,11}}{\text{MW}_{\text{Fe}_2\text{O}_3}} - \frac{(4)m_{\text{C}_2\text{H}_8\text{N}_2\text{O}_4,8}}{\text{MW}_{\text{C}_2\text{H}_8\text{N}_2\text{O}_4}} - \frac{(7)m_{\text{C}_6\text{H}_5\text{Na}_3\text{O}_7,8}}{\text{MW}_{\text{C}_6\text{H}_5\text{Na}_3\text{O}_7}} - \frac{(2)m_{\text{H}_2\text{O}_2,8}}{\text{MW}_{\text{H}_2\text{O}_2}} \right] \left[\frac{\text{MW}_{\text{O}_2}}{2} \right] \\ &= \left[\frac{(2)(100.1 \text{ lb})}{44.0098 \text{ lb/lb-mol}} + \frac{(4831 \text{ lb} - 4816 \text{ lb})}{18.01528 \text{ lb/lb-mol}} + \frac{(3)(1.428 \text{ lb})}{159.6882 \text{ lb/lb-mol}} - \frac{(4)(62.14 \text{ lb})}{124.0962 \text{ lb/lb-mol}} - \frac{(7)(51.69 \text{ lb})}{258.07061 \text{ lb/lb-mol}} - \frac{(2)(8.516 \text{ lb})}{34.0146 \text{ lb/lb-mol}} \right] \left[\frac{31.9988 \text{ lb/lb-mol}}{2} \right] \\ &= 23.94 \text{ lb} \end{aligned}$$

$$m_{\text{N}_2,9} = \frac{(3.7619)m_{\text{O}_2,9} \text{MW}_{\text{N}_2}}{\text{MW}_{\text{O}_2}} = \frac{(3.7619)(24.04 \text{ lb})(28.1034 \text{ lb/lb-mol})}{(31.9988 \text{ lb/lb-mol})} = 78.84 \text{ lb}$$

$$m_{\text{T},9} = m_{\text{O}_2,9} + m_{\text{N}_2,9} = 24.04 \text{ lb} + 79.43 \text{ lb} = 102.8 \text{ lb}$$

Stream 10

$$\begin{aligned} m_{\text{CO}_2,10} &= \left[\frac{(2)m_{\text{C}_2\text{H}_8\text{N}_2\text{O}_4,8}}{\text{MW}_{\text{C}_2\text{H}_8\text{N}_2\text{O}_4}} + \frac{(6)m_{\text{C}_6\text{H}_5\text{Na}_3\text{O}_7,8}}{\text{MW}_{\text{C}_6\text{H}_5\text{Na}_3\text{O}_7}} + \frac{(10)m_{\text{C}_{10}\text{H}_{22},8}}{\text{MW}_{\text{C}_{10}\text{H}_{22}}} \right] \text{MW}_{\text{CO}_2} \\ &= \left[\frac{(2)(62.14 \text{ lb})}{124.0962 \text{ lb/lb-mol}} + \frac{(6)(51.69 \text{ lb})}{258.07061 \text{ lb/lb-mol}} + \frac{(10)(0.9988 \text{ lb})}{142.2838 \text{ lb/lb-mol}} \right] (44.0098 \text{ lb/lb-mol}) \\ &= 100.1 \text{ lb} \end{aligned}$$

$$m_{\text{N}_2,10} = m_{\text{N}_2,9} = 78.84 \text{ lb}$$

$$m_{\text{T},10} = m_{\text{CO}_2,10} + m_{\text{N}_2,10} = 100.1 \text{ lb} + 79.43 \text{ lb} = 178.9 \text{ lb}$$

Stream 11

$$m_{C_2H_8N_2O_4,11} = 0.00 \text{ lb}$$

$$m_{C_6H_5Na_3O_7,11} = 0.00 \text{ lb}$$

$$m_{H_2O_2,11} = 0.00 \text{ lb}$$

$$m_{NaOH,11} = m_{NaOH,8} = 40.06 \text{ lb}$$

$$m_{C_{10}H_{22},11} = 0.00 \text{ lb}$$

$$m_{C_2HCl_3,11} = m_{C_2HCl_3,8} = 0.5508 \text{ lb}$$

$$m_{Cs,11} = m_{Cs,8} = 0.00 \text{ lb}$$

$$m_{U,11} = m_{U,8} = 0.09988 \text{ lb}$$

$$m_{Pu,11} = m_{Pu,8} = 0.0004994 \text{ lb}$$

$$m_{Fe,11} = 0.00 \text{ lb}$$

$$m_{Solids,11} = m_{Solids,8} = 0.00 \text{ lb}$$

$$\begin{aligned} m_{H_2O,11} &= m_{H_2O,8} + \left[\frac{(5)m_{C_6H_5Na_3O_7,8}}{MW_{C_6H_5Na_3O_7}} + \frac{(2)m_{H_2O_2,8}}{MW_{H_2O_2}} + \frac{(22)m_{C_{10}H_{22},8}}{MW_{C_{10}H_{22}}} \right] \left[\frac{MW_{H_2O}}{2} \right] \\ &= 4816 \text{ lb} + \left[\frac{(5)(51.69 \text{ lb})}{258.07061 \text{ lb/mol}} + \frac{(2)(8.516 \text{ lb})}{34.0146 \text{ lb/mol}} + \frac{(22)(0.9988 \text{ lb})}{142.2838 \text{ lb/mol}} \right] \left[\frac{18.01528 \text{ lb/mol}}{2} \right] \\ &= 4831 \text{ lb} \end{aligned}$$

$$m_{FeN_3O_9,11} = m_{FeN_3O_9,8} = 0.00 \text{ lb}$$

$$m_{NO_3^-,11} = m_{NO_3^-,8} = 2.996 \text{ lb}$$

$$m_{Fe_2O_3,11} = \frac{m_{Fe,8} MW_{Fe_2O_3}}{(2) MW_{Fe}} = \frac{(0.9988 \text{ lb})(159.6882 \text{ lb/mol})}{(2)(55.845 \text{ lb/mol})} = 1.428 \text{ lb}$$

