Proposed Use of a Constructed Wetland for the Treatment of Metals in the S-04 Outfall of the Defense Waste Processing Facility at the Savannah River Site

by

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Prepared for
Dr. Joe Morgan
CE 698
Auburn University

By
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November 9, 1999
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I. INTRODUCTION

Tim Glover
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Dr. Joe Morgan
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Dept. of Civil Engineering
Auburn University, AL 36849

Dr. Morgan,

The following report fulfills the requirements of my final engineering project for CE 698. The subject of the report is a research into the feasibility of constructing a wetland for the treatment of metals in the discharge of the S-04 outfall at the Defense Waste Processing Facility located at the Savannah River Site in Aiken, South Carolina.

My research concluded and recommended that a wetland be constructed to treat the S-04 outfall discharge, as it is a cost-effective as well as a technologically feasible alternative to more conventional means.

If questions should arise during the review of the project, feel free to contact me at my home number (803) 637-5276 or by e-mail at timmyg@triplet.net.

Sincerely,

Tim Glover
II. ABBREVIATION LIST

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>APS</td>
<td>Aquatic Plant System constructed wetland</td>
</tr>
<tr>
<td>BOD</td>
<td>Biochemical Oxygen Demand</td>
</tr>
<tr>
<td>CERCLA</td>
<td>Comprehensive Environmental Response, Compensation and Liability Act</td>
</tr>
<tr>
<td>COD</td>
<td>Chemical Oxygen Demand</td>
</tr>
<tr>
<td>CPC</td>
<td>Chemical Process Cell</td>
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<tr>
<td>CWA</td>
<td>Clean Water Act</td>
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<tr>
<td>DOE</td>
<td>Department of Energy</td>
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<tr>
<td>DWPF</td>
<td>Defense Waste Processing Facility</td>
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<tr>
<td>FWS</td>
<td>Free Water Surface System constructed wetland</td>
</tr>
<tr>
<td>MFT</td>
<td>Melter Feed Tank</td>
</tr>
<tr>
<td>NPDES</td>
<td>National Pollutant Discharge Elimination System</td>
</tr>
<tr>
<td>PHA</td>
<td>Precipitate Hydrolysis Aqueous</td>
</tr>
<tr>
<td>SCDHEC</td>
<td>South Carolina Department of Health and Environmental Control</td>
</tr>
<tr>
<td>SF</td>
<td>Subsurface Flow System constructed wetland</td>
</tr>
<tr>
<td>SITE</td>
<td>Superfund Innovative Technology Evaluation</td>
</tr>
<tr>
<td>SME</td>
<td>Slurry Mix Evaporator</td>
</tr>
<tr>
<td>SPC</td>
<td>Salt Process Cell</td>
</tr>
<tr>
<td>SRAT</td>
<td>Sludge Receipt and Adjustment Tank</td>
</tr>
<tr>
<td>SRS</td>
<td>Savannah River Site</td>
</tr>
<tr>
<td>TOC</td>
<td>Total Organic Carbon</td>
</tr>
<tr>
<td>TVA</td>
<td>Tennessee Valley Authority</td>
</tr>
<tr>
<td>WAPS</td>
<td>Waste Acceptance Product Specifications</td>
</tr>
<tr>
<td>WSRC</td>
<td>Westinghouse Savannah River Company</td>
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III. OVERVIEW

A. SAVANNAH RIVER SITE

The Savannah River Site (SRS) is owned by the United States Department of Energy (DOE) and is operated by the primary contractor, Westinghouse Savannah River Company (WSRC). SRS is an approximately circular tract of 310 square miles (198,3440 acres) within Aiken, Barnwell and Allendale counties in southwestern South Carolina (SC). (See Fig. 1)

The SRS has five production reactors, which are no longer operative, a heavy water plant that was shut down in early 1982, a fuel fabrication area, two separations plants for processing irradiated fuel and recovery of isotopes, tank farms where high level wastes are treated and stored, process development laboratories to support production operations and associated other support facilities.

Since startup of the F and H chemical separation areas in 1954, about 83 million gallons of aqueous radioactive wastes have been generated from reprocessing of irradiated reactor materials. This radioactive waste was sent to large underground tanks at the F & H Area Tank Farms for long-term storage. Waste management campaigns have reduced this volume, primarily by evaporation and concentration, to the present day volume of approximately 32 million gallons stored in 48 tanks. This waste contains approximately 500 megacuries of beta-gamma radioactivity. For years, storing the waste in large underground tanks proved to be a safe and efficient means of controlling the waste. However, over the past few decades, several of the waste storage tanks have developed leaks due to corrosion with one actually leaking into the environment. In the early 1980's the DOE recognized that there would be significant safety and cost advantages associated with immobilizing the radioactive waste in a stable solid form. The Defense Waste Processing Facility (DWPF) was designed and constructed to accomplish this task.

B. DEFENSE WASTE PROCESSING FACILITY

The DWPF is part of an integrated waste treatment system at the SRS to treat wastes containing radioactive contaminants. (See Fig. 2) The Saltstone Facility, or Z-Area is one of the components of the DWPF. This facility was designed to process the less radioactive water soluble salts. The salt solution is immobilized by mixing it with cement, slag and fly ash to form grout. The grout is
pumped into aboveground storage vaults where it hardens into concrete monoliths called saltstone. Over its design life, the Saltstone Facility is expected to process about 130 million gallons of salt solution from the Tank Farms, or 224 million gallons of saltstone will be produced. (See Fig. 3 for Saltstone) Since this research project will not deal with this facility, the use of the acronym DWPF in this paper will from now on refer to the Vitrification Facility only.

The other component, the DWPF Vitrification Facility, or S-Area (Photo 1), is the nation’s first high-level radioactive waste vitrification facility. The high level waste in the tank farms is washed to remove soluble salts. If necessary, insoluble aluminum is removed through high-temperature caustic dissolution. Thus the tank farm waste is transferred to the DWPF in two forms: Precipitate Slurry and Sludge Slurry.

