FY17 Technical Survey of Nitrogen Removal Alternatives for the Deer Island Treatment Plant

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Technical Survey of Nitrogen Removal Alternatives for the Deer Island Treatment Plant

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Contents

List of Tables

List of Figures

Executive Summary

Section 8.e.i of the Massachusetts Water Resources Authority's (MWRA's) wastewater NPDES discharge permit (No. MA0103284) requires MWRA to "maintain a comprehensive technical survey of effective treatment technologies for nitrogen removal which are applicable to the Deer Island treatment facility." The purpose of the survey is to "facilitate the speedy selection and implementation of nitrogen removal technology if necessary."

The requirement for the survey grows out of concern about the possible impacts of nitrogen, a nutrient, on the Massachusetts Bay ecosystem. Worries that nitrogen in effluent might lead to low dissolved oxygen or undesirable algal blooms in the Bay prompted the inclusion of the above clauses in the permit. Should MWRA need to reduce nitrogen discharges, the survey will allow MWRA to quickly make an informed decision on available removal options. However, over 15 years of monitoring data show no adverse effects. Despite a slight increase in effluent nitrogen loads during that time, the state of Massachusetts Bay has remained the same. Eutrophication has not been observed, nor have there been any nitrogen-related cyanobacteria or nuisance algae blooms. Bottom water dissolved oxygen depletion levels have also remained constant and well below the caution threshold in the past 15 years. In addition, the calibrated Bays Eutrophication Model computes that over an annual cycle only 3 percent of the total nitrogen entering the Massachusetts Bay system is derived from the MWRA effluent. The model also indicates that approximately 93 percent of the nitrogen entering the Massachusetts Bay system is associated with inflowing waters from the Gulf of Maine (Hunt et al., 2000). Current nitrogen levels in effluent appear to have no negative effect on Massachusetts Bay water quality.

This report was first submitted in November 2001 (Camp Dresser and McKee, 2001), and has been updated annually since then (Bigornia-Vitale and Wu, 2003, 2004a, 2004b, 2005, 2007a, 2007b, 2008, 2010, 2011, 2012; Smolow et al. 2013; Smolow 2013, 2015, 2016,2017). The design criteria for the selection of alternative treatment remain unchanged and are based on their suitability at Deer Island, process reliability, and land and space requirements.

Approximately 13 acres of usable area exist on Deer Island for siting potentially needed nitrogen removal facilities. This area was dedicated to future needed nitrogen facilities as part of long term Deer Island planning and would allow for the construction of nitrogen removal facilities without significantly encroaching on the landforms that were constructed to mitigate noise and visual impacts on the Town of Winthrop.

No new advances in nitrogen removal technology have emerged since the last report. At present, the alternatives previously identified in earlier reports appear to be still the most viable options at Deer Island. These treatment alternatives are biological aerated filters with submerged packed-bed reactors, biological aerated filters with fluidized-bed reactors, and moving-bed biofilm reactors. An integrated fixed-film activated sludge reactor retrofit into the existing aeration basins was also considered in this update, although this is not a new treatment technology.

This update adds sections considering sidestream treatment. Most sidestreams at Deer Island account for less than 1% of the total influent, but up to 10% of the total nitrogen (TN) load. The addition of sidestream treatment systems would come with a relatively small footprint and at a low cost and could reduce the overall nitrogen load to the plant, although sidestream treatment alone could likely not achieve sufficient nitrogen removal to meet hypothetical limits of 4 mg/L or 8 mg/L TN in the effluent. Sidestream treatment would also help to lower waste activated sludge production and reduce methanol requirements for mainstream treatment.

Biological nitrogen removal technologies appear to be the most feasible method of nitrogen removal at this time. A research project entitled *Sustainable Technology for Achieving Very Low Nitrogen and Phosphorus Effluent Levels* (WERF, 2003), funded by the Water Environment Research Foundation (WERF), assessed a variety of technologies to determine the feasibility and cost benefits of nutrient reduction at treatment plants around the nation. The final report was released in 2009. In addition, the US Environmental Protection Agency (EPA) released a reference document (USEPA, 2008) that presented information on recent advances in nutrient removal technology and practices. The technologies identified in these documents are included in this report. MWRA will continue to monitor progress and advances in nitrogen removal technologies for applicability to Deer Island.

Section 1. Introduction

1.1 Purpose of Report

MWRA's National Pollutant Discharge Elimination System (NPDES) permit requires maintenance of a comprehensive technical survey of nitrogen removal technologies that are applicable to the Deer Island Treatment Plant. This report updates the previous report, *Technical Survey of Nitrogen Removal Technologies for the Deer Island Treatment Plant*, released in March 2017. This update will help to facilitate selection and implementation of a nitrogen removal technology if such technology is required at Deer Island.

1.2 Content of Report

This report describes existing conditions at the Deer Island site, and identifies and evaluates various treatment alternatives capable of providing nitrogen removal at the Deer Island facility.

Section 2 begins with a description of existing facilities and of the remaining space available at Deer Island for siting nitrogen removal facilities. Section 2 also presents the most current nitrogen monitoring data available and updates estimates of flows and nitrogen loads used in the previously submitted reports.

