AIRCRAFT DEICING AND AQUEOUS FILM FORMING FOAM WASTEWATER TREATMENT SYSTEM FINAL REPORT

NAS WHIDBEY ISLAND, WA

1.0 INTRODUCTION

The U.S. Navy has adopted a proactive and progressive position toward protecting the environment and complying with environmental laws and regulations. Rather than merely controlling and treating hazardous waste by end-of-the-pipe measures, the Navy has instituted a program for pollution prevention (P2) to reduce or eliminate the volume and toxicity of waste, air emissions, and effluent discharges.

P2 allows the Navy to meet or exceed current and future regulatory mandates and to achieve Navy-established goals for reducing hazardous waste generation and toxic chemical usage. P2 measures are implemented in a manner that maintains or enhances Navy readiness. Additional benefits include increased operational efficiency, reduced costs, and increased worker safety.

The Navy has truly set the standard for the procurement and implementation of P2 equipment. The Chief of Naval Operations (CNO), Environmental Protection, Safety, and Occupational Health Division (N45), established the P2 Equipment Program (PPEP), through which both the Naval Air Systems Command Lakehurst (NAVAIR LKE) and the Naval Facilities Engineering Service Center (NFESC) serve as procurement agents under the direction of N45. P2 equipment is specified and procured under two complementary initiatives: the Preproduction Initiative (*i.e.,* technology demonstration) and the Competitive Procurement Initiative. The Preproduction Initiative directly supports both the Navy Environmental Leadership Program (NELP) for P2 shore applications and the P2 Afloat program, which prototypes and procures P2 equipment specific to the needs of ships.

This report provides an analysis of the procurement, installation, and operation of P2 equipment under the Preproduction Initiative. Technology demonstrations and evaluations are primarily performed under NELP at two designated NELP sites—Naval Air Station (NAS) North Island and Naval Station (NS) Mayport. Additional sites, including Naval Air Station Whidbey Island (NASWI), have been added as required to meet specific mission goals. The program involves defining requirements, performing site surveys, procuring and installing equipment, training operators, and collecting data during an operational test period. The equipment is assessed for environmental benefits, labor and cost savings, and ability to interface with site operations.

2.0 BACKGROUND

2.1 Glycol Deicing Fluid Wastewater

Aircraft deicing is an important function at many Navy facilities that support aircraft operations. Specifically, deicing and related anti-icing activities are performed at facilities that are subject to snow, sleet, or other forms of freezing precipitation, as well as facilities where cold weather has the potential to form frost on aircraft surfaces. Ice formation on aircraft surfaces has been shown to substantially impair the aircraft's ability both to take off and to fly. According to Air Transport Association data, as little as 1/64 of an inch of ice on the leading edge of an aircraft's wing can reduce lift during takeoff by as much as 24%. Aside from the obvious safety implications, this reduction in lift can increase fuel usage and engine wear. Another hazard related to icing is the potential for damage to and/or malfunction of an aircraft's systems. These can occur when pieces of ice fly off during taxiing or when ice jams control systems (e.g., flaps, rudder). To address these problems, deicing is typically performed from October through April; however, certain locations in colder climates extend the deicing season.

Deicing is usually performed shortly before the aircraft is ready to taxi out to the runway for takeoff. The operation traditionally has been accomplished by spraying aircraft with a deicing fluid that consists of a mixture of heated water and either propylene glycol or ethylene glycol. Glycol is used because it lowers the mixture's freezing point and prevents refreezing of the aircraft surface for a period of time after application (approximately 5 to 15 minutes for Type I deicing fluid). The proportion of glycol in the mixture is dependent upon the ambient air temperature during the deicing event. As lower ambient air temperatures are encountered, the percentage of glycol in the mixture is increased. Because the deicing fluid becomes diluted with new precipitation and begins to run off of the aircraft as soon as it is sprayed, it is sometimes necessary to deice an aircraft multiple times before takeoff. Most often this occurs in instances where a long waiting time is encountered between the initial deicing and the aircraft's actual takeoff.

Although existing deicing methods have proven to be effective in removing ice and snow from aircraft surfaces, the widespread use of glycol in these activities can have certain environmental impacts that must be addressed. The vast majority of the glycol mixture used in deicing operations ends up on the ground, primarily as the result of overspray and runoff. Berms and deicing pads can be used to limit the amount of used glycol entering the environment, but these measures do nothing to reduce the strength or toxicity of the runoff.

Both propylene glycol and ethylene glycol are water-soluble organic chemicals that are poisonous to various species of wildlife. While the increased use of propylene glycol—the less toxic of the two chemicals—has reduced these toxicity effects, they have not been eliminated. Both propylene glycol and ethylene glycol are regulated by the EPA under the Clean Water Act (CWA) and the Toxic Substances Control Act (TSCA), and by various states under their environmental laws. Ethylene glycol is further regulated by the EPA under the Comprehensive Environmental Restoration, Compensation and

Liability Act (CERCLA), the Clean Air Act (CAA), the Emergency Planning and Community Right-to-Know Act (EPCRA), and by the Occupational Safety and Health Administration (OSHA).

In addition to toxic effects exhibited by glycol-laden runoff, its chemical oxygen demand (COD) is as much as 3000 times that of municipal wastewater. Receiving waters (e.g., streams, lakes) that become contaminated with glycol often have diminished dissolved oxygen (DO) levels, have increased odors, and are less able to support aquatic life.

When captured for treatment, large quantities of deicing runoff can overwhelm the capabilities of existing wastewater treatment plants. Microorganisms used to digest municipal wastes at publicly owned treatment works (POTWs) and navy owned treatment works (NOTWs) can be severely impaired by such shock loadings, rendering the associated treatment systems ineffective. Operators of these facilities are then faced with the prospect of implementing costly treatment system upgrades to avoid violations of facility discharge permits. Consequently, many POTWs are refusing to accept glycol deicing runoff because of the potential effects of shock loading the system with such a high strength waste. Facilities that utilize NOTWs will also be forced to identify alternate treatment methods for this runoff to prevent treatment system upset and potential violations.

2.2 Aqueous Film Forming Foam Wastewater

Aqueous film forming foam (AFFF) is a chemical that is used to help extinguish fires. The film that is formed by AFFF drowns existing flames and prevents new ones from forming by preventing air from reaching the flame source. AFFF has proven to be very effective in fighting a variety of fire types. To ensure that the systems and personnel that utilize AFFF remain in a ready state it is necessary for the Navy to conduct fire control system tests and training exercises for the personnel responsible for using AFFF. It is during these tests and training exercises that the majority of the Navy's AFFF wastes are generated. Unfortunately, these wastes pose certain treatment and disposal problems for Navy operations.