The precipitate is processed in the DWPF Salt Processing Cell (SPC) to remove most of the organic material. The compounds comprising the precipitate react in the presence of formic acid and copper (II) catalyst. The products of this reaction are aromatic organic compounds (benzene, phenol, and minor amounts of higher boiling aromatics) and an aqueous phase known as Precipitate Hydrolysis Aqueous (PHA). The PHA contains the cesium, soluble formate salts, boric acid and excess formic acid. Since radioactive precipitate is not yet available from the tank farms for immobilization, simulated PHA (formic acid, water, and soluble copper nitrate) has been substituted. (See Fig. 4 for SPC operation)

The sludge is treated in the Chemical Process Cell (CPC) of the DWPF. (See Fig. 4 for CPC operation) The sludge is transferred directly into the Sludge Receipt and Adjustment Tank (SRAT) and then neutralized with nitric acid. The simulated PHA is added to the sludge after the sludge is heated to boiling. After the PHA and sludge are blended and processed in the SRAT, the SRAT product is transferred to the Slurry Mix Evaporator (SME) where a borosilicate glass frit is added and the slurry is concentrated to approximately 50 weight % solids. This is now considered melter feed. (See Table 1 for typical SME analysis)

The amount of sludge and PHA to be blended in the SRAT and the amount of SRAT product and frit to be blended in the SME are determined by the desired glass composition. The region of desired composition is determined by a series of glass property models and statistical algorithms. Any point within the acceptable region can be selected as the target for a particular batch.

The SME is the hold point in the process. The analysis of SME samples are used by the DWPF engineers to determine the acceptability (See Table 2 for Acceptance spreadsheet) of the batch versus a DOE approved Waste Acceptance Product Specifications (WAPS). The most important of the glass specifications is the product consistency specification which states that the DWPF
Environmental Assessment Glass that was set forth as the standard during initial design. This measurement is a crushed glass durability test in which the results are expressed as the amount of boron, lithium, and sodium measured in the leachate. The SME composition and thermodynamic hydration are used to predict the leach rates for boron, lithium and sodium. Acceptance of the melter feed is based on the results of this prediction. No material is transferred from the SME to the Melter Feed Tank (MFT) until it has been determined to be acceptable. A glass pour stream sample is taken occasionally during filling of a canister and a crushed glass durability test is performed to confirm that the glass durability is acceptable.

Once the melter feed material in the SME is determined to be acceptable, it is transferred to the MFT and then fed to the joule heated melter (See Fig. 5). The DWPF melter has two pair of diametrically opposed electrodes. The feed slurry is introduced from the top of the melter and forms a crust, or cold cap, on the surface of the melt pool as the water is evaporated and removed via the off-gas system. The cold cap melts from the bottom and forms a borosilicate glass matrix. The nominal glass pool temperature is 1130 deg. C. The mixing behavior of the glass is that of a continuous stirred tank reactor. The glass is removed from an opening near the bottom through a riser and pour spout. A vacuum is drawn on the pour spout to pour the glass into a stainless steel canister approximately 10 feet tall and 2.5 feet in diameter.

After a canister is filled, a temporary seal is installed to prevent free liquid from entering the canister during the decontamination process. Decontamination of the canister surface involves blasting the canister with a frit slurry mixture using high pressure air injection. This frit slurry mixture is used in the next SME batch as part of the required frit addition. The canister is then welded closed and transferred to an interim storage building. The future plans are that the canisters will be transferred to a final geological repository. (See Fig. 6 for overall DWPF canister processing)

Following a ten-year construction period and three-year non-radioactive test program, the DWPF began radioactive operations in March 1996. To date, approximately 740 radioactive canisters have been produced. Each canister contains an average of 4000 pounds of glass.

C. DWPF WASTE STREAMS

No liquids contaminated with radioisotopes of process origin are released to the environment from the DWPF. Radioactive liquid wastes generated
at the DWPF are collected, corrosion inhibited, and transferred back to the H-Area Tank Farm for reprocessing.

Releases of chemicals to the environment are maintained within the limits of the South Carolina Department of Health and Environmental Control (SCDHEC) permits. The water effluent system is designed to comply with all federal, state and local requirements as defined in the National Pollutant Discharge Elimination System (NPDES) approvals.

Non-radioactive wastes, consisting of chemical, industrial and sanitary streams generated at the DWPF are monitored, collected, and treated, if necessary, before discharge to the environment (See Fig. 7 for sources/routing). These wastes are also sampled continuously for radioactivity in one of two swirl cells (one cell monitors cooling tower blowdown and effluents from the chemical waste treatment facility; the second monitors the combined cooling water recirculation flow).

Facilities are provided to treat batches of chemically contaminated wastewaters before they are discharged to the environment. Hold tanks are provided for the caustic and various acid wastes. The effluents are neutralized by controlled blending of the caustic and acid wastes as much as possible. Otherwise, chemical agents are added to neutralize the waste before discharge.

Release of the neutralized wastes with the cooling tower blowdown is regulated to render the resultant waste stream acceptable for discharge to the environment via the S-04 outfall. (See Fig. 8 & Photo 6 for outfall location)

Industrial wastewater discharges from the DWPF are limited and monitored as required by the NPDES permit, issued by SCDHEC. This permit requires monitoring and reporting of all chemical waste discharges.

IV. PROBLEM DISCUSSION

Four water samples of the S-04 outfall (See Photos 5 & 7) were taken between 12/11/98 and 3/10/99. These were taken to ensure compliance with the discharge parameters as listed on the DWPF NPDES 2C application. Two were taken during the discharge of the Caustic Waste Neutralization Tanks and the other two were taken during the discharge of the Organic Acid Waste Neutralization Tanks. These samples were analyzed by a SCDHEC certified laboratory for metals, nitrates, nitrites, Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), and Total Organic Carbon (TOC).