Section 3 discusses processes available for nitrogen removal. This section summarizes physical/chemical nitrogen removal and biological nitrification and denitrification technologies. Processes are evaluated for applicability to the Deer Island site, and viable alternatives are selected for a more in-depth review. Sidestream processes are also described in section 3, including those that could be done on Deer Island and those that could be used at the Residuals Processing Plant in Quincy.

Section 4 investigates the alternatives selected in Section 3 for further review. Each alternative is sized to determine feasibility of implementation. Elements common to all feasible options, such as oxygen and chemical needs and sludge production, are evaluated separately. Section 4 evaluates one sidestream treatment method and also lists other considerations that should be evaluated in the selection of treatment alternatives.

Section 2. Basic Planning Criteria

This section reviews existing facilities and identifies available space that could be used for nitrogen removal facilities. In addition, this section summarizes July 2005 – June 2017 nitrogen monitoring data, updates flows and nitrogen loads from the previous year's report, and presents basic information used for selecting facilities.

2.1   Existing Facilities

The Deer Island Treatment Plant (DITP) is a pure oxygen activated sludge process treatment plant with an average design flow of 361 MGD and hydraulic capacity of 1,270 MGD. During wet weather, the secondary treatment process can treat up to a maximum of 700 MGD. Figure 1 depicts the DITP site layout and Table 1 lists major facilities and pertinent information regarding those facilities.

2.2   Available Space

Nitrogen removal would require additional facilities for wastewater treatment and solids processing. The goal of this analysis is to site these facilities in areas previously allocated for treatment processes or support facilities that were not built, and to avoid construction on the landforms developed to lessen the impact of wastewater treatment facilities on Winthrop.

Areas available for nitrogen removal facilities are highlighted on Figure 2 and include:

- Area A: 5.7 acres, the space west of the existing secondary batteries
- Area B: 0.4 acres, the area to the north of the secondary clarifiers
- Area C: 3.2 acres, the area north of secondary Batteries B, C, and D
- Area D: 3.5 acres, the area located north of the maintenance dry storage warehouse

While the total available gross area is 12.8 acres, piping and operational considerations limit the use of available space and each option with its particular design requirements needs more in-depth evaluation for its feasibility. Section 4 presents these conceptual design evaluations.

OUTFALL TUNNEL

HYDROPOWER PLANT

CRYOGENIC OXYGEN FACILITY

NORTH SYSTEM HEADWORKS

GRAVITY THICKENER COMPLEX

RESIDUALS ODOR CONTROL FACILITY

CENTRIFUGE THICKENER BUILDING

DIGESTER COMPLEX

DISINFECTION BASINS

SECONDARY CLARIFIER BATTERY A

SECONDARY CLARIFIER BATTERY B

SECONDARY CLARIFIER BATTERY C

OXYGEN REACTOR BATTERY A

OXYGEN REACTOR BATTERY B

OXYGEN REACTOR BATTERY C

PRIMARY CLARIFIER BATTERY A

PRIMARY CLARIFIER BATTERY B

PRIMARY CLARIFIER BATTERY C

PRIMARY CLARIFIER BATTERY D

EAST ODOR CONTROL

WEST ODOR CONTROL

MAINTENANCE WAREHOUSE

ADMIN LAB

PILOT PLANT

SOUTH SYSTEM PUMP STATION

INTER-ISLAND TUNNEL

RECEPTION-TRAINING BUILDING

NORTH SYSTEM TUNNELS (2)