$$m_{Na^+,11} = \frac{(3)m_{C_6H_5Na_3O_7,8} MW_{Na^+}}{MW_{C_6H_5Na_3O_7}} = \frac{(3)(51.69 \text{ lb})(22.98977 \text{ lb/mol})}{258.07061 \text{ lb/mol}} = 13.81 \text{ lb}$$

$$m_{\text{NH}_4^+,11} = \frac{(2)m_{\text{C}_2\text{H}_8\text{N}_2\text{O}_4,8}\text{MW}_{\text{NH}_4^+}}{\text{MW}_{\text{C}_2\text{H}_8\text{N}_2\text{O}_4}} = \frac{(2)(62.14 \text{ lb})(18.03846 \text{ lb/lb-mol})}{124.0962 \text{ lb/lb-mol}} = 18.06 \text{ lb}$$

$$m_{\text{T},11} = m_{\text{T},8} + m_{\text{T},9} - m_{\text{T},10} = 4984 \text{ lb} + 102.8 \text{ lb} - 178.9 \text{ lb} = 4908 \text{ lb}$$

Stream 12

$$m_{\text{Fe}_2\text{O}_3,12} = m_{\text{Fe}_2\text{O}_3,11} = 1.428 \text{ lb}$$

$$m_{\text{H}_2\text{O},12} = m_{\text{Fe}_2\text{O}_3,12} = 1.428 \text{ lb}$$

$$m_{\text{T},12} = m_{\text{Fe}_2\text{O}_3,12} + m_{\text{H}_2\text{O},12} = 1.428 \text{ lb} + 1.428 \text{ lb} = 2.856 \text{ lb}$$

Stream 13

$$m_{\text{C}_2\text{H}_8\text{N}_2\text{O}_4,13} = m_{\text{C}_2\text{H}_8\text{N}_2\text{O}_4,11} = 0.00 \text{ lb}$$

$$m_{\text{C}_6\text{H}_5\text{Na}_3\text{O}_7,13} = m_{\text{C}_6\text{H}_5\text{Na}_3\text{O}_7,11} = 0.00 \text{ lb}$$

$$m_{\text{H}_2\text{O}_2,13} = m_{\text{H}_2\text{O}_2,11} = 0.00 \text{ lb}$$

$$m_{\text{NaOH},13} = m_{\text{NaOH},11} = 40.06 \text{ lb}$$

$$m_{\text{C}_{10}\text{H}_{22},13} = m_{\text{C}_{10}\text{H}_{22},11} = 0.00 \text{ lb}$$

$$m_{\text{C}_2\text{HCl}_3,13} = m_{\text{C}_2\text{HCl}_3,11} = 0.5508 \text{ lb}$$

$$m_{\text{CS},13} = m_{\text{CS},11} = 0.00 \text{ lb}$$

$$m_{\text{U},13} = m_{\text{U},11} = 0.09988 \text{ lb}$$

$$m_{\text{Pu},13} = m_{\text{Pu},11} = 0.0004994 \text{ lb}$$

$$m_{\text{Fe},13} = m_{\text{Fe},11} = 0.00 \text{ lb}$$

$$m_{\text{Solids},13} = m_{\text{Solids},11} = 0.00 \text{ lb}$$

$$m_{\text{H}_2\text{O},13} = m_{\text{H}_2\text{O},11} - m_{\text{H}_2\text{O},12} = 4831 \text{ lb} - 1.428 \text{ lb} = 4830 \text{ lb}$$

$$m_{\text{FeN}_3\text{O}_9,13} = m_{\text{FeN}_3\text{O}_9,11} = 0.00 \text{ lb}$$

$$m_{\text{NO}_3^-,13} = m_{\text{NO}_3^-,11} = 2.996 \text{ lb}$$

$$m_{\text{Fe}_2\text{O}_3,13} = m_{\text{Fe}_2\text{O}_3,11} - m_{\text{Fe}_2\text{O}_3,12} = 1.428 \text{ lb} - 1.428 \text{ lb} = 0.00 \text{ lb}$$

$$m_{\text{Na}^+,13} = m_{\text{Na}^+,11} = 13.81 \text{ lb}$$

$$m_{\text{NH}_4^+,13} = m_{\text{NH}_4^+,11} = 18.06 \text{ lb}$$

$$m_{\text{T},13} = m_{\text{T},11} - m_{\text{T},12} = 4908 \text{ lb} - 2.856 \text{ lb} = 4905 \text{ lb}$$

Stream 14

$$m_{\text{O}_2,14} = \frac{(0.21)m_{\text{T},14,\text{H}}\text{MW}_{\text{O}_2}}{(0.21)\text{MW}_{\text{O}_2} + (0.79)\text{MW}_{\text{N}_2}} = \frac{(0.21)(10000 \text{ lb})(31.9988 \text{ lb/lb-mol})}{(0.21)(31.9988 \text{ lb/lb-mol}) + (0.79)(28.0134 \text{ lb/lb-mol})} = 2329 \text{ lb}$$

$$m_{\text{N}_2,14} = \frac{(0.79)m_{\text{T},14,\text{H}}\text{MW}_{\text{N}_2}}{(0.21)\text{MW}_{\text{O}_2} + (0.79)\text{MW}_{\text{N}_2}} = \frac{(0.79)(10000 \text{ lb})(28.0134 \text{ lb/lb-mol})}{(0.21)(31.9988 \text{ lb/lb-mol}) + (0.79)(28.0134 \text{ lb/lb-mol})} = 7671 \text{ lb}$$

$$m_{\text{T},14} = m_{\text{O}_2,14} + m_{\text{N}_2,14} = 2329 \text{ lb} + 7671 \text{ lb} = 10,000 \text{ lb}$$