The laboratory results indicated elevated levels of copper, zinc, lead, aluminum, iron and manganese. Zinc was found at concentrations greater than expected per the current S-04 NPDES 2C application. The expected zinc
concentration is .286 ppm monthly average and .639 ppm daily maximum. The average zinc concentration in the samples was .463 ppm with a maximum concentration of .653 ppm. Iron is listed on the NPDES 2C as “Believed Present” but at trace concentrations due to make-up well water. The other metals listed above are “Believed Absent” on the application.

It was decided that the source(s) of the elevated metal concentrations must be identified, so samples of all major contributors discharging to the S-04 outfall were taken and analyzed. Samples of the Raw Well Water & Neutralized Well Water (See Photo 2), Cooling Tower (See Photo 3), Clean Condensate Tank, Effluent Lift Station, Caustic Waste Neutralization Tanks 1 & 2, and the Organic Acid Waste Neutralization Tanks 1 & 2 were taken and analyzed for copper, zinc, lead, nickel, chromium, aluminum, manganese and iron.

The results of these samples (See Table 3) indicated that the major source of the metals in the S-04 outfall is from the DWPF make-up water sources via the Cooling Tower blowdown. Both Neutralized Well Water and Clean Condensate is used as make-up to the Cooling Tower. The Cooling Tower blowdown is the major contributor to discharges at the S-04 outfall. Approximately 630,000 gallons per month is discharged to the S-04 outfall from this blowdown (See Photos 4 & 8). The Caustic Waste and Organic Acid Waste Neutralization tanks combined discharge only 17,000 gallons per month.

The Neutralized Well Water sample showed concentrations of aluminum, copper, iron, & lead above the potential discharge concentration limits for these metals. These potential limits were calculated by the DWPF Environmental Department engineers based on the SCDHEC Toxic Control Strategy. These are the limits that could be expected to be imposed by SCDHEC based on past dealings with this agency. The Clean Condensate sample also showed concentrations of copper, iron, lead and zinc above expected discharge limits for these metals. The samples of the Caustic/Organic Acid Waste Neutralization Tanks showed elevated concentrations of copper, iron, lead, zinc, and also manganese. Manganese was the only metal not shown to be concentrated in the make-up water sources, but present in the process waste stream. It can not, at this time, be quantified how much of the metal concentration comes from the process; it can be said that any process contribution is overwhelmed by the concentration of metals in the make-up water sources, and their relative volumes.

A list of feasible options was generated by DWPF Engineering for consideration by Management. They are as follows:

1) Evaluate replacement of the make-up water sources.
2) Treat the existing water sources by filtration, orthophosphate addition or some other proven means to remove metals.

3) Treat the effluent before discharge by similar means as #2 above.

4) Send the effluent back to Tank Farm to be treated with their non-rad effluent.

5) Construct a wetland to treat metals in effluent discharge.

The cost and difficulties associated with items 1-4 above are significant. The purpose of this paper is to evaluate the feasibility of use of a constructed wetland to treat the metals in the effluent being discharged to the S-04 outfall.

V. CONSTRUCTED WETLANDS

A. BACKGROUND

Wastewater has been discharged to wetlands for centuries, but only within the last two decades has this alternative received considerable attention for engineered use in wastewater management. The term “wetlands” has only recently come into popular use, referring collectively to what for years have been known more commonly as marshes, bogs, swamps, mires, etc. Wetlands occur in a wide range of geographical settings all over the world and are generally defined as the transitional zone between land and open water. Wetlands can vary in size, from a small pothole to an area covering several million acres. The water table in wetlands is usually found either at or near the surface of the soil; the land may be periodically covered with shallow water and is inhabited by water-tolerant vegetation. Until only recently wetlands were considered a waste of what might otherwise be valuable real estate or agricultural land. In fact, they were often drained in order to be used for such purposes.

Wetlands are likely to form where the land directs surface water to shallow basins and where a relatively impermeable subsurface layer prevents the surface water from seeping into the ground. These conditions can also be created to form a wetland. A wetland can be built almost anywhere in the landscape by shaping the land surface to collect surface water and by sealing the basin to retain this water. A constructed wetland consists of a properly designed basin that
components of wetlands, such as communities of microbes and aquatic invertebrates, develop naturally over time.

The mechanisms that are available to improve water quality are numerous and often interrelated. These include, but are not limited to:

* settling of suspended particulate matter
* filtration and chemical precipitation through contact of the water with the substrate and litter (primarily plant material)
* chemical transformation
* adsorption and ion exchange on the surfaces of plants, substrate, sediment, and litter
* breakdown and transformation of pollutants by microorganisms and plants
* uptake and transformation of nutrients by microorganisms and plants
* predation and natural death of pathogens

In general, metals are removed by the oxidation of iron followed by precipitation of iron hydroxides, which leads to the removal of various other metals by precipitation. Increasing alkalinity, with lime addition or other means, hastens the formation of the hydroxides and subsequent precipitation.

There are generally three types of constructed wetlands: free-water surface systems (FWS), subsurface flow systems (SF), and aquatic plant systems (APS). An FWS wetland (See Fig. 9) typically consists of shallow basins or channels with slow-flowing water and plant life. An SF wetland (See Fig. 10) typically consists of basins or channels filled with a permeable substrate material which the water flows through rather than over as in an FWS. An APS wetland is essentially an FWS with deeper channels containing floating or suspended plants such as water hyacinths or microorganisms such as algae. The different types of wetlands can be used alone, in combination, or with other remediation technologies to address a variety of treatment needs.

In general, a FWS is an aerobic wetland that removes metals by the method mentioned above. FWS wetlands are most successful at removing metals when the waste being treated is at a moderately low to neutral pH. SF wetlands are anaerobic systems that can vary significantly in both size and complexity. Basically, SF wetlands remove metal contaminants by reaction with hydrogen sulfide produced by sulfate-reducing bacteria, forming insoluble metal sulfides. Aluminum, cadmium, iron, manganese, molybdenum, and zinc have the strongest tendencies to form these sulfides.
Figure 11 shows an example of a general schematic of a FWS wetland. This system uses a limestone drain (to increase alkalinity), both deep and shallow ponds, marshes, a rock filter, and an alkaline bed to remediate the wastewater. Finally, pH is adjusted to regulatory levels by chemical amendment in the alkaline bed followed by Total Suspended Solids (TSS) removal in the polishing cell. The various cells shown in Figure 11 can be used in any combination to meet specific treatment requirements.