WINTHROP TERMINAL FACILITIES

NORTH MAIN PUMP STATION

PUBLIC PARKING

NORTH

35

PROJECT NORTH

0 100 200 300
SCALE IN FEET

Figure 1. Deer Island Site Plan

Table 1. Facilities at Deer Island Treatment Plant

Stacked Rectangular Primary Clarifiers	
Number of batteries	4
Clarifiers per battery (stacked sets)	12
Effective surface area per clarifier (ft^2)	15,252
Aeration Tanks	
Number of batteries	3
Number of trains per battery	3
Total number of trains	9
Number of stages for selectors	3/train
Volume of selectors per train (MG)	1.07
Number of aeration stages per train	4
Aeration volume per train (MG)	3.55
Stacked Rectangular Secondary Clarifiers	
Number of batteries	3
Clarifiers per battery (stacked sets)	18
Effective surface area per clarifier (ft^2)	13,940
Gravity Thickeners (for Primary Sludge)	
Number of units	6
Diameter (ft)	70
Sidewater depth (ft)	12
Centrifuges for Thickening Waste Activated Sludge	
Number	12
Allowable range of flow/centrifuge (gpm)	300 to 900
Anaerobic Digesters/Thickened Sludge Storage	
Number of digesters	12
Volume of each digester (MG)	3.0
Number of storage tanks	2
Diameter (ft)	90
Total depth (ft)	130
Volume each (MG)	3.0
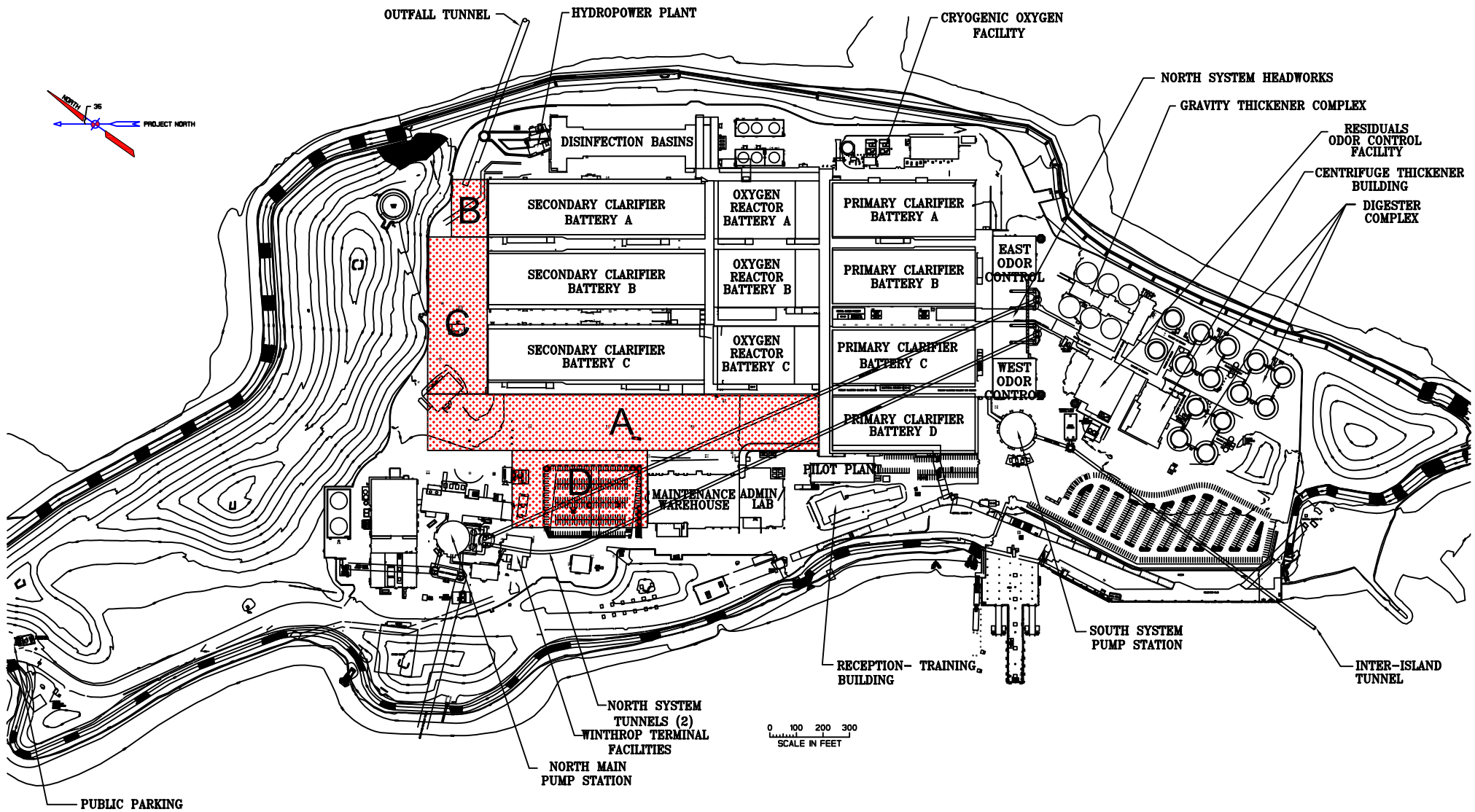
Figure 2. Areas Available for Nutrient Removal

2.3   Flows and Loads

This section provides a summary of monitoring results conducted during the period July 2005 to June 2017 and quantifies nitrogen loads from various wastewater streams. Due to operational changes in 2005, these load calculations supersede the estimates that were used in developing and sizing the conceptual designs of the selected nitrogen removal alternatives in the July 2001 report (CDM, 2001).

In addition to the required NPDES permit influent and effluent monitoring, MWRA implemented a comprehensive nitrogen monitoring program (Coughlin, 2000), to characterize wastewater streams within the treatment plant. If necessary, these data will facilitate the selection and design of nitrogen removal facilities at Deer Island.

Figure 3 shows the Deer Island process flow and the various sampling locations along the process. South system flow arrives at Deer Island's south system pump station via the inter-island tunnel and combines with the north system flow after the grit removal facility. This combined raw wastewater is characterized by taking the flow-weighted average of the individual north and south system measurements.

2.3.1   Flows

The average daily flow for the period July 2005 to June 2017 was 343 MGD. This flow and the maximum sustainable flow to secondary treatment of 700 MGD (based on experiments conducted from October 2005 to June 2006), will be used to size nitrogen removal facilities at Deer Island. Figure 4 shows the daily effluent flow while Figure 5 graphs the monthly averages.