Stream 15

$$m_{\text{O}_2,15} = m_{\text{O}_2,14} = 2329 \text{ lb}$$

$$m_{\text{N}_2,15} = m_{\text{N}_2,14} = 7671 \text{ lb}$$

$$m_{\text{T},15} = m_{\text{H}_2\text{O},15,\text{H}} + m_{\text{O}_2,15} + m_{\text{N}_2,15} = 205.7 \text{ lb} + 2329 \text{ lb} + 7671 \text{ lb} = 10206 \text{ lb}$$

Stream 16

$$m_{\text{H}_2\text{O},16} = m_{\text{C}_2\text{HCl}_3,16,\text{H}} = 0.5501 \text{ lb}$$

$$m_{\text{T},16} = m_{\text{C}_2\text{HCl}_3,16,\text{H}} + m_{\text{H}_2\text{O},16} = 0.5501 \text{ lb} + 0.5501 \text{ lb} = 1.100 \text{ lb}$$

Stream 17

$$m_{\text{C}_2\text{H}_8\text{N}_2\text{O}_4,17} = m_{\text{C}_2\text{H}_8\text{N}_2\text{O}_4,13} = 0.00 \text{ lb}$$

$$m_{C_6H_5Na_3O_7,17} = m_{C_6H_5Na_3O_7,13} = 0.00 \text{ lb}$$

$$m_{H_2O_2,17} = m_{H_2O_2,13} = 0.00 \text{ lb}$$

$$m_{NaOH,17} = m_{NaOH,13} = 40.06 \text{ lb}$$

$$m_{C_{10}H_{22},17} = m_{C_{10}H_{22},13} = 0.00 \text{ lb}$$

$$m_{Cs,17} = m_{Cs,13} = 0.00 \text{ lb}$$

$$m_{U,17} = m_{U,13} = 0.09988 \text{ lb}$$

$$m_{Pu,17} = m_{Pu,13} = 0.0004994 \text{ lb}$$

$$m_{Fe,17} = m_{Fe,13} = 0.00 \text{ lb}$$

$$m_{Solids,17} = m_{Solids,13} = 0.00 \text{ lb}$$

$$m_{H_2O,17} = m_{H_2O,13} - m_{H_2O,15} - m_{H_2O,16} = 4830 \text{ lb} - 205.7 \text{ lb} - 0.5501 \text{ lb} = 4623 \text{ lb}$$

$$m_{FeN_3O_9,17} = m_{FeN_3O_9,13} = 0.00 \text{ lb}$$

$$m_{NO_3^-,17} = m_{NO_3^-,13} = 2.996 \text{ lb}$$

$$m_{Fe_2O_3,17} = m_{Fe_2O_3,13} = 0.00 \text{ lb}$$

$$m_{Na^+,17} = m_{Na^+,13} = 13.81 \text{ lb}$$

$$m_{NH_4^+,17} = m_{NH_4^+,13} = 18.06 \text{ lb}$$

$$\begin{aligned} m_{T,17} &= m_{C_6H_5Na_3O_7,17} + m_{C_6H_5Na_3O_7,13} + m_{H_2O_2,17} + m_{NaOH,17} + m_{C_{10}H_{22},17} + m_{C_6H_5Cl,17,H} + m_{Cs,17} + m_{U,17} + m_{Pu,17} + m_{Fe,17} + m_{Solids,17} + m_{H_2O,17} + m_{FeN_3O_9,17} + m_{NO_3^-,17} + m_{Fe_2O_3,17} + m_{Na^+,17} + m_{NH_4^+,17} \\ &= 0.00 \text{ lb} + 0.00 \text{ lb} + 0.00 \text{ lb} + 40.06 \text{ lb} + 0.00 \text{ lb} + 0.0007300 \text{ lb} + 0.00 \text{ lb} + 0.09988 \text{ lb} + 0.0004994 \text{ lb} + 0.00 \text{ lb} + 0.00 \text{ lb} + 4623 \text{ lb} + 0.00 \text{ lb} + 2.996 \text{ lb} + 0.00 \text{ lb} + 13.81 \text{ lb} + 18.07 \text{ lb} \\ &= 4698 \text{ lb} \end{aligned}$$

Stream 18

$$m_{NaOH,18} = m_{NaOH,17} = 40.06$$

$$m_{U,18} = m_{U,17} = 0.09988 \text{ lb}$$

$$m_{Pu,18} = m_{Pu,17} = 0.0004994 \text{ lb}$$

$$m_{\text{H}_2\text{O},18} = (0.1)m_{\text{H}_2\text{O},17} = (0.1)(4623 \text{ lb}) = 462.3 \text{ lb}$$

$$m_{\text{NO}_3^-,18} = m_{\text{NO}_3^-,17} = 2.996 \text{ lb}$$

$$m_{\text{Na}^+,18} = m_{\text{Na}^+,17} = 13.81 \text{ lb}$$

$$m_{\text{NH}_4^+,18} = m_{\text{NH}_4^+,17} = 18.06 \text{ lb}$$

$$\begin{aligned} m_{\text{T},18} &= m_{\text{NaOH},18} + m_{\text{U},18} + m_{\text{Pu},18} + m_{\text{H}_2\text{O},18} + m_{\text{NO}_3^-,18} + m_{\text{Na}^+,18} + m_{\text{NH}_4^+,18} \\ &= 40.06 \text{ lb} + 0.09988 \text{ lb} + 0.0004994 \text{ lb} + 462.3 \text{ lb} + 2.996 \text{ lb} + 13.81 \text{ lb} + 18.06 \text{ lb} \\ &= 537.4 \text{ lb} \end{aligned}$$