The flow scheme of SF wetlands is simple. The treatment stream may first flow through a bed of limestone as above. The drainage then flows into a wetland cell where it flows through the substrate. Depending on the cell design, the drainage may flow vertically up or down, or horizontally through the substrate. Within the substrate, inorganic contaminants are sorbed, precipitated, or biologically reduced and precipitated. The treatment water then flows out of the cell.

After almost 30 years of use in wastewater treatment, constructed wetlands now number over 500 in Europe and over 600 in North America. FWS wetlands are most common in North America, but SF wetlands predominate in Europe where the technology originated in a German laboratory. SF wetlands are desirable in Europe because they provide more intensive treatment in a smaller space than FWS wetlands; this is important in countries where open space is limited.

Constructed wetland systems in North America have been designed mainly for large-scale treatment of municipal wastewater, but since the 1980’s they have also been built to treat other wastewaters. These include mine drainage, agricultural and storm water runoff, effluent from livestock operations, and industrial wastewater.

B. LAWS AND REGULATIONS

Interest in implementing federal policy for wetland protection began in the early 1970’s as scientists began to understand the valuable functions of these systems. Prior to this, as mentioned earlier, the destruction of wetlands was often encouraged by federal and state governments for the purpose of converting them to agricultural land, extracting minerals or oil, constructing highways, and improving flood control and navigation. These policies resulted in a loss of 30 - 50% of the estimated 230 million acres of wetlands in the continental United States.

As public support for wetland protection grew, the federal government responded to pressure to create more consistent wetland protection policies. In
1977, President Carter issued two executive orders requiring all federal agencies to consider wetland protection as a priority in their policies, and to revise their procedures to avoid where possible adverse impacts on these areas. The Federal Water Pollution Control Act (PL 92-500), otherwise known as the Clean Water Act (CWA), was also amended during this year to provide additional mechanisms to protect wetlands.

While there was no specific mention of wetlands in the regulatory language, the definition of "waters of the United States" as cited in the act, was expanded to include wetlands, thus providing the federal government with a powerful tool for wetland protection. Other legislation, such as the Coastal Resource Management Act (1972), the Flood Disaster Prevention Act (1973, 1977), the Federal Aid to Wildlife Restoration Act (1974), and the Endangered Species Act (1973) have provided various other legal mechanisms through which wetlands are protected. In addition, many states have developed wetland protection regulations as the trend increases for the federal government to delegate its authority to state and local control.

To date, there have been no specific federal regulations established for the use of wetlands in wastewater management. Likewise, there are no federal water quality standards developed specifically for wetlands. Because of the inclusion of natural wetlands in the definition of "waters of the United States" under the CWA, the standards developed for surface water bodies have been applied for wetlands. The absence of federal water quality standards specific for wetlands and the delay of state issued standards have resulted in the lack of consistent national policy on the use of natural wetlands for wastewater management. The use of wetlands for managing wastewater falls under the domain of the CWA. A NPDES permit is required for anyone wishing to discharge effluent to wetlands. The water quality requirements for these discharge permits are usually equal to or lower than limits set for secondarily-treated effluent, and only after approval on a case-by-case basis. A CWA section 404 permit, for dredging and filling, administered by the Army Corp. of Engineers, is required for any physical modifications to a natural wetland site.

The Portland, Oregon regional office of the Environmental Protection Agency (EPA) has developed definitions to differentiate between natural wetlands and constructed wetlands to assist in the application of the CWA section 404 permit review process:

"Constructed wetland: Those wetlands intentionally created from non-wetland sites for the sole purpose of wastewater or storm water treatment. .......... These are not normally considered waters of the U.S. Constructed wetlands are to
be considered treatment systems (i.e. not waters of the U.S.); these systems must be managed and monitored. Upon abandonment, these systems may revert to waters of the U.S. Discharge to constructed wetlands are not regulated under the CWA. Discharges from constructed wetlands to waters of the U.S. (including natural wetlands) must meet applicable NPDES permit effluent limits and state water quality standards.”

The EPA has recognized the benefits of wetland wastewater management. In their 1987 report “Use of Wetland for Municipal Wastewater Treatment and Disposal” they confirm that both natural and constructed wetland management systems can remove high levels of nutrients, BOD, organic, solids, pathogens, and metals from wastewater. However, EPA has also stated that it prefers constructed over natural wetlands when projects for wetland management systems are proposed.

Section 121(b) of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) requires the EPA to select remedies that “utilize permanent solutions and alternative treatment technologies or resource recovery technologies to the maximum extent practicable” and to prefer remedial actions in which treatment “permanently and significantly reduces the volume, toxicity, or mobility of hazardous substances, pollutants, and contaminants as a principal element.”

The State of South Carolina does not impose any further regulations concerning the construction and operation of a wetland for wastewater management. The state only requires that the discharge be NPDES permitted. The SRS company policies and procedures only offer guidance on this permitting process to ensure compliance with the federal and state wetland regulations.

C. TREATMENT EFFECTIVENESS

Constructed wetlands have been demonstrated effective in removing organic, nutrient elements such as nitrogen and phosphorus, as well as metals from municipal wastewater, mine drainage, agricultural runoff, and industrial effluents. For the most part, the development of constructed wetland technology in the U.S. has focused on the remediation of coal mine drainage. The U.S. Bureau of Mines and the Tennessee Valley Authority (TVA) have conducted considerable research in developing constructed wetland technology.
One of the first wetlands constructed to treat mine drainage was the SIMCO wetland of Coshocton, Ohio which was completed in 1985. SIMCO consists of four cells separated by small ponds followed by three larger settling ponds. The total area of the system is 4138 m² and is planted with cattails (typha latifolia). The cells are composed of 15 cm of crushed limestone overlain with 45 cm of spent mushroom compost for the substrate. Performance evaluation data compiled by Penn State researchers indicate metal removal efficiencies have steadily increased over the life of the wetland to the present-day efficiency of 70 - 100 % depending on the specific metal removed.