Return streams from sludge processing at Deer Island include overflow from the gravity thickeners, centrate from waste sludge centrifuges, and centrate from the digested sludge centrifuges. Before 2005, these streams were all pumped back to the head of the primary clarifier. However, gravity thickener overflow can now go to the primary tanks or to the south system pump station depending on pump availability. As of April 1, 2005, approximately 1.2 MGD of digested sludge is sent to the Residuals Processing Plant in Quincy via the inter-island tunnel. The wastewater from digested sludge dewatering at the Residuals Processing Plant is returned via the wastewater collection system (south system). Thus, the only constant internal return streams from on-site residual processing that are pumped back to the head of the primary clarifier are the waste sludge centrate from the gravity thickeners and the centrate from waste sludge centrifuges. Mass balance calculations reflect these operational changes. Sludge centrate overflow from the gravity thickeners averages about 6.5 MGD and waste sludge centrifuge centrate averages about 5.5 MGD. While these flows can be considered negligible compared to the raw influent (342.8 MGD), their nitrogen loads are high. Sludge centrate overflow from the gravity thickeners accounts for only 1.6% of the total influent flow but 4.0% of the total nitrogen load, and waste sludge centrifuge centrate accounts for 1.9% of the total influent flow but 6.7% of the influent nitrogen load.

North Metro →
Boston Main Drainage Tunnel →
North Main Pump Station

North Metro Trunk Sewer → Winthrop Terminal

Inter-Island → South System Pump

North System Grit Facility

Centrate recycled to primary

GT overflow recycled to South System

South System flows are degritted at Nut Island and include sludge centrate flows from the Pelletizing Plant via the Intermediate Pump Station (IPS)

Secondary Bypass (high flow conditions only)

Primary Batteries A-D

Secondary Batteries A-C

Final Clarifiers

Hypochlorite

Disinfection Basin

Sludge/Scum Centrifuges

Gravity Thickeners

Digesters

Bisulfite

To Pelletizing Plant

To Outfall

Grit

To Landfill

Legend:
(S) .... Sampling Location
→ Wastewater
·····► Recycle streams
- - -► Sludge, scum, grit
-··-► Chemical Addition

Figure 3. Deer Island Treatment Plant Process Flow Diagram

Figure 4. Average Daily Flow
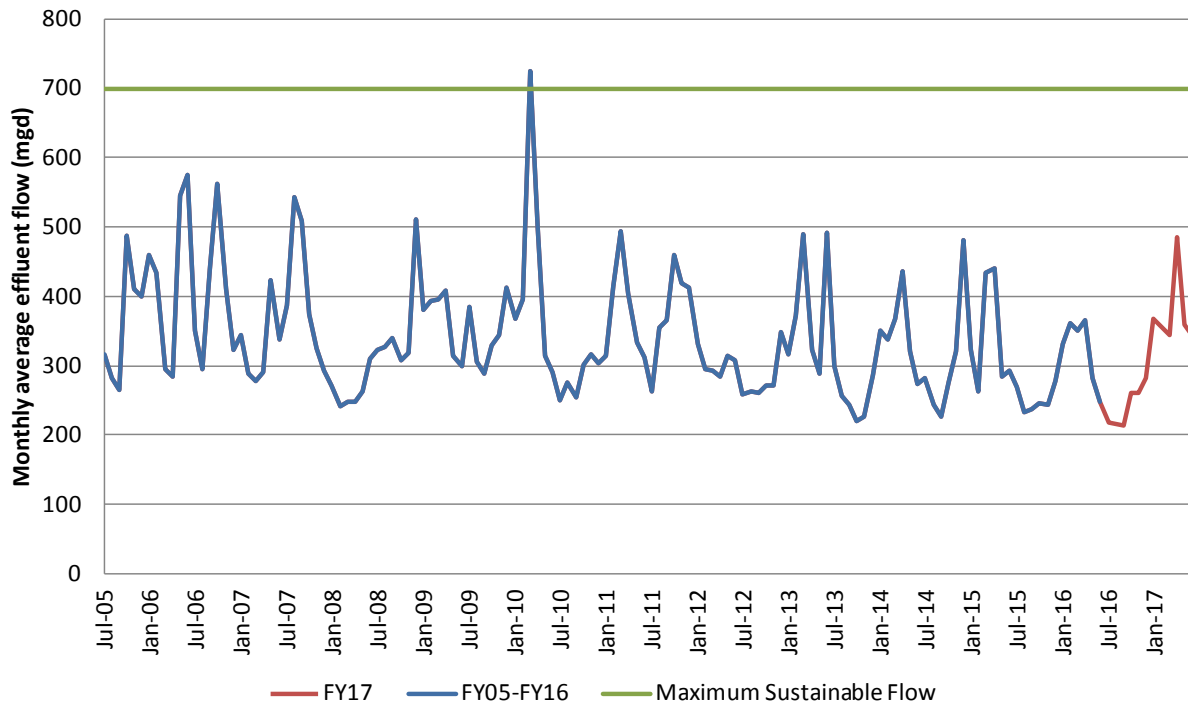
Figure 5. Average Monthly Flow

2.3.2 Nitrogen Loads

Extensive nitrogen data have been gathered from the nitrogen monitoring program. While the first report in 2001 used estimated nitrogen loads, actual data are now available to quantify nitrogen in the major waste streams at Deer Island. These data are presented in Table 2.