The wastes generated during tests and training are often rejected by POTWs and Navy owned treatment works (NOTWs) for two main reasons. First, AFFF wastes typically exhibit about 50 times the COD of municipal wastewater and can result in a shock loading of a municipal treatment system. As is the case with deicing fluid wastes, sudden high strength loads of AFFF wastewater can impair the microorganisms used to digest municipal wastes at POTWs and NOTWs, rendering the associated treatment systems ineffective. In addition, when AFFF is agitated to a level typical of that found in a municipal wastewater treatment system it generates excessive amounts of foam that can severely reduce the system's operational efficiency. For both of these reasons, the affected treatment plant would have to make costly system improvements or be faced with the potential of a temporary shutdown or fines for permit violations.

2.3 Anaerobic Fluidized Bed Reactor Technology Description

Because of the regulatory and environmental problems presented by both glycol deicing wastewater and AFFF wastewater, the Navy has undertaken an effort to find an alternate treatment and disposal method for these wastes. This report details the prototyping of an anaerobic fluidized bed reactor (AFBR) based treatment system that was tested as part of this effort under the PPEP.

The AFBR system that was tested as part of this PPEP preproduction initiative is an attached-growth biological treatment system that utilizes bacteria (microorganisms, or collectively biomass) to convert complex organic compounds into biogas [consisting primarily of carbon dioxide (CO_2) and methane (CH_4)] and additional biomass. The system is considered anaerobic because the digestion process occurs in the absence of the free dissolved oxygen found in aerobic biological systems. Free dissolved oxygen is actually toxic to the anaerobic microorganisms that digest the waste. To minimize oxygen-related toxicity problems, the AFBR system uses a sealed reaction vessel to limit the amount of dissolved oxygen that comes in contact with the biomass.

While conventional anaerobic (e.g., stirred tank reactor) and other types of attached-growth anaerobic treatment systems (e.g., trickling filter, rotating biological contactor) are effective at reducing COD concentrations in many types of wastewater, they are susceptible to shock loadings and can be adversely affected by a variety of toxic substances. To improve the resilience of the biomass, AFBR technology utilizes a carrier media as a foundation on which the biomass grows. Typical carrier media particle diameters range from 0.5 to 2.5 millimeters (mm), and commonly used carrier media materials include granular activated carbon (GAC), sand, diatomaceous earth, and pumice.

AFBR systems pump untreated wastewater into the reaction vessel from the bottom and use the hydraulic force of the incoming wastewater flow to lift and fluidize the bed of biomass-laden carrier media. As the bed fluidizes, the carrier media surface area available for biomass growth increases to approximately 2,000 square meters per cubic meter (m^2/m^3) of reactor volume compared to the 80 to 160 m^2/m^3 of available growth sites found in other attached-growth systems. This increased available surface area allows for much higher biomass concentrations than those typically found in other attached-growth treatment systems. The higher biomass concentrations generated by the AFBR system means that such systems tend to be more resistant to toxic shock and operational variations. In addition, the higher biomass concentration allows for a smaller reactor vessel, which helps reduce capital costs and space requirements.

As the system converts the wastewater's complex organics into additional biomass, the newly created microorganisms form additional layers on the existing biomass-coated carrier media. The growth of these microorganisms (which have a lower density than the carrier media) causes the volume of the individual carrier media granules to increase and their density to decrease. As the density of the granules decreases, the larger granules tend to be carried upwards by the force of the incoming water and are sometimes carried out of the reactor vessel. Consequently, AFBRs usually employ some form of solids capture system to minimize biomass loss and prevent excess biomass from being released into the effluent stream. Solids collected in this capture system (collectively called sludge) include microorganisms sheared from the carrier granules and oversized biomass covered carrier granules with extremely low densities. These solids are typically either recycled back into the reactor or processed for disposal as waste sludge. In general, AFBR systems produce approximately 1/10 of the sludge of an aerobic system treating the same wastewater.

In addition to the treated effluent that is sent to the solids capture system, a portion of the wastewater is recycled back through the reactor. This is done to increase the time that the wastewater is in contact with the microorganisms and to aid in the fluidization of the carrier media bed. The rate at which the wastewater is recycled is referred to as the recycle rate.

Figure 2.1 is a process diagram for a typical AFBR system.

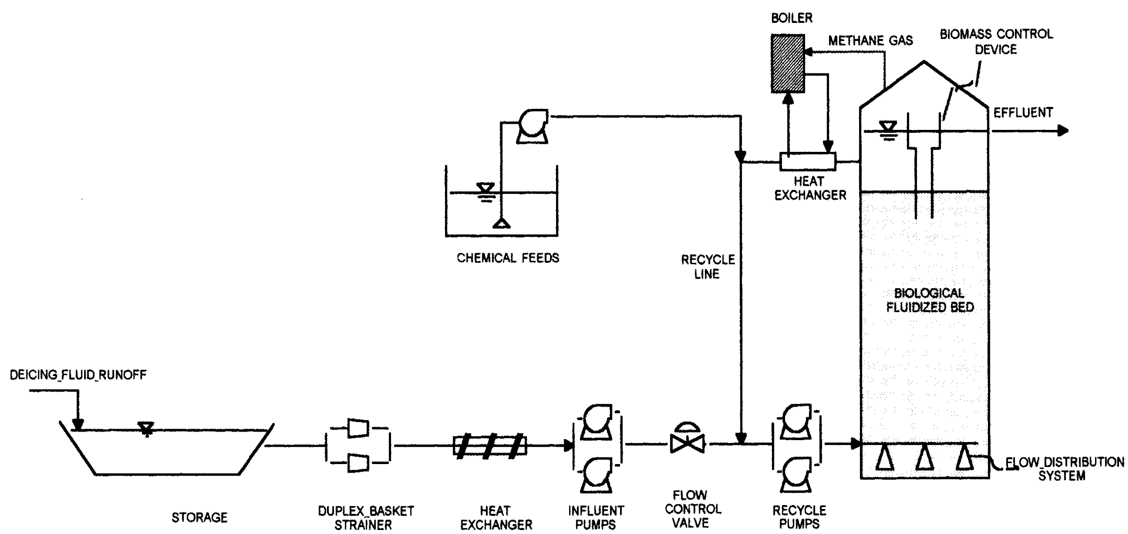

Figure 2.1. AFBR Design Process Diagram

2.4 Prototype Test Site and Facilities

NASWI was selected as the host site for this preproduction initiative. NASWI generates propylene glycol wastewater as the result of its aircraft deicing operations and AFFF wastewater from training activities related to and testing of its aircraft hangar fire control systems. In addition, the NOTW located at NASWI has experienced difficulties treating the deicing and AFFF wastewater streams.