Stream 19

$$m_{\text{C}_2\text{H}_8\text{N}_2\text{O}_4,19} = m_{\text{C}_2\text{H}_8\text{N}_2\text{O}_4,17} = 0.00 \text{ lb}$$

$$m_{\text{C}_6\text{H}_5\text{Na}_3\text{O}_7,19} = m_{\text{C}_6\text{H}_5\text{Na}_3\text{O}_7,17} = 0.00 \text{ lb}$$

$$m_{\text{H}_2\text{O}_2,19} = m_{\text{H}_2\text{O}_2,17} = 0.00 \text{ lb}$$

$$m_{\text{NaOH},19} = m_{\text{NaOH},17} - m_{\text{NaOH},18} = 40.06 \text{ lb} - 40.06 \text{ lb} = 0.00 \text{ lb}$$

$$m_{\text{C}_{10}\text{H}_{22},19} = m_{\text{C}_{10}\text{H}_{22},17} = 0.00 \text{ lb}$$

$$m_{\text{C}_2\text{HCl}_3,19} = m_{\text{C}_2\text{HCl}_3,17,\text{H}} = 0.0007300 \text{ lb}$$

$$m_{\text{Cs},19} = m_{\text{Cs},17} = 0.00 \text{ lb}$$

$$m_{\text{U},19} = m_{\text{U},17} - m_{\text{U},18} = 0.09988 \text{ lb} - 0.09988 \text{ lb} = 0.00 \text{ lb}$$

$$m_{\text{Pu},19} = m_{\text{Pu},17} - m_{\text{Pu},18} = 0.0004994 \text{ lb} - 0.0004994 \text{ lb} = 0.00 \text{ lb}$$

$$m_{\text{Fe},19} = m_{\text{Fe},17} = 0.00 \text{ lb}$$

$$m_{\text{Solids},19} = m_{\text{Solids},17} = 0.00 \text{ lb}$$

$$m_{\text{H}_2\text{O},19} = (0.9)m_{\text{H}_2\text{O},17} = (0.9)(4623 \text{ lb}) = 4161 \text{ lb}$$

$$m_{\text{FeN}_3\text{O}_9,19} = m_{\text{FeN}_3\text{O}_9,17} = 0.00 \text{ lb}$$

$$m_{\text{NO}_3^-,19} = m_{\text{NO}_3^-,17} - m_{\text{NO}_3^-,18} = 2.996 \text{ lb} - 2.996 \text{ lb} = 0.00 \text{ lb}$$

$$m_{\text{Fe}_2\text{O}_3,19} = m_{\text{Fe}_2\text{O}_3,17} = 0.00 \text{ lb}$$

$$m_{\text{Na}^+,19} = m_{\text{Na}^+,17} - m_{\text{Na}^+,18} = 13.81 \text{ lb} - 13.81 \text{ lb} = 0.00 \text{ lb}$$

$$m_{\text{NH}_4^+,19} = m_{\text{NH}_4^+,17} - m_{\text{NH}_4^+,18} = 18.06 \text{ lb} - 18.06 \text{ lb} = 0.00 \text{ lb}$$

$$m_{\text{T},19} = m_{\text{T},17} - m_{\text{T},18} = 4698 \text{ lb} - 537.4 \text{ lb} = 4161 \text{ lb}$$

Stream 20

$$m_{\text{C}_2\text{HCl}_3,20} = m_{\text{C}_2\text{HCl}_3,19} = 0.0007300 \text{ lb}$$

$$m_{\text{H}_2\text{O},20} = m_{\text{C}_2\text{HCl}_3,20} = 0.0007300 \text{ lb}$$

$$m_{\text{T},20} = m_{\text{C}_2\text{HCl}_3,20} + m_{\text{H}_2\text{O},20} = 0.0007300 \text{ lb} + 0.0007300 \text{ lb} = 0.001460 \text{ lb}$$

Stream 21

$$m_{\text{C}_2\text{H}_8\text{N}_2\text{O}_4,21} = m_{\text{C}_2\text{H}_8\text{N}_2\text{O}_4,19} = 0.00 \text{ lb}$$

$$m_{\text{C}_6\text{H}_5\text{Na}_3\text{O}_7,21} = m_{\text{C}_6\text{H}_5\text{Na}_3\text{O}_7,19} = 0.00 \text{ lb}$$

$$m_{\text{H}_2\text{O}_2,21} = m_{\text{H}_2\text{O}_2,19} = 0.00 \text{ lb}$$

$$m_{\text{NaOH},21} = m_{\text{NaOH},19} = 0.00 \text{ lb}$$

$$m_{\text{C}_{10}\text{H}_{22},21} = m_{\text{C}_{10}\text{H}_{22},19} = 0.00 \text{ lb}$$

$$m_{\text{C}_2\text{HCl}_3,21} = m_{\text{C}_2\text{HCl}_3,19} - m_{\text{C}_2\text{HCl}_3,20} = 0.0007300 \text{ lb} - 0.0007300 \text{ lb} = 0.00 \text{ lb}$$

$$m_{\text{Cs},21} = m_{\text{Cs},19} = 0.00 \text{ lb}$$

$$m_{\text{U},21} = m_{\text{U},19} = 0.00 \text{ lb}$$

$$m_{\text{Pu},21} = m_{\text{Pu},19} = 0.00 \text{ lb}$$

$$m_{\text{Fe},21} = m_{\text{Fe},19} = 0.00 \text{ lb}$$

$$m_{\text{Solids},21} = m_{\text{Solids},19} = 0.00 \text{ lb}$$

$$m_{\text{H}_2\text{O},21} = m_{\text{H}_2\text{O},19} - m_{\text{H}_2\text{O},20} = 4161 \text{ lb} - 0.0007300 \text{ lb} = 4161 \text{ lb}$$

$$m_{\text{FeN}_3\text{O}_9,21} = m_{\text{FeN}_3\text{O}_9,19} = 0.00 \text{ lb}$$

$$m_{\text{NO}_3^-,21} = m_{\text{NO}_3^-,19} = 0.00 \text{ lb}$$

$$m_{\text{Fe}_2\text{O}_3,21} = m_{\text{Fe}_2\text{O}_3,19} = 0.00 \text{ lb}$$

$$m_{\text{Na}^+,21} = m_{\text{Na}^+,19} = 0.00 \text{ lb}$$

$$m_{\text{NH}_4^+,21} = m_{\text{NH}_4^+,19} = 0.00 \text{ lb}$$

$$m_{\text{T},21} = m_{\text{T},19} - m_{\text{T},20} = 4161 \text{ lb} - 0.001460 \text{ lb} = 4161 \text{ lb}$$