Monitored nitrogen species include ammonia-nitrogen (NH_3^-), nitrites (NO_2^-), nitrate (NO_3^-), and total Kjeldahl nitrogen (TKN), which consists of ammonia and organic nitrogen, all expressed as nitrogen. Total nitrogen (TN) is the sum of TKN, NO_3^-, and NO_2^-. For each monitoring event, the actual flow for each waste stream is used to derive the daily loads of each nitrogen species. The TN load is determined from these calculated loads.

From July 2005 – June 2017, the average flow-weighted Deer Island raw wastewater concentration of ammonia was 29 mg/L and TN was 39 mg/L. These concentrations are typical of medium-strength wastewater (Metcalf & Eddy, 1991). The average TN load from raw influent during the same period was about 103,650 lbs/d.

Figure 6 shows the TN mass balance across the unit processes at Deer Island. Figure 7 shows the monthly average total nitrogen loads to the primary clarifiers, while Figure 8 shows the total nitrogen monthly average effluent loads out of the primary clarifiers, secondary clarifiers, and final effluent.

Table 2. Summary of Nitrogen Monitoring Results

| Sampling Location	Flow* (mgd)	TKN (mg/L)	TKN (lb/d)	NH3-N (mg/L)	NH3-N (lb/d)	NO3-N (mg/L)	NO3-N (lb/d)	NO2-N (mg/L)	NO2-N (lb/d)	NO3+NO2 (mg/L)	NO3+NO2 (lb/d)	Total Nitrogen (mg/L)	Total Nitrogen (lb/d)
North System Influent (7/1/05 - 6/30/17)													
Minimum	121.9	7.1	30043	3.6	17030	0.0	0	0.0	0	0.00	0	8.0	32452
Maximum	887.7	66.0	108002	41.3	71420	4.0	17732	4.1	6243	5.91	20585	67.3	108906
Average	221.7	29.4	51559	20.0	34507	0.3	714	0.3	523	0.80	1546	30.0	52800
Standard Deviation	77.3	7.4	9385	5.7	5547	0.5	1581	0.3	614	0.81	2107	7.3	9576
South System Influent (7/1/05 - 6/30/17)													
Minimum	56.3	8.5	19585	5.8	10600	0.00	0	0.00	0	0.00	0	10	19596
Maximum	389.6	132.0	133708	88.9	68465	2.79	8487	1.82	2010	2.98	9065	132	136479
Average	116.9	57.4	50531	46.4	40526	0.14	210	0.21	221	0.44	525	58	50974
Standard Deviation	46.6	18.2	10274	15.5	7321	0.32	742	0.35	376	0.62	1060	18	10331
Calculated Raw Influent													
Minimum	188.8	9.3	52750	5.9	36079	0.0	0	0.0	0	0.00	0	11	52482
Maximum	1261.7	86.8	214050	47.8	129640	3.2	26219	2.9	6560	4.59	28679	87	218548
Average	338.6	38.6	102052	28.7	74968	0.3	927	0.3	744	0.53	1675	39	103649
Standard Deviation	119.1	9.9	15903	8.1	10124	0.4	2143	0.3	775	0.61	2600	10	16300
Waste Activated Sludge Centrate (7/1/05 - 6/30/17)													
Minimum	0.1	21.7	419.24	4.7	41	~	~	~	~	0.00	0.00	21.7	419
Maximum	8.0	949.0	33666.59	50.0	2750	~	~	~	~	0.16	7.22	949.0	33667
Average	5.4	132.2	6041.94	29.2	1356	~	~	~	~	0.02	0.72	132.1	6031
Standard Deviation	1.1	59.3	3010.94	7.9	523	~	~	~	~	0.02	1.01	59.2	2995
Calculated Primary Influent													
Minimum	194.9	9.3	57924	5.9	37011	~	~	~	~	0.00	0	11.0	59793
Maximum	1261.6	92.6	216464	47.7	132034	~	~	~	~	4.46	28679	92.7	220962
Average	344.0	40.4	108116	28.8	76440	~	~	~	~	0.53	1651	40.9	109782
Standard Deviation	118.3	10.5	16332	8.0	10179	~	~	~	~	0.59	2491	10.4	16534
Primary Effluent (7/1/05 - 6/30/17)													
Minimum	188.9	9.2	48772	6.3	39165	~	~	~	~	0.00	0	11	49810
Maximum	1261.7	91.1	199776	89.2	195883	~	~	~	~	3.05	25361	91	200320
Average	341.0	36.7	97363	29.6	78179	~	~	~	~	0.22	904	37	98267
Standard Deviation	121.3	10.9	16093	9.1	13691	~	~	~	~	0.40	2465	11	16195
Secondary Effluent (7/1/05 - 6/30/17)													
Minimum	188.8	7.6	33177	6.3	31506	~	~	~	~	0.00	0	9.6	36303
Maximum	700.7	48.9	142867	58.2	135670	~	~	~	~	7.02	22578	76.1	148229
Average	333.3	27.1	71442	26.0	68144	~	~	~	~	1.84	5192	29.0	76636
Standard Deviation	99.6	7.5	12744	7.5	11937	~	~	~	~	0.70	2612	7.7	13048
Gravity Thickener Overflow (7/1/05 - 6/30/17)													
Minimum	0.1	11.5	39	6.0	19	~	~	~	~	0.00	0	12.5	39
Maximum	12.7	993.0	49054	496.0	24502	~	~	~	~	4.46	169	993.0	49055
Average	6.4	82.8	4160	32.4	1653	~	~	~	~	0.03	2	83.0	4167
Standard Deviation	1.7	93.9	4357	21.6	1055	~	~	~	~	0.22	13	94.0	4358
Final Effluent (7/1/05 - 6/30/17)													
Minimum	188.8	5.8	22489	4.6	18927	0.0	0.0	0.0	0.0	0.01	24	8.1	27999
Maximum	1261.7	72.0	167301	61.3	149891	8.9	26288.5	3.0	12915.4	9.25	35779	74.5	173134
Average	338.6	24.8	65408	24.2	63264	1.0	2856.0	0.7	2173.2	1.66	5119	26.4	70387
Standard Deviation	119.1	8.2	17573	8.3	15997	0.9	3121.4	0.6	2403.8	1.21	4820	7.8	17661