The NOTW consists of two main areas known as the headworks and the treatment plant. The headworks includes influent flow measuring and sampling, and the primary treatment facilities (raw wastewater screening and grit removal). The treatment plant area is located approximately ½ mile from the headworks, and includes two 430,100 gallon sequencing batch reactors (SBRs), two digester tanks, and chlorination/ dechlorination facilities. The treatment plant discharges its treated effluent into the Strait of Juan De Fuca.

NASWI's average treatment system influent flow is 0.435 million gallons per day (MGD). The system's influent and effluent biochemical oxygen demand (BOD) average 188 milligrams per liter (mg/L) and 12 mg/L, respectively. Total suspended solids (TSS) average 134 mg/L in the influent and 12 mg/L in the effluent. Because the volume of water entering the current treatment system is relatively low, it cannot easily absorb variations in influent contaminant loading. In the past, upsets have occurred when AFFF, glycol, and other wastewaters with high organic loads were received for treatment.

Prior to the start of the test, samples of the deicing fluid waste and the AFFF waste were analyzed at the Environmental Chemistry Laboratory at Navy Public Works Center NAS North Island (NASNI). The influent parameters measured included BOD, COD, TSS, Total Dissolved Solids (TDS), Total Organic Carbon (TOC), Methylene Blue Activated Substances (MBAS), pH, and Title 22 Metals. MBAS is a test for the presence of surfactants that can adversely affect the normal operation of biological treatment systems like those found at most NOTWs and POTWs. The results of the analyses are summarized below in Table 2.1 and Table 2.2.

The deicing wastewater treated during this test is fairly typical of those found in military operations (approximately 20% glycol) but is more concentrated than those that are typically generated in civilian aircraft deicing operations. This variation in composition can be attributed to differences in deicing fluid application methods (greater use of centralized deicing areas in military operations) and collection methods (greater military use of vacuum trucks).

Table 2.1. Chemical Characterization of Deicing Fluid Waste.

Parameter	Result (mg/L)	Parameter	Result (mg/L)
BOD	222,000	Chromium	ND
COD	312,000	Cobalt	ND
TDS	2,480	Copper	0.09
TSS	13	Lead	0.01
TOC	70,900	Mercury	ND
MBAS	59.2	Molybdenum	0.01
pH	7.0*	Nickel	ND
Antimony	ND	Selenium	0.01
Arsenic	ND	Silver	ND
Barium	ND	Thallium	ND
Beryllium	ND	Vanadium	ND

Parameter	Result (mg/L)	Parameter	Result (mg/L)
Cadmium	ND	Zinc	ND

ND – Not detected

Table 2.2. Chemical Characterization of AFFF Waste

Parameter	Result (mg/L)	Parameter	Result (mg/L)
BOD	7,700	Chromium	ND
COD	10,210	Cobalt	ND
TDS	730	Copper	0.05
TSS	10	Lead	0.02
TOC	2,930	Mercury	ND
MBAS	7.8	Molybdenum	ND
pH	7.0*	Nickel	ND
Antimony	ND	Selenium	0.02
Arsenic	ND	Silver	ND
Barium	0.02	Thallium	ND
Beryllium	ND	Vanadium	ND
Cadmium	ND	Zinc	0.17

* - pH is unitless
ND - Not detected

A review of NASWI's wastewater records revealed that annual generation rates for wastes containing deicing fluid and AFFF were highly variable during the years 1995 to 2000. According to these records, deicing fluid wastes were only generated in 1995 and 2000 (average volume for these two years was 1,084 gallons). Records for the intervening four years showed no generation of deicing related wastewater (presumably due to warm winters). A review of records for these same six years showed that annual AFFF waste generation was limited to less than 500 gallons in five of these years. Records for the remaining year (1999) showed that spill-related wastes pushed that year's annual AFFF wastewater volume to approximately 69,718 gallons.

3.0 EQUIPMENT DESCRIPTION

3.1 Vendor Selection

Following a search of available wastewater treatment vendors, EFX Systems, Inc. (EFX) was selected to supply the prototype AFBR system. One of the primary factors that led to EFX's selection was their existing capability to treat similar glycol-laden deicing wastewaters. This capability has been demonstrated during the successful implementation and operation of EFX's AFBR system at the Albany County International Airport in Albany, New York.

As part of the PPEP preproduction evaluation of the AFBR technology, EFX performed bench scale testing of NASWI's deicing and AFFF wastewaters, provided a pilot scale treatment system, and performed necessary installation/startup engineering and procedures. EFX also sized the system's pumps and associated hardware for the projected wastewater throughput and installed an anti-foam pump, injection system, and programmable timer circuitry to address potential AFFF foaming problems. During the testing of the pilot-scale system, EFX shared system operations, maintenance, and data analysis duties with Space and Naval Warfare Systems Center, San Diego (SSC-SD) personnel.

3.2 AFBR Equipment Description and Layout

The EFX system utilized for this test was a pilot-scale system that consisted of a skid mounted fluidized bed reactor and associated growth control system, nutrient addition equipment, fluidization and recycling pumps, and associated plumbing. Additionally, a gas/liquid/solid separation system, utilizing a proprietary cyclone-like separator, was located at the reactor overflow to help minimize biomass washout. Four 500-gallon polyethylene tanks (supplied by EFX) were used to store deicing wastewater influent and the system effluent. NASWI supplied a separate 3,000-gallon tank for the AFFF influent. With the exception of the 3,000-gallon tank, one of the 500-gallon tanks, and some associated piping and wiring, the entire treatment system was housed in a temporary eight-sided structure measuring 11.75 foot (ft) on each side. The structure rose to a maximum height of approximately 16 ft at the central framework joint. Secondary containment for the system was provided through the use of temporary berms installed around the storage tanks and the treatment system skids.

The system's primary skid had a 7.5 ft by 14 ft footprint and was 8 ft high. Mounted on this skid was the bulk of the treatment system's instrumentation. The reactor vessel and the aforementioned solids separation system were located on a second skid that occupied an area of 3.5 ft by 5.5 ft. This second skid required a total clearance of approximately 14 ft (including two ft of space needed for access to the top of the reactor vessel). The larger skid weighed approximately 8,000 pounds; and the smaller reactor/separator skid weighed about 1,500 pounds. The reactor had a working volume of 1,100 liters (38.5 cubic ft). To maximize the AFBR system's organics removal rate, an air bubbler was installed in the AFBR's effluent tank. This configuration served as an aerobic polishing step by increasing the dissolved oxygen levels in the treated effluent and promoting aerobic digestion prior to discharge.

Figure 3.1 depicts the treatment system equipment layout.