Filter 1

$$A_{\text{F1}} = L_{\text{F1}} W_{\text{F1}} = (2 \text{ ft})(2 \text{ ft}) = 4 \text{ ft}$$

$$C_{\text{F1},1999} = C_{\text{F1},1980} \left(\frac{M \& S_{1999}}{M \& S_{1980}} \right) = (\$15,000) \left(\frac{1075.6}{565} \right) = \$28,556$$

Holding Tank 1

$$V_{\text{HT1}} = \frac{\pi D_{\text{HT1}}^2 H_{\text{HT1}}}{4} = \frac{\pi (5 \text{ ft})^2 (5 \text{ ft}) (7.4805 \text{ gal/ft}^3)}{4} = 734 \text{ gal}$$

$$F_{\text{c,HT1}} = F_{\text{m,HT1}} + F_{\text{p,HT1}} = 2.25 + 1.00 = 3.25$$

$$C_{\text{HT1},1999} = \left(\frac{M \& S_{1999}}{280} \right) (101.9) D_{\text{HT1}}^{1.066} H_{\text{HT1}}^{0.802} (2.18 + F_{\text{c,HT1}}) = \left(\frac{1075.6}{280} \right) (101.9) (5)^{1.066} (5)^{0.802} (2.18 + 3.25) = \$42,968$$

Pump 1

$$C_{\text{P1},1999} = C_{\text{P1},1980} \left(\frac{M \& S_{1999}}{M \& S_{1980}} \right) = (\$5,500) \left(\frac{1075.6}{565} \right) = \$10,470$$

Co-Precipitation Stirred Tank

$$V_{\text{CPST}} = \frac{\pi D_{\text{CPST}}^2 H_{\text{CPST}}}{4} = \frac{\pi (5 \text{ ft})^2 (5 \text{ ft}) (7.4805 \text{ gal/ft}^3)}{4} = 734 \text{ gal}$$

$$F_{\text{c,CPST}} = F_{\text{m,CPST}} + F_{\text{p,CPST}} = 2.25 + 1.00 = 3.25$$

$$C_{\text{CPST},1999} = \left(\frac{M \& S_{1999}}{280} \right) (101.9) D_{\text{CPST}}^{1.066} H_{\text{CPST}}^{0.802} (2.18 + F_{\text{c,CPST}}) = \left(\frac{1075.6}{280} \right) (101.9) (5)^{1.066} (5)^{0.802} (2.18 + 3.25) = \$42,968$$

Filter 2

$$A_{\text{F2}} = L_{\text{F2}} W_{\text{F2}} = (2 \text{ ft})(2 \text{ ft}) = 4 \text{ ft}$$

$$C_{\text{F2},1999} = C_{\text{F2},1980} \left(\frac{M \& S_{1999}}{M \& S_{1980}} \right) = (\$15,000) \left(\frac{1075.6}{565} \right) = \$28,556$$

Pump 2

$$C_{\text{P2},1999} = C_{\text{P2},1980} \left(\frac{M \& S_{1999}}{M \& S_{1980}} \right) = (\$5,500) \left(\frac{1075.6}{565} \right) = \$10,470$$

Holding Tank 2

$$V_{\text{HT2}} = \frac{\pi D_{\text{HT2}}^2 H_{\text{HT2}}}{4} = \frac{\pi (5 \text{ ft})^2 (5 \text{ ft}) (7.4805 \text{ gal/ft}^3)}{4} = 734 \text{ gal}$$

$$F_{\text{c,HT2}} = F_{\text{m,HT2}} + F_{\text{p,HT2}} = 2.25 + 1.00 = 3.25$$

$$C_{\text{HT2},1999} = \left(\frac{M \& S_{1999}}{280} \right) (101.9) D_{\text{HT2}}^{1.066} H_{\text{HT2}}^{0.802} (2.18 + F_{\text{c,HT2}}) = \left(\frac{1075.6}{280} \right) (101.9) (5)^{1.066} (5)^{0.802} (2.18 + 3.25) = \$42,968$$

Pump 3

$$C_{\text{P3},1999} = C_{\text{P3},1980} \left(\frac{M \& S_{1999}}{M \& S_{1980}} \right) = (\$11,000) \left(\frac{1075.6}{565} \right) = \$20,941$$

UV Rector

$$V_{\text{UVR}} = \frac{\pi D_{\text{UVR}}^2 H_{\text{UVR}}}{4} = \frac{\pi (5 \text{ ft})^2 (5 \text{ ft}) (7.4805 \text{ gal/ft}^3)}{4} = 734 \text{ gal}$$

$$F_{c,UVR} = F_{m,UVR} + F_{p,UVR} = 2.25 + 1.00 = 3.25$$

$$C_{UVR,1999} = \left(\frac{M \& S_{1999}}{280} \right) (101.9) D_{UVR}^{1.066} H_{UVR}^{0.802} (2.18 + F_{c,UVR}) = \left(\frac{1075.6}{280} \right) (101.9) (5)^{1.066} (5)^{0.802} (2.18 + 3.25) = \$42,968$$