Notes:

* Flows reported are averages of the whole sampling period. The flow-weighted concentrations were calculated using flows during sampling events.
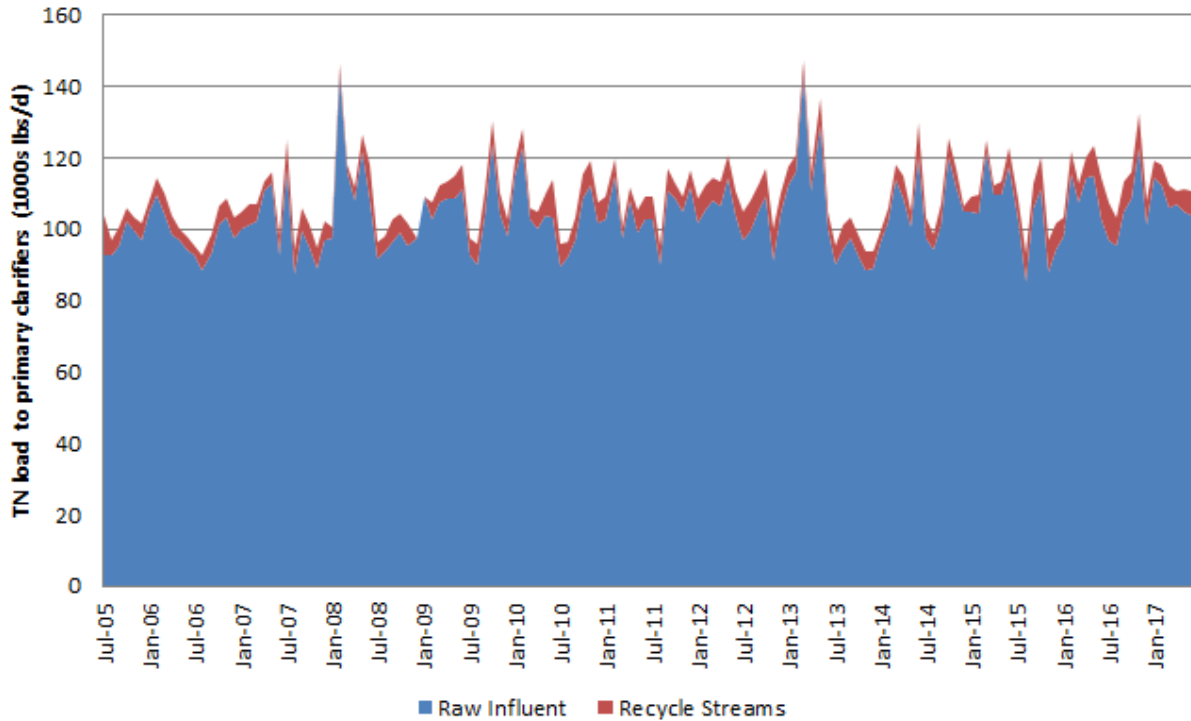
~ No samples collected.