Between 1984 and 1993, the Bureau of Mines monitored 13 constructed wetlands designed to treat coal mine drainage. These systems included constructed wetlands in combination with anoxic limestone drains, retention ponds, and modified ditches. In addition, a variety of substrate materials was evaluated and cattails was the most common vegetation used during the studies. The results indicated that alkalinity in the influent was very important in the metal removal process. For example, iron removal averaged 53 % at one wetland with 0 ppm alkalinity in the influent while at another wetland 85 % removal was achieved with an alkalinity level of 200 mg/L. The study also concluded that oxygen transfer was the limiting process in metal removal.

TVA constructed 14 wetland systems for treating drainage at coal mining facilities. The wetland at the Fabius coal plant was completed in 1985 and contains four aerobic cells covering 5700 m². The influent water has a pH of 3.1, iron concentration of 69 mg/l, and manganese concentration of 9.3 mg/L. Effluent water contains .9 mg/l iron, 1.8 mg/l manganese and a pH of 6.7. Five species of plants were originally incorporated in the design; the wetland has evolved today to over 70 plant species and 30 different invertebrate species.

The EPA Superfund Innovative Technology Evaluation (SITE) Program evaluated a SF wetland system at Burleigh Tunnel in Colorado. Mine drainage contained zinc concentrations of 45 - 90 mg/l at a neutral pH. The wetlands consistently removed better than 99 % of the zinc contamination.

Locally, the Augusta, Georgia waste treatment plant has a wetland consisting of twelve 30-acre cells. Only two cells are presently online treating a portion of the 64 million gallons/day wastewater flow. Although the wetlands was designed to treat ammonia and BOD, metals are being removed to non-detectable levels.

The use of a constructed wetland to reduce metals concentration in the outfall (A-01) of another area at the SRS was evaluated as a treatment option earlier this year. To demonstrate the feasibility of a wetlands, four mesocosm systems were tested to determine the effectiveness of the technique on a pilot scale. Each of
the systems consisted of a 750 gallon plastic tank with gravel on the bottom overlain with 900 kg of commercial potting soil as the media. A-01 outfall wastewater was input on the surface and drained from the bottom of the tank to simulate a SF wetland system. Two of the four had vegetation while the other two consisted only of the soil and gravel. Influent and effluent water samples were collected and analyzed for total metals. Initially the effluent samples showed elevated levels of such metals as copper and zinc due to the presence of it in the topsoil, but after a week the copper in the effluent was reduced to below detectable levels. After 2.5 weeks the zinc was reduced by more than 50%. No clear effect of the vegetation was seen in this short time. The results of this test were seen as satisfactory and the wetland system was chosen as the treatment option to be used. At present, the design is 40% complete with construction slated to begin later this year.

From the examples presented above, constructed wetlands appear to be very effective in the removal of metals from aqueous wastewater streams. Given the low concentrations of metals in the S-04 outfall, the efficiencies shown above are more than adequate to ensure compliance to the expected NPDES permit limits for metals.

D. BENEFITS AND LIMITATIONS

Conventional wastewater treatment systems employ the same physical and biological principles that operate in wetlands used for wastewater management. However, the processes of filtration and purification that take place naturally in wetland systems can only occur with substantial inputs of energy and chemicals in conventional systems. Wetland systems, on the other hand, can take advantage of natural conditions to accomplish these processes. The submerged roots and stems of wetland plants act as natural filters. Wetland soils bind metals and remove them from the water column. The slow-moving waters and thick stands of plants cause solids to settle out.

While wetland systems have lower energy requirements than conventional systems, the rate at which wetlands remove pollutants is significantly less than conventional systems. Therefore, more land area is required to achieve the same level of removal from a wetland system than from conventional systems. Constructed wetland systems typically have extensive land requirements as compared to a conventional system. In areas of high land values, a constructed wetland may not be an appropriate choice. Land available close to the source of contaminated water is preferable to avoid extended transport of contaminated water.
Land that is relatively level facilitates the construction of wetlands, while locations with steep slopes and drainage will make construction more difficult and costly.

The climate of potential constructed wetland sites can limit the effectiveness and operation of the system. Extended periods of severe cold, extreme hot and arid conditions, and frequent severe storms or flooding may result in operational and performance problems. Extreme cold can freeze a wetland and substantially reduce the microbial population, rendering it ineffective for an extended period. The large water surface areas and plant life associated with wetlands enhance evaporation and evapotranspiration. A constructed wetland may periodically dry up at a site with low water flow rates in a hot and arid location. If the wetland is not designed for cyclical periods of wet and dry, it may be less effective during the wet periods. Constructing wetlands in areas with frequent flooding or severe storms can lead to washout of substrate materials or exposure of the microorganisms to toxic levels of metal contamination. Extensive engineering controls to overcome climatic or geographic limitations may eliminate the cost and maintenance advantages that make wetlands attractive.

Contaminant types and concentrations in the treatment stream can be limiting factors for constructed wetland system applications. High concentrations of contaminants may shorten the effective life of a constructed wetland, which have a limited life based on the volume of the wetland or the amount of organic substrate placed in the wetland. Substrate limitations include the number of sites for adsorption of inorganic contaminants and the amount of organic nutrients for biological activity. The wetlands are no longer effective once the sites are full and the organic matter is exhausted. High concentrations of suspended solids in the waste stream may also reduce the life of a constructed wetland. Suspended solids fill aerobic wetlands and the substrate pore spaces, reducing permeability and preventing flow through the treatment system.