Computerized monitoring of reactor operation and data acquisition was accomplished through the use of personal computer-based software. The reactor was fitted with online probes for pH and temperature and had sampling ports to enable both manual and semi-automated collection of samples from the system's influent and effluent streams. These sampling ports also provided for the attachment of additional probes as needed. Other instrumentation included gas flow meters (wet test) to quantify biogas production and a dual channel infrared gas monitor to measure methane and carbon dioxide content in the effluent biogas.

It was determined that once the pilot-scale system was fully acclimated to the wastewaters, throughput would be maximized at approximately 30 gallons per day (GPD) for deicing fluid wastewater and approximately 600 GPD for the AFFF wastewater. In

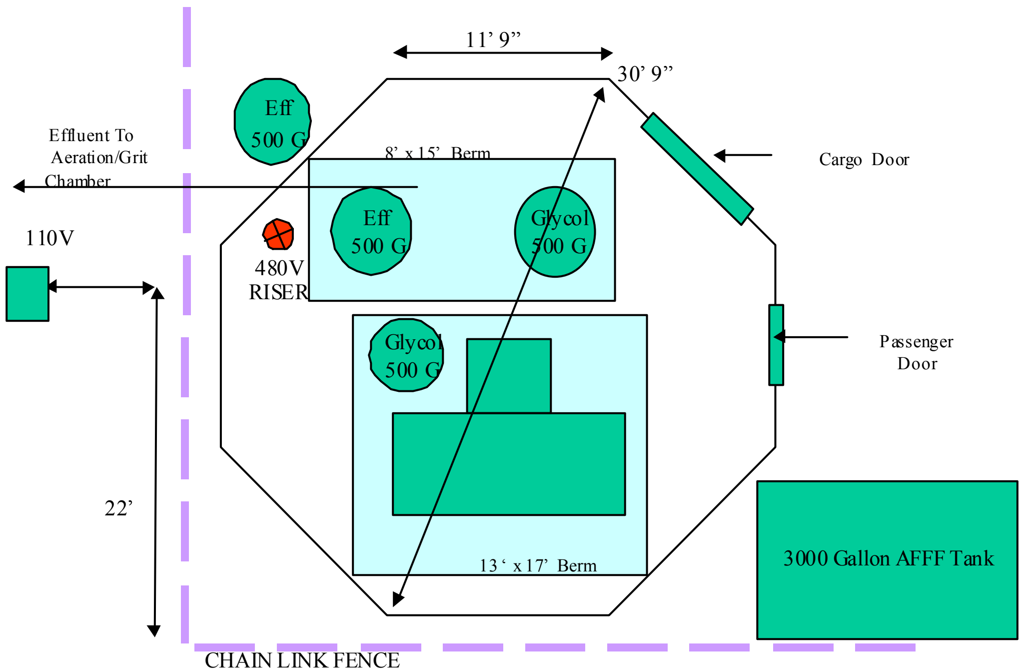

Figure 3.1. Equipment Layout Diagram.

calculating these values EFX and SSC-SD personnel took into account the known strength of the two wastewaters (312,000 mg/L COD for deicing and 10,210 mg/L COD for AFFF), as well as the projected recycle rate for the system.

Process biogas emissions for the system were projected to consist of between 60% and 80% methane with the remainder composed of carbon dioxide and nitrogen. Because of the pilot study nature of the testing, the generated biogas was not captured and was instead emitted to the atmosphere. At a full-scale installation of this type of system, the generated gas should be recovered for use as an alternative fuel or, at the least, flared before its release. Based on calculations by EFX and SSC-SD personnel, it was expected that the pilot-scale unit would generate approximately 18 standard cubic feet per hour (SCFH) of methane once maximum loading was achieved.

In addition to the aforementioned gas/liquid/solid separation system, the EFX system employed a settling tank where excess solids that had been carried out of the reactor were subsequently removed from the effluent flow. This settled material was then disposed of periodically as a nonhazardous solid waste or released to the local NOTW or POTW for treatment and disposal. The pilot-scale plant was projected to produce approximately 2.5 pounds of sludge per day when operating at its maximum load.

Nutrients (e.g., phosphorus, nitrogen, and salts not present in the wastewater) were introduced to the system on an as-needed basis. 50-pound bags of nitrogen (as prilled urea) and phosphorus (as diammonium phosphate) were purchased from a farm store and mixed onsite for addition to the reactor. Nutrient feed-rates were determined by organic loading rates. pH control was managed through the addition of caustic (as sodium hydroxide). These additions were automatically metered using a signal from the online pH electrode. A "vitamin pill' of trace nutrients was added approximately once per week.

The reactor vessel was delivered to NASWI partially filled with fresh GAC media. The system was then seeded with an equal volume of biomass-coated media taken from a full-scale EFX system located at the Albany County International Airport in Albany, NY. The Albany system was selected as the source for the seed material because it is being used to treat a similar propylene glycol deicing wastewater. Use of the seeded media shortened the needed acclimation time for the NASWI system.

3.3 Implementation Requirements and Specifications

Operational specifications and requirements for the pilot-scale EFX AFBR system include:

- Required Available Installation Space: Approximately 1,600 square ft (including tankage).
- Weight: Approximately 9,500 lb (not including tankage or water).
- Electrical: 480-volt three-phase AC power.

3.4 Benefits

Using the AFBR System provides several benefits compared to current and proposed conventional wastewater treatment practices, including the following:

- Provides alternate source of energy (methane) to offset cost of treatment system operation.
- Reduces/eliminates potential for discharge permit violations.
- Reduces/eliminates potential surcharges and fines levied by POTW/NOTW for high strength wastewaters.
- Eliminates POTW/NOTW disruptions resulting from system shocks caused by high strength deicing wastes.
- Eliminates POTW/NOTW disruptions resulting from foaming caused by AFFF wastes.
- Eliminates potential of local POTW/NOTW refusing to accept wastewater

- Eliminates cost and liabilities associated with trucking high strength wastewater to industrial wastewater treatment plant.
- Small footprint required for AFBR installation.
- Minimal electrical, piping, and site preparation required for AFBR installation.

4.0 DATA ANALYSIS

4.1 Quantitative Analysis

4.1.1 Aircraft Deicing Fluid Waste Operational Data

Following an initial startup and acclimation period, the EFX AFBR system was used to treat deicing wastewater for a period of 55 days. Following this, the feedstock was changed to AFFF wastewater.

A maximum organic loading of 26.8 kilograms of COD per cubic meter per day ($kg/m^3/day$) was achieved before the system's feedstock was switched to AFFF wastewater on day 56 of the test. This loading equated to a daily throughput of approximately 25 gallons per day (GPD). Based on existing data from a similar full-scale system in use at Albany County International Airport, it is projected that a maximum loading of between 35 and 40 $kg/m^3/day$ could have been achieved if time constraints had not required the change in feedstock.