Figure 6. Total Nitrogen Mass Balance (July 2005-June 2017)
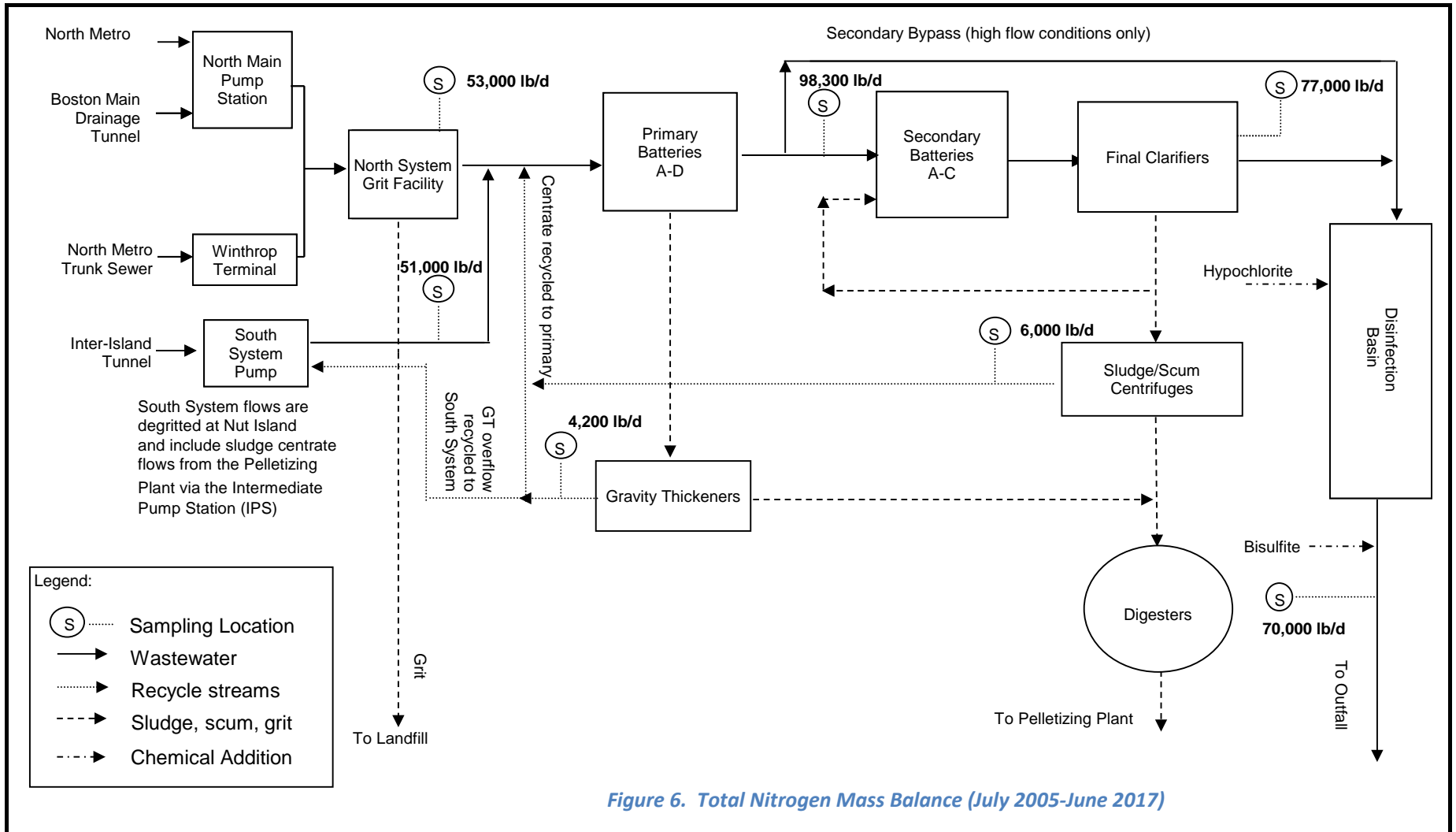
Figure 7. Total Nitrogen Load to Primary Clarifiers (Monthly Average)
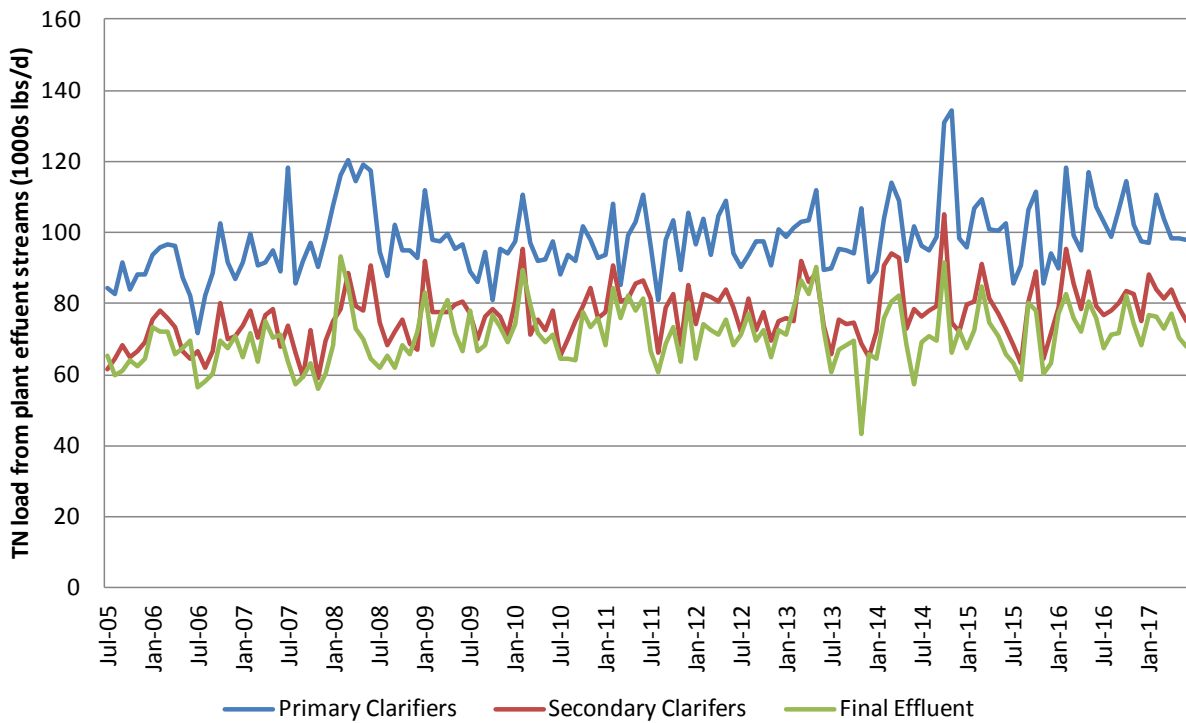

Figure 8. Total Nitrogen Load From Plant Effluent Streams

2.4   Basic Design Information

To develop a conceptual design for a nitrogen removal system, some basic information is required. This includes ambient temperature, design flows and loads, and the target effluent quality.