Blower 1

$$Q_{B1} = \frac{m_{T,9} R T_{AIR}}{t_{B1} M W_{AIR} P_{UVR}} = \frac{(102.8 \text{ lb})(0.730 \text{ (atm)(ft}^3\text{)}/\text{(lb-mol)(}^\circ\text{R)}) (75^\circ\text{F} + 459.67)^\circ\text{R}}{(3 \text{ min})(28.850334 \text{ lb}/\text{lb-mol})(2 \text{ atm})} = 231.8 \text{ ft}^3/\text{min}$$

$$C_{B1} = \left(\frac{M \& S_{1999}}{260} \right) (39.7) Q_{B1}^{0.529} (4.0) = \left(\frac{1075.6}{260} \right) (39.7) (231.8)^{0.529} (4.0) = \$11,713$$

Filter 3

$$A_{F3} = L_{F3} W_{F3} = (1.5 \text{ ft})(1.5 \text{ ft}) = 2.25 \text{ ft}$$

$$C_{F3,1999} = C_{F3,1980} \left(\frac{M \& S_{1999}}{M \& S_{1980}} \right) = (\$12,000) \left(\frac{1075.6}{565} \right) = \$22,845$$

Pump 4

$$C_{P4,1999} = C_{P4,1980} \left(\frac{M \& S_{1999}}{M \& S_{1980}} \right) = (\$11,000) \left(\frac{1075.6}{565} \right) = \$20,941$$

Holding Tank 3

$$V_{HT3} = \frac{\pi D_{HT3}^2 H_{HT3}}{4} = \frac{\pi (5 \text{ ft})^2 (5 \text{ ft}) (7.4805 \text{ gal}/\text{ft}^3)}{4} = 734 \text{ gal}$$

$$F_{c,HT3} = F_{m,HT3} + F_{p,HT3} = 2.25 + 1.00 = 3.25$$

$$C_{HT3,1999} = \left(\frac{M \& S_{1999}}{280} \right) (101.9) D_{HT3}^{1.066} H_{HT3}^{0.802} (2.18 + F_{c,HT3}) = \left(\frac{1075.6}{280} \right) (101.9) (5)^{1.066} (5)^{0.802} (2.18 + 3.25) = \$42,968$$

Pump 5

$$C_{P5,1999} = C_{P5,1980} \left(\frac{M \& S_{1999}}{M \& S_{1980}} \right) = (\$5,000) \left(\frac{1075.6}{565} \right) = \$9,519$$

Heat Exchanger 1

$$\Delta T_{m,HE1} = \frac{(T_{H2,HE1} - T_{C1,HE1}) - (T_{H1,HE1} - T_{C2,HE1})}{\ln \left(\frac{T_{H2,HE1} - T_{C1,HE1}}{T_{H1,HE1} - T_{C2,HE1}} \right)} = \left[\frac{(634.67^\circ \text{R} - 534.67^\circ \text{R}) - (671.67^\circ \text{R} - 609.67^\circ \text{R})}{\ln \left(\frac{634.67^\circ \text{R} - 534.67^\circ \text{R}}{671.67^\circ \text{R} - 609.67^\circ \text{R}} \right)} \right] F = 79.49^\circ \text{F}$$

$$A_{HE1} = \frac{F_{HE1} \rho C_{p,H_2O} \Delta T_{HE1}}{MW_{H_2O} U_{HE1} \Delta T_{m,HE1}} = \frac{(1 \text{ gal/min})(62.261 \text{ lb/ft}^3)(18 \text{ Btu/lb-mol}^\circ \text{R})(609.67^\circ \text{R} - 534.67^\circ \text{R})(60 \text{ min/h})}{(18.01528 \text{ lb/lb-mol})(50 \text{ Btu/h ft}^2 \cdot ^\circ \text{F})(79.49^\circ \text{F})(7.4805 \text{ gal/ft}^3)} = 9.42 \text{ ft}^2$$

$$F_{c,HE1} = (F_{d,HE1} + F_{p,HE1})F_{m,HE1} = (0.85 + 0.00)(3.75) = 3.19$$

$$C_{HE1,1999} = \left(\frac{M \& S_{1999}}{280} \right) (101.3) A_{HE1}^{0.65} (2.29 + F_{c,HE1}) = \left(\frac{1075.6}{280} \right) (101.3) (9.42)^{0.65} (2.29 + 3.19) = \$9,155$$

Gas Stripper

$$V_{GS} = \frac{\pi D_{GS}^2 H_{GS}}{4} = \frac{\pi (2 \text{ ft})^2 (8 \text{ ft})(7.4805 \text{ gal/ft}^3)}{4} = 188 \text{ gal}$$

$$F_{c,GS} = F_{m,GS} + F_{p,GS} = 2.25 + 1.00 = 3.25$$

$$C_{GS,1999} = \left(\frac{M \& S_{1999}}{280} \right) (101.9) D_{GS}^{1.066} H_{GS}^{0.802} (2.18 + F_{c,GS}) = \left(\frac{1075.6}{280} \right) (101.9) (2)^{1.066} (8)^{0.802} (2.18 + 3.25) = \$23,585$$

Heat Exchanger 2

$$\Delta T_{m,HE2} = \frac{(T_{H2,HE2} - T_{C1,HE2}) - (T_{H1,HE2} - T_{C2,HE2})}{\ln \left(\frac{T_{H2,HE2} - T_{C1,HE2}}{T_{H1,HE2} - T_{C2,HE2}} \right)} = \left[\frac{(534.67^\circ \text{R} - 519.67^\circ \text{R}) - (609.67^\circ \text{R} - 549.67^\circ \text{R})}{\ln \left(\frac{534.67^\circ \text{R} - 519.67^\circ \text{R}}{609.67^\circ \text{R} - 549.67^\circ \text{R}} \right)} \right] F = 32.46^\circ \text{F}$$