When comparing the benefits and limitations of a constructed wetland for the DWPF, the benefits seem to far outweigh any limitations. The few limitations presented above do not appear to be applicable in this situation.

Land is available in abundance; the SRS is a massive tract of land owned by the DOE. All of the land adjacent to the DWPF, that is not already developed, is available for use as a constructed wetland; most of it has already been leveled and graded as part of the original construction.

Since the DWPF is located in South Carolina, weather is not a concern in the decision of whether or not to construct a wetland. The climate is very mild in the winter, so extremely cold temperatures are not common and seldom last more than a few days. The summers are hot, but usually accompanied by enough precipitation to prevent plant dehydration. Since the wetland would be fed by a
continuous flow of water from the cooling tower blowdown, the concern of drying up should not be a realistic one for this application.

The contaminant concentrations are small when compared to other applications researched, such as coal mine drainage. There is plenty of available land to provide enough area for the wetland to give service to DWPF for the remaining 25 years of the facilities design life; after 25 years all of the waste in the tank farms should be immobilized and the DWPF decommissioned. Solids in the waste stream occupying available pore space is also not a concern, since this is a secondarily treated effluent with low suspended solids content.

It can be seen that constructing a wetland at the DWPF to remove metals from the S-04 outfall is a viable option worth further investigation and preliminary engineering. The remainder of this paper will focus on the development of a basic design for the proposed DWPF S-04 constructed wetland.

VI. PROPOSED DWPF CONSTRUCTED WETLAND

A. LOCATION

Selection of an appropriate site should be the first step in the design of a constructed wetland. Site selection should consider land use and access, availability of the land, site topography, soils, environmental resources of the site and adjoining land, and possible effects on the surroundings. The site should be located as close to the source of the wastewater as possible, and down gradient if at all possible so that the water can move through the system by gravity. The site should also provide adequate space for the wetland, be above the water table, and not be in a flood plain. The area should not contain threatened or endangered species, archaeological or historic resources.

Land use and access is not a concern in this case. The DWPF is located at the DOE owned SRS, and therefore all adjacent land is available for use at DOE’s discretion. Since all of the adjacent land to the DWPF has already been cleared and graded as part of the original construction, there is no archaeological or wildlife concerns. As is the case with all nuclear facilities, topography indicates that the DWPF is located on a local high point 275 feet above sea level. Also, the nearest surface stream to S-Area is over a mile away, so flooding of the wetland is not a realistic event.

A walk down of the S-04 outfall revealed the perfect site for a constructed wetland. Just south of the DWPF and east of the S-04 outfall, outside the security fence, is a tract of land that has been cleared and graded as part of the
original DWPF construction. The site (See Fig. 12 & Photo 9) is less than 100 feet from the present location of the S-04 outfall and is slightly graded from north to south to aid in storm water runoff. There are no trees to be cleared or any other obstructions to the construction of a wetland. There are also access roads already cut to this area. The tie-in to the S-04 discharge line would be simple, as would the tie-in of the wetland discharge back to the present outfall. The tract is approximately 15 acres which should provide more than the area needed for the constructed wetland.

B. TYPE AND SIZE

The next step in the preliminary design process is to select the type of wetland to be used. Metals in wastewater must be removed prior to final discharge to protect the environment from toxic effects. Surface flow (FWS) wetland treatment systems are open to allow free movement of biota between the treatment wetland and adjacent environments. So, organisms exposed to metals in wetland treatment systems may move off-site and contribute to the contamination of natural areas or become part of the human food chain. To prevent this from occurring, the opportunity for ingestion of metals should be minimized. Subsurface flow (SF) wetlands accomplish this by keeping the metals below the surface and away from the surrounding environment. For this reason, a SF wetland treatment system will be chosen as the type for the DWPF preliminary design:

Having decided on the type of wetland system to use, it is now necessary to determine an estimate of size requirements and area of land needed. An estimate of the required wetland size can be arrived at by the employment of a few assumptions combined with the following calculations from WASTEWATER ENGINEERING - Treatment, Disposal and Reuse, Metcalf and Eddy:

First the cross-sectional area of the SF wetland must be determined by the following calculation:

\[ A_c = \frac{Q}{K_s} \times S = \frac{2941 \text{ ft}^3/\text{day}}{(1380 \text{ ft}^3/\text{ft}^2/\text{day})(.01)} \]
\[ A_c = 213 \text{ ft}^2 \]

Where \( K_s \) = hydraulic conductivity of the media (assumed to be that of loamy soil)

\[ S = \text{ slope of land (assumed to be 1 \% to match present grade)} \]
Q = flow to wetland (assumed to be approximately 660,000 gallons per month or 2941 ft³ per day)

The width of the basin can then be determined using the cross-sectional area and the following:

\[ W = \frac{A_c}{d} = \frac{213.12 \text{ ft}^2}{1.0 \text{ ft}} = 213.12 \text{ ft} \]

Where \( d = \) depth of SF basin (assumed to be 1.00 ft to match typical SF depths required for plant root interaction)

The length can then be determined using the width in the following equation:

\[ T = \frac{LW\alpha d}{Q} = \frac{L(213.12)(0.42)(1.00)}{2941} \]

or \( L = 131.43 \text{ ft} \)

Where \( T = \) hydraulic detention time (assumed to be 4 days based on recommendations of various references including Metcalf & Eddy).

\( \alpha = \) porosity of media (assumed to be that of loamy soil)

From the above calculations it can be seen that the effective area of the wetland will be \( (213.12)(131.43) = 28,010 \text{ ft}^2 \) or .64 acres. The lot chosen is more than adequate to support the construction and operation of a wetland this size. Also as a sanity check, the specific area of the wetland (acre/Mgal-day) = 29 acres/Mgal-day which is well within the recommended range of 20 - 67 for SF wetlands.