During the test period, the EFX AFBR system achieved substantial reductions in the overall strength of deicing fluid wastewater. In the period following startup and acclimation, the AFBR system (with incorporated aerobic polishing step) achieved maximum removal rates of approximately 99.9% for BOD and COD and 99.6% for TOC and MBAS. Both TDS and TSS concentrations increased as a result of the AFBR treatment. Increases in TSS and TDS concentrations are typical of treatment with an anaerobic process. It should be noted that while the TSS concentration should be acceptable for discharge to most POTWs and NOTWs, an effluent filtration step should be added to the treatment system to reduce the concentration of TDS to acceptable levels. The achieved effluent concentrations and the corresponding influent values are listed for all of these parameters in Table 4.1.

Table 4.1. Comparison of Influent and Effluent Pararmeters for Deicing Fluid Wastewater

Parameter	Concentration (mg/L)	
	Influent	Effluent
BOD	222,000	40
COD	312,000	405*
TDS	2,480	8,350
TSS	13	119
TOC	70,900	292

Parameter	Concentration (mg/L)	
	Influent	Effluent
MBAS	59.2	0.2

* - COD in the effluent from the AFBR reactor was measured at approximately 800 mg/l. Additional removal took place as the result of aerobic treatment that occurred in the effluent tank.

As a result of the digestion process, the AFBR system generated approximately 10 liters per minute (L/min) of biogas when operating at its peak loading of 26.8 kg/m^3/day. Analysis of the generated biogas (performed by the NASNI Environmental Lab) showed that its averaged composition was approximately 64% methane, 34% carbon dioxide, and less than 2% other trace materials. Because the biogas flow rate was not sufficient to maintain a flare, this gas was vented to the atmosphere through the support building's roof vent.

4.1.2 AFFF Waste Operational Data

Following the initial testing of the AFBR system's ability to digest deicing fluid wastewater alone, Navy personnel began to introduce a mixture of AFFF wastewater and deicing fluid wastewater. After subsequently determining that the microorganisms in the reactor preferentially digested the deicing waste and did not degrade the AFFF waste (approximately 11 days after introducing the mixture), the feedstock was changed to straight AFFF wastewater. Once this change was implemented, the AFBR microorganisms began to acclimate to the AFFF waste and evidence of digestion was observed. Following the acclimation period, the AFBR system was used to treat AFFF wastewater for a period of approximately 40 days.

Using the AFFF wastewater as the system's influent, a maximum organic loading of approximately 4.2 kg/m^3/day was achieved before the end of the test. This loading equated to a daily throughput of approximately 120 GPD. A maximum throughput of 175 GPD was attempted using the AFFF wastewater, but the system had to be shut down because of foaming problems. It is unknown to what extent these foaming problems would continue if the throughput were increased in an AFBR system incorporating a larger reactor vessel.

As with the deicing fluid waste, the EFX AFBR system achieved substantial reductions in the overall strength of the AFFF wastewater. In the period following acclimation, the AFBR system (with incorporated aerobic polishing step) achieved maximum removal rates of approximately 98% for BOD and COD and 97% for TOC. Some reduction was also observed in the concentration of MBAS as a result of the AFBR treatment, but both TDS and TSS concentrations increased following treatment. As stated in Section 4.1.1, increases in TSS and TDS concentrations are typical of treatment with an anaerobic process. As is the case with the deicing wastewater, the TSS concentration should be acceptable for discharge to most POTWs and NOTWs, but an effluent filtration step would probably need to be added to the treatment system to reduce the concentration of

TDS to acceptable levels. The achieved effluent concentrations and the corresponding influent values are listed for all of these parameters in Table 4.2.

Table 4.2. Comparison of Influent and Effluent Parameters for AFFF Wastewater

Parameter	Concentration (mg/L)	
	Influent	Effluent
BOD	7,700	150
COD	10,210	179
TDS	730	2,850
TSS	10	47
TOC	2,930	76
MBAS	7.8	5.5

In addition to these benefits, treatment with the AFBR system substantially reduced the foaming potential of the AFFF waste. In the field, a "shake test" was performed to assess how much foam remained in the effluent fluid after treatment. Samples of the influent and effluent were placed in separate jars and shaken for about one minute. A 91% reduction in foam height was observed based on this test. Furthermore, the foam present in the effluent was weaker and dissipated one hour after the shake test. The foam in the untreated sample remained in tact for more than 24 hours following shake test.

To assess the system's ability to reduce perfluorooctane sulfonate (PFOS) concentrations in the AFFF wastewater, individual samples of the influent and treated effluent were analyzed by the Department of Environmental and Molecular Toxicology at Oregon State University. The AFFF influent had a PFOS concentration of 28.0 ± 0.5 mg/L and the treated effluent had a concentration of 1.6 ± 0.5 mg/L. This equates to a removal rate in excess of 94% for this constituent.

During the digestion of the AFFF waste, the AFBR system generated approximately 1.2 L/min of biogas when operating at its peak loading of 4.2 kg/m^3/day. Analysis of the generated biogas (performed by the NASNI Environmental Lab) showed that its average composition was approximately 76% methane, 14% nitrogen, 5.6% carbon dioxide, 3.7% oxygen, and less than 1% other trace materials. As with the biogas that resulted from the deicing fluid digestion, the generation rate observed here was insufficient to maintain a flare, and the biogas was vented to the atmosphere through the support building's roof vent.

Subsequent to the start of the AFBR test, 3M Corporation (3M) released data showing that PFOS, one of the key components of AFFF, is a persistent bioaccumulative toxin (PBT) that has been shown to cause increased infant mortality rates in laboratory animals under certain conditions. In addition PFOS, which is also a primary component in 3M's Scotchgard™ product, has been found in groundwater and surface water samples collected from various locations around the United States. Because of this data, 3M began a phase out of PFOS production that will stop AFFF production by the end of 2002 at the latest. Although research to develop an alternative for AFFF is ongoing, no replacement is currently available.

4.1.3 System Capital Costs

The AFBR system described herein was leased to the Navy for the purposes of the four-month pilot test. The $100,000 lease fee included delivery and setup of the system, start up operations, technical support for the length of the project, and dismantling and removal of the system at the end of the test. EFX has stated that the outright purchase cost of a similar-sized skid-mounted system (approximately 1,100-liter reactor capacity) would be approximately $140,000. This figure includes the costs of the reactor, separator tank, instrumentation and controls, fluidization pumps, nutrient tank and feed pump, caustic feed pump, foam control systems, media return and growth control pumps, pH control system, temperature control system, influent strainer, fluidization and influent flow meters, and all piping and valving. Additional costs not built into this purchase price include biogas-handling equipment, influent pumps, influent and effluent storage tanks, remote system alarm/monitoring capabilities, and any required post-treatment systems (e.g., aerobic polishing for additional BOD removal, additional solids removal and/or processing). Furthermore, the base price does not include site preparation costs such as pad construction (if necessary), protective structure costs, piping, and wiring. Other site-specific factors (e.g., labor costs, permitting, etc.) could also affect the overall capital costs.