$$A_{HE2} = \frac{F_{HE2} \rho C_{p,H_2O} \Delta T_{HE2}}{MW_{H_2O} U_{HE2} \Delta T_{m,HE2}} = \frac{(1 \text{ gal/min})(62.261 \text{ lb/ft}^3)(18 \text{ Btu/lb-mol}^\circ \text{R})(609.67^\circ \text{R} - 534.67^\circ \text{R})(60 \text{ min/h})}{(18.01528 \text{ lb/lb-mol})(30 \text{ Btu/h ft}^2 \cdot ^\circ \text{F})(32.46^\circ \text{F})(7.4805 \text{ gal/ft}^3)} = 38.4 \text{ ft}^2$$

$$F_{c,HE2} = (F_{d,HE2} + F_{p,HE2})F_{m,HE2} = (0.85 + 0.00)(3.75) = 3.19$$

$$C_{HE2,1999} = \left(\frac{M \& S_{1999}}{280} \right) (101.3) A_{HE2}^{0.65} (2.29 + F_{c,HE2}) = \left(\frac{1075.6}{280} \right) (101.3) (38.4)^{0.65} (2.29 + 3.19) = \$22,841$$

Separation Tank

$$V_{ST} = \frac{\pi D_{ST}^2 H_{ST}}{4} = \frac{\pi (3 \text{ ft})^2 (3 \text{ ft})(7.4805 \text{ gal/ft}^3)}{4} = 159 \text{ gal}$$

$$F_{c,ST} = F_{m,ST} + F_{p,ST} = 2.25 + 1.00 = 3.25$$

$$C_{ST,1999} = \left(\frac{M \& S_{1999}}{280} \right) (101.9) D_{ST}^{1.066} H_{ST}^{0.802} (2.18 + F_{c,ST}) = \left(\frac{1075.6}{280} \right) (101.9) (3)^{1.066} (3)^{0.802} (2.18 + 3.25) = \$16,547$$

Pump 6

$$C_{P6,1999} = C_{P6,1980} \left(\frac{M \& S_{1999}}{M \& S_{1980}} \right) = (\$5,000) \left(\frac{1075.6}{565} \right) = \$9,519$$

Blower 2

$$Q_{B2} = \frac{m_{T,14} R T_{AIR}}{t_{B2} MW_{AIR} P_{GS}} = \frac{(10,000 \text{ lb})(0.730 \text{ (atm)(ft}^3\text{)}/(\text{lb-mol})(^\circ\text{R}))(75^\circ\text{F} + 459.67)^\circ\text{R}}{(600 \text{ min})(28.850334 \text{ lb/lb-mol})(1 \text{ atm})} = 225.5 \text{ ft}^3/\text{min}$$

$$C_{B2} = \left(\frac{M \& S_{1999}}{260} \right) (39.7) Q_{B2}^{0.529} (4.0) = \left(\frac{1075.6}{260} \right) (39.7) (225.5)^{0.529} (4.0) = \$11,543$$

Pump 7

$$C_{P7,1999} = C_{P7,1980} \left(\frac{M \& S_{1999}}{M \& S_{1980}} \right) = (\$5,000) \left(\frac{1075.6}{565} \right) = \$9,519$$

Pump 8

$$C_{P8,1999} = C_{P8,1980} \left(\frac{M \& S_{1999}}{M \& S_{1980}} \right) = (\$4,000) \left(\frac{1075.6}{565} \right) = \$7,615$$

Heat Exchanger 3

$$\Delta T_{m,HE3} = \frac{(T_{H2,HE3} - T_{C1,HE3}) - (T_{H1,HE3} - T_{C2,HE3})}{\ln \left(\frac{T_{H2,HE3} - T_{C1,HE3}}{T_{H1,HE3} - T_{C2,HE3}} \right)} = \left[\frac{(534.67^\circ\text{R} - 519.67^\circ\text{R}) - (671.67^\circ\text{R} - 549.67^\circ\text{R})}{\ln \left(\frac{534.67^\circ\text{R} - 519.67^\circ\text{R}}{671.67^\circ\text{R} - 549.67^\circ\text{R}} \right)} \right]^\circ\text{F} = 51.05^\circ\text{F}$$

$$A_{HE3} = \frac{F_{HE3} \rho (C_{p,H_2O} \Delta T_{HE3} + \Delta H_v MW_{H_2O})}{MW_{H_2O} U_{HE3} \Delta T_{m,HE3}} = \frac{(0.9 \text{ gal/min})(62.261 \text{ lb/ft}^3) \left[(18 \text{ Btu/lb-mol}^\circ\text{R})(671.67^\circ\text{R} - 534.67^\circ\text{R}) + (970.3 \text{ Btu/lb})(18.01528 \text{ lb/lb-mol}) \right] (60 \text{ min/h})}{(18.01528 \text{ lb/lb-mol})(150 \text{ Btu/h ft}^2 \text{ }^\circ\text{F})(51.05^\circ\text{F})(7.4805 \text{ gal/ft}^3)} = 65.0 \text{ ft}^2$$

$$F_{c,HE3} = (F_{d,HE3} + F_{p,HE3}) F_{m,HE3} = (0.85 + 0.00)(3.75) = 3.19$$

$$C_{HE3,1999} = \left(\frac{M \& S_{1999}}{280} \right) (101.3) A_{HE3}^{0.65} (2.29 + F_{c,HE3}) = \left(\frac{1075.6}{280} \right) (101.3) (65.0)^{0.65} (2.29 + 3.19) = \$32,137$$

Pump 9

$$C_{P9,1999} = C_{P9,1980} \left(\frac{M \& S_{1999}}{M \& S_{1980}} \right) = (\$4,800) \left(\frac{1075.6}{565} \right) = \$9,138$$

Pump 10

$$C_{P10,1999} = C_{P10,1980} \left(\frac{M \& S_{1999}}{M \& S_{1980}} \right) = (\$4,800) \left(\frac{1075.6}{565} \right) = \$9,138$$