C. WETLAND COMPONENTS

The bottom of the basin must be sealed to avoid possible metal contamination of the groundwater and also to prevent groundwater from infiltrating the wetland. The on-site soil can probably be compacted enough to accomplish this since the soil contains more than 15% clay. If research determined that it could not be adequately compacted, then either additional clay would have to be incorporated in the design and compacted or a synthetic liner such as asphalt, rubber or plastic utilized.
Many soils are suitable for use as substrates for constructed wetlands. Soil properties that should be considered in selecting soils include cation exchange capacity, pH, electrical conductivity, texture, and organic matter.

The pH of the soil affects the availability and retention of heavy metals. Soil pH should be between 6.5 and 8.5. The electrical conductivity of a soil affects the ability of plants to process the waste flowing into a wetland. Soils with an electrical conductivity of less than 4 mmho/cm work best.

The surface area of the soil particles and the electrical charge on the surface of the soil particles account for much of the soil’s activity. Most soils carry a net negative charge, providing bonding sites for cation metals such as magnesium, iron, aluminum, and manganese.

A soil’s capacity to remove and retain contaminants is a function of soil-water contact. Sandy or gravely soils have high porosity values and water moves quickly through these soils. In contrast, the finer textures of loamy soils promote longer soil-water contact.

Soil texture affects root growth and the retention of pollutants. Loamy soils are a good choice, as these soils have high retention of pollutants and little restriction on plant growth. For this and the above characteristics, a loamy soil will be used as the substrate for this preliminary design.

Water levels are controlled by flow control structures; these structures should be simple and easy to adjust. Inlets at SF systems include surface and subsurface manifolds as well as weir boxes. A subsurface manifold avoids the buildup of slime and subsequent clogging that can occur next to surface manifolds, but is difficult to adjust and maintain. A surface manifold with adjustable outlets provides the maximum flexibility for future adjustments and maintenance, and is recommended. Outlets of SF systems include surface manifolds and weir boxes. The manifold should be located just above the bottom of the bed to provide for complete level control. The use of an adjustable outlet can have significant benefits in operation and maintenance of the wetland. The surface can be flooded to encourage plant growth or the level can be lowered in anticipation of storms and to allow for thermal protection in the winter. A perforated subsurface manifold connected to an adjustable outlet offers the maximum flexibility and reliability as the outlet device and is therefore recommended for this application.

The next step in the design process is to select the type of vegetation to be used. The plants that are most often used in constructed wetlands are persistent emergent plants such as bulrushes (*Scirpus*), spikerush (*Eulercharis*), sedges (*Cyperus*), rushes (*Juncus*), common reed (*Phragmites*), and cattails (*Typha*). Any species that will grow well and have the correct root depth can be chosen. Species should be chosen to mimic the communities of emergent plants of nearby natural
wetlands. The three most effective for SF wetland metal removal are the common reed, bulrushes, and cattails. All three of these are native to the area and can be used for this application.

D. CONSTRUCTION

Activities involved in wetland construction may include clearing land and access roads, building dikes and excavating basins, installing piping and substrate media, planting or seeding, and fertilizing. In the construction of the DWPF proposed wetland, a few of these are either not necessary or are very simple due to existing conditions with the chosen site.

All of the access roads to the site have already been constructed. The site has already been cleared of all trees and grubbed of all roots. The first step in the construction would be the excavation of the basin and the building of any necessary dikes or berms. Following the removal of the topsoil, the general contours of the wetland would be graded and the features located by standard surveying methods. Berms and dikes are typically constructed in lifts or successive steps of placing and compacting soils. Wire mesh should be placed in the core of the berm to prevent animal burrowing. Liners are usually installed following this rough grading. The liner would require extensive compaction; following installation a leak test should be performed prior to the incorporation of media, topsoil, and vegetation.

Since much of the piping involved would be beneath the surface, installation of it should come next. Because of the relatively small size of the distribution system, it would be possible to install the piping and weir boxes with light equipment and/or hand tools. This is important to prevent altering the grading of the basin and liner which could cause future channeling or leakage.

Following completion of the distribution system, the media or substrate would be installed. SF wetland systems depend on high hydraulic conductivities in the substrate, and special provisions must be taken to avoid compacting and rutting the substrate during construction. The importance of using low-ground-pressure equipment in the wetland and of controlling small machine and foot traffic would have to be stressed during the construction. Following placement of the loamy soil substrate, a layer of topsoil and any lime deemed necessary should be added. At this time it is customary to flood the wetland to design depth so that all components can be tested to ensure water level and flow distribution systems meet expectations.

Once the testing determined the wetland is acceptable and the moisture of the soil was correct, the vegetation should be incorporated. Vegetation can be
established using either seeds, seedlings or harvested plants. Sowing or planting would probably be done by hand given the size of the wetland. It is important to use walk boards to allow seeding/planting without compaction of the media. Once the vegetation has been added, fertilizer or other growth additives may be applied.

According to Treatment Wetlands (Kadlec & Knight), the average cost of a SF wetland in 1996 was $145,000 per acre. The maximum expected cost of a SF wetland complete with land costs, liners, pumps, etc., was $400,000 per acre. Given that the only costs associated with the DWPF proposed wetland is construction and minimal distribution piping, this wetland should be well below the $400,000 per acre cost. This cost is minimal as compared to other treatment options and would be seen as favorable by WSRC management and DOE.

E. OPERATION AND MAINTENANCE

Startup of a new wetland system is a critical time. Startup is a period in which the media, plants and microbes adjust to the conditions of the wetland. Like all living systems, wetlands are better able to tolerate change if they are allowed time to stabilize initially.

After the initial stabilization period, a gradual increase in wastewater flow to allow the system to adjust to the new water chemistry is often wiser than immediately operating at maximum flows. Often a full growing system is allowed before wastes are added, although several months of stabilization is recommended and considered adequate by most experts. Wastewater should not be added until the plants have shown new growth, indicating the roots have recovered, if transplanted. If seeding was the sowing method, wastes should not be added until the plants are well established.