Although the tankage costs that are associated with any AFBR installation will be dependent on the volume of wastewater being treated, the rate of treatment, and the storage requirements for the water, costs of preformed polyethylene tanks were researched to develop an estimating guideline. Based on the gathered pricing information, it is suggested that an incremental tankage cost of approximately $1.00 be added for every 1 gallon of required storage capacity. Because the bulk of the wastewater treated during the test period was AFFF wastewater, it was assumed (for costing purposes) that the bulk of waste generation would occur on a fairly regular basis throughout the year. Consequently, the tanks from the tested pilot scale system were used as guides for assigning cost to influent and effluent tanks. As a result, a cost of $5,000 was used for the influent tank and $500 for the effluent tank in the pilot-scale cost analysis. In addition, an influent pump of sufficient size to meet the needs of an AFBR system similar in size to the tested unit should add approximately $600, and a monitoring/autodialer alarm system will increase system capital costs by approximately $1,500. Because the gas flow generated by a system of the size tested here would be too low to maintain a flare, no additional gas handling equipment was priced for the system.

The temporary structure that was used to house the AFBR system was leased from Sprung Structures, Inc. for the four-month test period at a cost of $8,286. This lease fee included delivery of the structure, four days of construction consulting, and removal of the structure. Construction of the structure required the use of four people over a two-day period, and dismantling was accomplished using four people for a period of one day. NASWI and SSC-SD personnel built and dismantled the structure. Sprung Structure has since quoted a price of $16,850 plus shipping to purchase a similar sized building. This price includes four days of on site construction consulting by a Sprung Structures consultant. It should be noted that a stressed-membrane structure of the type proposed here might be deemed inappropriate for certain large permanent installations. The capital and site preparation costs for the in place construction of a permanent support structure could exceed those for the tested Sprung Structures' building.

To assess the potential capital costs related to the implementation of a full-scale AFBR treatment system, an additional quote was obtained for an AFBR system capable of treating 100,000 gallons of propylene glycol deicing fluid wastewater (15% propylene glycol) annually. This waste volume and composition was chosen based on a review of glycol usage data obtained from deicing operations at NAS Brunswick. According to EFX, a skid-mounted system of this size would have a base cost of approximately $290,000 FOB East Lansing, MI. This price includes a steel reactor vessel and separator (epoxy coating inside, paint outside), system heater, heat exchanger and temperature control, system pumps (e.g., influent, nutrient and pH control, recycle), system piping, electrical and control panel, pH controller, and system instrumentation. In addition, an included five horsepower (hp) compressor provides aerobic post-treatment by bubbling air though the effluent tank. When developing tankage costs for the full-scale system, the $1.00 per 1,000-gallon guideline was used. In addition, because the bulk of deicing wastes are typically generated during the three-month winter season, an influent tank large enough to contain any deicing wastewater that would not be treated by the system in that three-month period was assumed. Effluent tank size was selected based on the projected wastewater throughput for a full-scale system and the desire to obtain maximum benefit from the aerobic post-treatment. Additional costs that would be incurred to install a complete full-scale system include the following:

- PLC control (includes autodialer capacity) – $ 5,000
- Flare stack – $20,000
- Influent tank(s) – $79,000 (est.)
- Effluent tank – $1,500 (est.)
- System discharge pump with level control – $600 (est.)
- Shipping – $1.70/mile (approx.)

For purposes of the cost analysis, NAS Brunswick was used as the destination when calculating shipping expenses.

Note that the above system costs assume that the generated methane would be vented to the atmosphere or flared. Alternatively, the biogas could be captured and used to power an existing boiler. In a system designed to utilize the generated gas for power, the flare stack would be replaced by gas handling equipment (approximately the same price) and the following features would be added:

- On-line gas analysis (CH_4 and CO_2) – $10,000
- Biogas Blower – $1,600

Because of the relatively high CO_2 levels in the generated biogas (between 20% and 40%), it is possible that some modification of the existing boiler would be necessary to allow the biogas' use as a fuel source. In addition, the above costs do not include the construction of secondary containment features for the influent tank(s) or any foundation upgrades necessary to support either the treatment system or its associated tanks.

4.1.4 System Operations and Maintenance Costs

Operations and maintenance expenses incurred during the pilot test of the AFBR system at NASWI consisted primarily of labor, electricity, chemicals, and outside laboratory costs. Although additional costs were incurred for water supplied to the system and for the discharge of the pilot system's effluent to the NASWI NOTW, the value of these costs is not currently available. It is expected that similar costs will be incurred in any instance where AFBR effluent is discharged to a POTW or NOTW for final treatment and disposal. In addition, while labor costs related to the field chemical analysis of influent and effluent samples were captured in the overall labor costs for the system, the costs of chemical supplies and waste disposal related to these tests are not currently available. These uncaptured costs are not expected to substantially affect the overall analysis in this instance, but their potential impact should be taken into account when considering the installation of any full-scale wastewater treatment system.

Labor requirements for the maintenance and operations of the reactor during the experiment were estimated to include approximately one hour for daily operation and maintenance activities (seven days per week), two hours for weekly maintenance, 12 hours for monthly maintenance, and 80 hours for an annual overhaul. Daily operation and maintenance activities conducted during the test period included collecting effluent samples, performing a field COD test on the system effluent, measuring the reactor bed height, recording instrumentation readings on a checklist, and doing a general inspection of the system's hardware. Weekly maintenance activities included mixing nutrient feeds, shipping effluent samples to an outside laboratory, and in the event of low influent flow rates, cleaning out system piping. Monthly maintenance included calibrating pH probes, cleaning system components, and replacing worn and malfunctioning components where needed. The costs of the actual replacement components were included in the lease price and are therefore not available as separate line items.

Using the above listed hour estimates, and the current NASWI contract rate for a Wastewater Plant Technician ($18.14/hr), an annual labor cost of $10,195 is projected for a similar-sized treatment system operating 270 days per year. Additional expenses would be incurred if effluent treatment and gas-handling systems were added to the tested AFBR system. Because a full-scale AFBR system is expected to require additional operator attention and is projected to operate over a larger number of days, its associated labor costs are estimated to be approximately $21,188.

Electricity costs for the pilot-scale system were calculated using NASWI's current rate of $0.04587 per kilowatt-hour (kWh). To determine the AFBR system's annual power usage, amperage and voltage drawn by the system were measured directly at the breaker box for each of the following four cases:

- compressor off/ heater off
- compressor on/ heater off
- compressor off/ heater on
- compressor on/ heater on.