Piping

$$C_{P,1999} = (0.13) \Sigma C_{X,1999} = (0.13)(\$566,226) = \$73,609$$

Instrumentation and Controls

$$C_{IC,1999} = (0.0475) \Sigma C_{X,1999} = (0.0475)(\$566,226) = \$26,896$$

Electrical Equipment and Materials

$$C_{EEM,1999} = (0.0575) \Sigma C_{X,1999} = (0.0575)(\$566,226) = \$32,558$$

Fixed Capital Investment

$$\begin{aligned} \text{Fixed Capital Investment} &= \Sigma C_{X,1999} + C_{P,1999} + C_{IC,1999} + C_{EEM,1999} + C_{TE,1999} \\ &= \$566,266 + \$73,609 + \$26,896 + \$32,558 + \$224,000 = \$923,289 \end{aligned}$$

Annualized Fixed Capital

$$\begin{aligned} \text{Annualized Fixed Capital} &= \text{Fixed Capital Investment} \left[\frac{i(1+i)^n}{(1+i)^n - 1} \right] \\ &= (\$923,289) \left[\frac{(0.10)(1+0.10)^{15}}{(1+0.10)^{15} - 1} \right] = \$121,388/\text{yr} \end{aligned}$$

Depreciation (Douglas, 1988)

$$\begin{aligned}\text{Depreciation} &= (\text{Fixed Capital Investment} - \text{Salvage Value}) \left[\frac{(2)(\text{Depreciable Life} - \text{Year} + 1)}{\text{Depreciable Life}(\text{Depreciable Life} + 1)} \right] \\ &= (\$923,289 - \$0) \frac{(2)(9 - 1 + 1)}{(9)(9 + 1)} = \$184,658\end{aligned}$$

Utilities Expense (Peters, 1980)

$$\text{General} = (0.10)\text{Total Operating Expenses} = (0.10)(\$3,210,936/\text{yr}) = \$321,094/\text{yr}$$

$$\text{UVR} = (5225.6 \text{ kW}/_{\text{batch}})(9 \text{ hr})(\$0.0358/\text{kWh})(720 \text{ batches}/_{\text{yr}}) = \$1,212,256/\text{yr}$$

Maintenance Expense (Douglas, 1980)

$$\text{Maintenance Expense} = (0.04)\text{Fixed Capital Investment} = (0.04)(\$923,289) = \$36,931/\text{yr}$$

Waste Disposal Expense (Watson, 2000)

$$\begin{aligned}\text{Waste Disposal Expense} &= \frac{(720 \text{ batches}/_{\text{yr}})(m_{T,2} + m_{T,4} + m_{T,7} + m_{T,12} + m_{T,16} + m_{T,20})(\$1,000/\text{ft}^3)}{124.85 \text{ ft}^3/\text{h}^3} \\ &= \frac{(720 \text{ batches}/_{\text{yr}})(9.988 \text{ ft}^3/\text{batch} + 0.01998 \text{ ft}^3/\text{batch} + 3.606 \text{ ft}^3/\text{batch} + 2.856 \text{ ft}^3/\text{batch} + 1.100 \text{ ft}^3/\text{batch} + 0.001460 \text{ ft}^3/\text{batch})(\$1,000/\text{ft}^3)}{124.85 \text{ ft}^3/\text{h}^3} = \$101,331/\text{yr}\end{aligned}$$

Materials Expense

$$\text{Iron Nitrate} = \frac{(\$64.00/\text{batch})(453.59 \text{ lb}/_{\text{g}})(3.896 \text{ lb})(720 \text{ batches}/_{\text{yr}})}{500 \text{ g}} = \$162,864/\text{yr}$$

$$\text{Titanium Dioxide} = \frac{(\$66.97)(453.59 \text{ lb}/_{\text{g}})(2.492 \text{ lb})}{25 \text{ g}} = \$3,028/\text{yr}$$

$$\text{Activated Carbon} = \frac{(\$14.20/\text{month})(10 \text{ months}/_{\text{yr}}) \pi D_{ACB}^2 H_{ACB}}{(4)(1 \text{ ft}^3)} = (\$111.53/\text{ft}^3/\text{yr})(4.5 \text{ ft}^2)(5.5 \text{ ft}) = \$12,421/\text{yr}$$

$$\text{Empore Filters} = (\$1,000/\text{batch})(720 \text{ batches}/_{\text{yr}}) = \$720,000/\text{yr}$$

Labor and Overhead Expense

$$\text{Labor and Overhead Expense} = (\$30/\text{worker hr})(2 \text{ workers})(365 \text{ days}/_{\text{yr}})(24 \text{ hr}/_{\text{day}}) = \$525,600/\text{yr}$$

Salaries Expense (Douglas, 1980)

$$\text{Salaries Expense} = (0.125)\text{Fixed Capital Investment} = (0.125)(\$923,289) = \$115,411/\text{yr}$$

Total Operating Expenses

$$\text{Total Operating Expenses} = \frac{\sum C_z}{0.9} = \frac{\$2,889,843}{0.9} = \$3,210,936/\text{yr}$$

Total Cost

$$\text{Total Cost} = \text{Annualized Fixed Capital} + \text{Total Operating Expenses} = \$121,388/\text{yr} + \$3,210,936/\text{yr} = \$3,332,325/\text{yr}$$

After Tax Cash Flow

$$\begin{aligned}\text{ATCF} &= (1 - \text{Tax Rate})(\text{Revenue} - \text{Total Cost}) + (\text{Tax Rate})(\text{Depreciation}) \\ &= (1 - 0.40)(\$3,588,764 - \$3,332,325) + (0.40)(\$184,658) = \$227,727\end{aligned}$$

Present Value of the After Tax Cash Flow

$$\text{Present Value of the ATCF} = \frac{\text{ATCF}}{(1 + \text{MARR})^{\text{Year}}} = \frac{\$227,727}{(1 + 0.20)^1} = \$189,772$$