Wetlands must be managed if they are to perform well. This management should focus on the most important factors in the treatment performance. These factors are ample water/wetland contact, complete coverage of wetland with wastewater flow, and healthy environments for microbes and vegetation.

An operation and maintenance plan should be created for the DWPF wetland. The plan should provide a schedule for the cleaning of the distribution system, mowing/inspection of dikes, and system monitoring. The plan should address:

* setting of water depth control structure
* schedule for cleaning/maintaining flow control structures and monitoring devices, as well as general inspections
Dikes, spillways, and water control structures should be inspected on a regular basis and immediately after any unusual flow event. Any damage, erosion or blockage should be corrected as soon as possible to prevent catastrophic failure. Water level management is the key to the success of wetland vegetation. While wetland plants can tolerate temporary changes in water depth, care should be taken not to exceed the limits of desired species for extended periods of time. Water depth can be increased during cold months to increase retention time and to prevent plant freezing. Alternating flows and draw downs may help oxidize organic matter and encourage new plant growth. Vegetative cover on dikes should be maintained by mowing, fertilizing, and liming as needed. Frequent mowing encourages grass growth that can resist erosion and prevent shrubs and trees from establishing roots. Tree and shrub roots can create channels and subsequent leakage.

Monitoring is an important operational tool that provides data for improving performance, identifies any problems, and determines compliance with regulatory requirements. Monitoring is needed to measure whether the wetland is meeting the objectives of the treatment system. Monitoring can identify problems early on, when intervention is the most effective. Monitoring for compliance with the limitations of the discharge permit represents the minimum of sampling and analysis required. System performance can also be determined by monitoring such factors as hydraulic loading rates, flow volumes, water quality changes, and excursions from normal operating conditions.

Since the wetland will be considered a wastewater treatment system, a SCDHEC licensed wastewater operator will be required to perform the above duties. This is not a problem since a majority of the DWPF operators have a SCDHEC wastewater license.

Operation and maintenance costs for SF wetlands are estimated to be approximately $2000/acre per year based on 1996 figures compiled in Treatment Wetlands (Kadlec & Knight). This expense is minimal as compared to a conventional treatment system.
VII. CONCLUSION

This research has determined that constructed wetlands are a cost-effective and technically feasible approach to treating wastewater for several reasons:

* wetlands are less expensive to build than other treatment options
* operation and maintenance expenses are very low
* operation and maintenance require only periodic, rather than continuous, on-site labor
* wetlands are able to tolerate fluctuations in flow
* wetlands facilitate water reuse and recycling
* wetlands are effective in the removal of metals from wastewater

It is for the above reasons, that the conclusion of this research is that the DWPF should construct a subsurface flow (SF) wetland to treat the metals in the S-04 outfall.
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Table 1 - Typical SME Analysis
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### SME Acceptability

| Ov 1 | Ov 2 | B Leaching | Li Leaching | Na Leaching | Temp | Vaccinity | High Vaccinity | Homogeneity | AOD3 | Low Cond | High Cond | High Fert | Fr | TDO | NaCl | NaF | CO3 | Na2SO4 | Cu | Fe2O
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### Property Value

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<th>Na Leaching</th>
<th>Temp</th>
<th>Vaccinity</th>
<th>Homogeneity</th>
<th>AOD3</th>
<th>Low Cond</th>
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<th>High Fert</th>
<th>Fr</th>
<th>TDO</th>
<th>NaCl</th>
<th>NaF</th>
<th>CO3</th>
<th>Na2SO4</th>
<th>Cu</th>
<th>Fe2O</th>
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### Notes
- SME Acceptability
- Property Value
- Property Unit
- B Leaching
- Li Leaching
- Na Leaching
- Temp
- Vaccinity
- Homogeneity
- AOD3
- Low Cond
- High Cond
- High Fert
- Fr
- TDO
- NaCl
- NaF
- CO3
- Na2SO4
- Cu
- Fe2O
### Table 3 - S-04 Source Sample Results

<table>
<thead>
<tr>
<th>Element</th>
<th>Conc, mg/L</th>
<th>Conc, mg/L</th>
<th>Conc, mg/L</th>
<th>Conc, mg/L</th>
<th>Conc, mg/L</th>
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<tbody>
<tr>
<td>Al</td>
<td>0.711</td>
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<tr>
<td>Mn</td>
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<td>0.0231</td>
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<td>Ni</td>
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<td>0.00746</td>
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<td>Pb</td>
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<td>0.091</td>
<td>1.68</td>
<td>0.237</td>
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<table>
<thead>
<tr>
<th>Element</th>
<th>Conc, mg/L</th>
<th>Conc, mg/L</th>
<th>Conc, mg/L</th>
<th>Conc, mg/L</th>
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<td>Al</td>
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<tr>
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<td>Cu</td>
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<tr>
<td>Fe</td>
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<td>Mn</td>
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<td>Zn</td>
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<td>2.24</td>
<td>1.29</td>
<td>2.627</td>
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</table>

**Potential Limit**

- **Avg.**
- **Max.**
X. PHOTOS

Photo 1 - DWPF Vitrification Building
Photo 2 - DWPF Raw Well Water Pump/Neutralization Tank
Photo 3 - DWPF Cooling Tower (blowdown line to the right)
Photo 4 - Cooling Tower Blowdown/Treated Industrial Waste Discharge
Photo 5 - S-04 Outfall Sample Station Entrance
Photo 6 - S-04 Outfall
Photo 7 - S-04 Outfall NPDES Sample Station
Photo 8 - S-04 Outfall Discharge
Photo 9 - Proposed DWPF Constructed Wetland Site
Photo 3 - DWPF Cooling Tower (blowdown line to right)

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Photo 4 - Cooling Tower blowdown/Treated Industrial Waste Discharge
Page 45 of 52
Photo 5 - S-04 Outfall Sample Station Entrance
Page 46 of 52
Photo 8 - S-04 Outfall Discharge
Page 49 of 52
Photo 9 - Proposed Constructed Wetland Site
Page 50 of 52
XI. REFERENCES