During three separate sessions, the power draw (in watts) and the power on and off times of the hardware were tabulated. This data was then averaged and extrapolated to 270 days per year run time. Using this method, power usage for the pilot-scale AFBR utilized in this test was calculated to be 20,347 kWh. This equates to an annual electricity cost of approximately $934. The larger full-scale system is expected to use approximately $2,268 in electricity over the course of an operating year.

Additional costs incurred during the pilot-test period resulted from the addition of chemicals for pH adjustment and to provide nutrients not available in the influent. Twenty-five percent strength sodium hydroxide (NaOH) was used to maintain system pH. A total of one 55-gallon barrel of NaOH (at a cost of $181 per barrel) was used over the course of the test. This equates to an annual NaOH cost of $543. Macronutrients (urea, phosphate, and salts) and micronutrients (trace metals) were added to the system as needed based on the organic load to the unit. Based on usage during the pilot-test period, the projected annual cost of macro- and micronutrient for a similarly sized AFBR is $58. Annual chemical costs for a full-scale AFBR system are projected to be approximately $16,225, with the higher costs largely attributable to increased caustic usage.

During the test of the system, daily field tests of effluent COD were conducted. In addition, effluent samples were collected on a weekly basis and forwarded to the Environmental Chemistry Laboratory at the Navy Public Works Center, NASNI for analysis. When operating a full-scale pretreatment system, regular analyses (BOD, TSS, TDS, and ammonia-nitrogen) of treated effluent being discharged to a local POTW are typically required. Based on an average of available pricing data from commercial laboratories the annual cost of these outside analyses is projected to be approximately $5,265 for the tested pilot-scale system. Laboratory costs for a full-scale system are projected to be slightly higher at $5,805.

4.1.5 System Permitting Costs

The effluent produced by the AFBR at NASWI was collected and subsequently discharged to the NOTW located on base for final treatment and disposal. Depending on the available facilities and the post-treatment effluent processing employed, other sites might dispose of the treated effluent by discharging to a POTW, discharging to a local waterway, or applying the water to the ground for irrigation purposes. Each of these disposal methods have different permitting and monitoring requirements and costs that must be addressed to ensure continued compliance.

Biogas emissions (consisting primarily of methane and carbon dioxide) resulting from the operation of the AFBR were covered under NASWI's existing base-wide air permit. At another facility, additional permitting costs could be incurred if a new or amended permit is needed to flare or release the generated biogas. On the other hand, using the generated biogas as an alternate fuel source for an existing boiler(s) would likely not require any modification of preexisting air permits.

4.1.6 Potential AFBR Cost Savings

Although the aforementioned costs must be considered when deciding if an AFBR treatment system is practical for a given situation, there are a number of ways that a full-scale AFBR system can be used to generate savings that can be balanced against these costs.

First, whereas a facility might be prohibited from discharging untreated wastewater containing deicing fluid or AFFF to a local POTW or NOTW (as is the case at NASWI), discharge of treated effluent from an AFBR system will most likely be allowed. Currently NASWI pays $0.36/pound ($3.00/gallon) to dispose of AFFF wastes and $0.22/pound ($1.83/gallon) to dispose of deicing fluid wastes. By using a full-scale AFBR system to pretreat these wastes prior to discharge, NASWI would most likely be able to avoid having these wastes hauled offsite for treatment and could thus eliminate these fees. Using the fees paid by NASWI as a basis, a successfully implemented full-scale system treating 100,000 gallons of deicing fluid waste per year would eliminate approximately $183,000 in fees each year.

Second, in many cases where a facility is allowed to discharge untreated deicing and AFFF waste to a local POTW, they incur substantial surcharges and/or fines because of the waste's strength or other characteristics (e.g., foaming problems). Pretreatment of wastes prior to discharge will reduce the waste strength and foaming potential and consequently reduce or eliminate these extra fees.

Third, in those instances where a facility discharges their untreated wastes to a NOTW, the incorporation of an AFBR pretreatment system will reduce or eliminate treatment plant upsets related to the high strength and foaming of the untreated waste. Reduction or elimination of these upsets will most likely lead to a corresponding reduction in the NOTW's labor and consumables costs.

Finally, the biogas that is generated by the digestion of deicing fluid wastewater in an AFBR system is composed of approximately 64% methane and could be used to power an existing onsite boiler(s). For a full-scale system treating 100,000 gallons of deicing fluid waste per year, it is projected that approximately 2,028,240 standard cubic feet (SCF) of biogas would be generated annually. This equates to an average hourly production of just over 200 SCF of methane per hour during operating hours. The heating value of pure methane is approximately 1,000 british thermal units per SCF (Btu/SCF) or 0.010 therms per SCF (therm/SCF). Given the aforementioned composition of the generated biogas, it is expected that a full-scale system operating continuously for 270 days per year would be able to supply approximately 1.298 billion Btu or 12,981 therms per year. Using a current per unit price of natural gas ($0.93 per therm), it is projected that heating costs could be reduced by more than $12,072 per year.

An alternate use of the generated biogas that should become more cost-effective in future years is onsite electricity cogeneration. By using the generated biogas as a fuel source for fuel cells it should be possible to increase the energy recovered from the AFBR system and reduce polluting emissions compared to those associated with methane combustion. General Electric's HomeGen 7000 fuel cell (developed by Plug Power) system should be released to the commercial market in July of 2001 with an initial cost of $12,000 (although this cost is expected to decrease as the systems become more readily available). This fuel cell system will be capable of supplying a continuous 7 kilowatts (kW) of electricity given an 82.4

SCF/hour supply of methane. Although this particular fuel cell system is being marketed to the residential market, the aforementioned expected methane generation rate (200 SCF/hour) from the AFBR system will be sufficient to power two to three of these fuel cells operated in parallel. The gas flow would probably be insufficient however to operate the currently available commercial-scale fuel cell units. By using three of the HomeGen 7000 fuel cell systems, a total of approximately 17 kW of electricity could be generated on a continuous basis with less than 1 part per million of sulfur oxides (SO_x) or nitrogen oxides (NO_x). The annual cost for purchase of an equivalent amount of electricity would be approximately $11,000.

4.1.7 System Payback

Using the data collected during the preproduction initiative, a cost/benefit analysis was performed for both a pilot-scale AFBR system and a 100,000-gallon per year deicing fluid full-scale AFBR treatment system. Using pilot-scale data, a payback period of 9.1 years was determined with a ten-year return on investment of $17,376.90. By substituting projected data from a 100,000 gallon per year deicing fluid treatment system, a payback period of 3.0 years was determined with a ten-year return on investment of $971,313.80. Details of analyses for both the pilot-scale and full-scale systems are presented in the accompanying cost analysis for this project.

4.2 Qualitative Analysis

4.2.1 Installation and Training

Installation of the EFX AFBR system and erection of the temporary shelter structure at NASWI was completed over a five-day period with minimal site preparation. EFX representatives installed the AFBR system and the associated piping and tankage, while Sprung Instant Structures personnel worked with NASWI personnel to erect the temporary building that was used to house the treatment system. EFX personnel performed startup procedures and then provided hands on training to staff members from SSC-SD and NASWI.

Training included the operations, maintenance, and emergency procedures for the AFBR system. During the system acclimatization period, NASWI and SSC-SD personnel were able to familiarize themselves with the AFBR system under the supervision of EFX technicians and engineers. AFBR system operations and maintenance was then incorporated into the Navy personnel’s regular work schedule.

4.2.2 Maintainability

During the test period the EFX unit experienced a variety of minor problems with maintainability. Problems encountered during the pilot-scale test included small cracks in system hoses and piping, failure of the system’s programmable logic controller (PLC), temporary malfunction in the system heater controls, and clogging of system piping and hoses. In addition, some minor spills of wastewater and biomass occurred when the system’s piping became clogged. Each of the maintenance situations resulted in minimal or no down time and was addressed through the efforts of NASWI, SSC-SD, and EFX personnel. All of the spills were captured by the system's secondary containment and were cleaned up by NASWI and SSC-SD personnel. To minimize the potential for future spills, the system's effluent lines were replaced with larger diameter piping, and effluent line cleanouts were incorporated into weekly maintenance activities.

Standard upkeep consists of a basic preventive maintenance and monitoring program. EFX has a customer support program with an emergency number to call if any problems arise. Troubleshooting advice can be given over the phone, and if repairs are required, an EFX technician can be dispatched.

4.2.3 Interface with Site Operations

Site personnel readily integrated the equipment into operating procedures. Following startup procedures and initial stabilization of the AFBR system, site personnel took over all day to day operations and maintenance activities. During testing of the unit, occasional foaming problems were encountered when treating AFFF. Although these problems forced temporary system interruptions, in each case NASWI and/or SSC-SD personnel were able to quickly rectify the situation. Although the EFX system does provide instrumentation to monitor various aspects of AFBR performance, close operator attention will be required to assure that the system is maintained in proper operating condition. In addition, frequent sampling and laboratory analysis of both influent and effluent wastewaters will be necessary during full-scale implementation of any on site treatment system.

4.2.4 Overall Performance

Following acclimation of the AFBR system to the deicing wastewater, biochemical oxygen demand (BOD), COD, and total organic carbon (TOC) removals in excess of 99.5% were achieved. Similarly, BOD and COD removals in excess of 98% and TOC removals in excess of 97% were achieved during the treatment of AFFF wastewater. Concentrations of total suspended solids (TSS) and total dissolved solids (TDS) in both treated wastewaters increased substantially compared to those found in the respective influents. While effluent TSS concentrations (119 mg/l and 47 mg/l for deicing and AFFF wastewaters, respectively) remained below those that typically incur surcharges upon discharge to a POTW, TDS concentrations (8,350 mg/l and 2,850 mg/l for deicing and AFFF wastewaters, respectively) would most likely incur some surcharge. It should be noted that TDS are not typically as serious a problem for POTWs as BOD and TSS. Consequently, TDS surcharge rates can be expected to be lower than those for BOD and TSS.

These advantages and the test results showed that treatment of the deicing and AFFF wastewaters with EFX system is superior to the currently employed disposal method (i.e., paying to have the wastes trucked off site and disposed of at an industrial wastewater treatment facility). Because foaming problems caused a shut down of the AFBR system when the AFFF feed throughput was increased to 175 GPD, further testing in this area would be recommended before any full-scale implementation is undertaken for AFFF treatment.

5.0 LESSONS LEARNED

During the test period at NASWI, it was noted that the effluent piping was too small to handle the flow being generated by the treatment system. As a result of this undersized piping, the system experienced multiple backups and overflowed the reactor vessel on more than one occasion. Although NASWI and SSC-SD personnel quickly addressed the clogging and overflow problems and were able to replace the problematic sections of pipe, it is recommended that larger diameter effluent piping be required on any AFBR systems purchased subsequent to this test.

To gain insight into NASWI's annual volume of deicing wastewater and necessary sizing of a full-scale AFBR system, the facility's historical wastewater generation/disposal records for the years 1995 through 2000 were reviewed. Such a review is necessary to ensure the proper sizing of any full-scale treatment system. According to these records, no deicing wastewater was disposed of during the period from 1996 through 1999. Although the tested AFBR system's microorganisms are capable of surviving up to six months without having wastewater to digest, it would be impractical to install and attempt to use a system of the type tested here at a location where deicing activities are limited in scope. At sites where the system is deemed practical, the seasonal nature of deicing activities will necessitate the capture and storage of the deicing fluid waste so that the feed supply will remain consistent over the course of the year. In any event, it is important to review the historical deicing wastewater generation and disposal records of any candidate site to ensure that an AFBR system will, if installed, be able to function properly and cost effectively.

When considering treatment of AFFF wastewater, it is necessary to ensure that the required throughput for the wastewater in question will not cause excessive foaming in the AFBR system that could result in a system shutdown. In addition, because testing at NASWI showed that the AFBR system bacteria preferentially digested the deicing wastewater, AFFF wastewater should be stored until the AFBR system can be transitioned completely from deicing fluid treatment. Finally, the need for an AFFF-specific treatment system could be preempted by the ongoing phase-out of PFOS production.

6.0 CONCLUSIONS

In the past, allowing deicing wastes to runoff and degrade in the environment was an accepted industry practice. Discharging AFFF and deicing wastes to POTWs and NOTWs has often resulted in treatment plant disruptions, surcharges, and fines. Increased awareness of the environmental effects of aircraft deicing wastes and wastewaters containing AFFF, together with increased enforcement of surface water regulations, has highlighted the need for alternative treatment and disposal methods for these wastes. The AFBR system tested here appears to be an effective, environmentally friendly, and cost-effective method of degrading glycol-laden deicing wastewater and should be considered for sites that generate substantial volumes of deicing wastes on an annual basis. Further bolstering the case for the AFBR system is the potential to utilize the system's generated biogas as a fuel source for heating or electricity production.

Because of the foaming problems exhibited during the high-rate treatment of AFFF wastewater, it is recommended that further studies be performed before implementing an AFBR system for the sole purpose of treating AFFF wastewater. Furthermore, because the primary manufacturer is currently phasing out production of AFFF it is recommended that any AFFF treatment system implementation be delayed until a substitute for AFFF is identified and can undergo bench-scale and pilot-scale treatability studies.