2.4.1   Wastewater Temperature

Wastewater temperature is important for sizing biological systems for nitrification. As in most biochemical reactions, temperature greatly influences nitrification rates. The rate of ammonium oxidation depends on the growth rate of the bacteria *Nitrosomonas*, which in turn depends on temperature. Based on monitoring data and the possible requirement for year-round nitrification, this report uses the consultant's recommendation of a minimum wastewater temperature of 51.8°F (11°C) (CDM, 2001). Between FY05 and FY17, the wastewater temperature measurements of the south system influent averaged about 2.5°F colder than the north system influent. Figures 9 and 10 graph the north and south system influent temperatures, respectively.

Final effluent is probably the best source for determining the temperature in designing a biological nitrogen removal system. There were no days during FY17 when the temperature dipped below the 51.8°F design criterion. Plant performance would deteriorate during very cold weather but the lessened performance should not cause the plant to exceed a hypothetical permit limit. Figure 11 depicts effluent temperatures during the monitoring period.

2.4.2   Design Flows and Nitrogen Loads

As a result of operational experiments conducted from March 2006 to June 2007, Deer Island established that it has a maximum-day capacity of 700 MGD for secondary treatment.   As a result of the experiments, Deer Island set its process limit at 700 MGD. The design average plant flow of 361 MGD and the maximum sustainable flow to secondary treatment of 700 MGD were used in the conceptual design of the nitrogen removal facility. The corresponding loads in primary and in secondary effluent are presented in Table 3. Table 3 also compares previous load estimates with more current data. As shown, the estimates used in previous reports compare well with actual data.
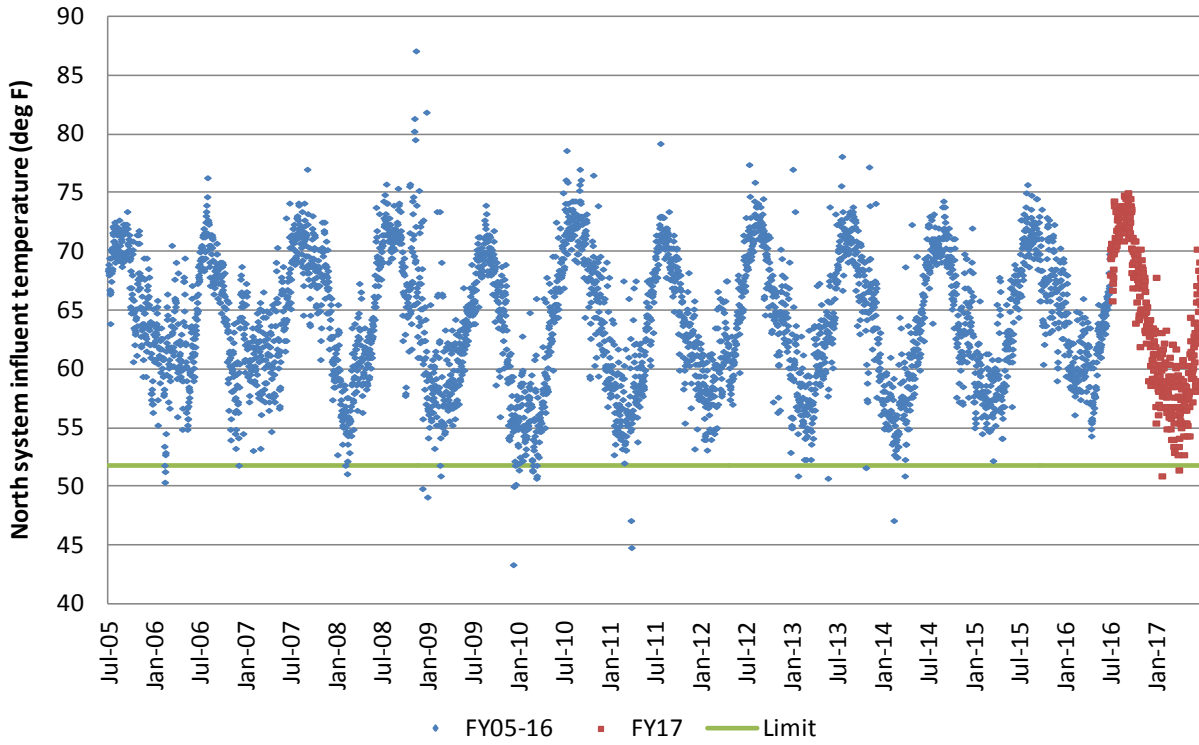
Figure 9. North System Influent Temperatures
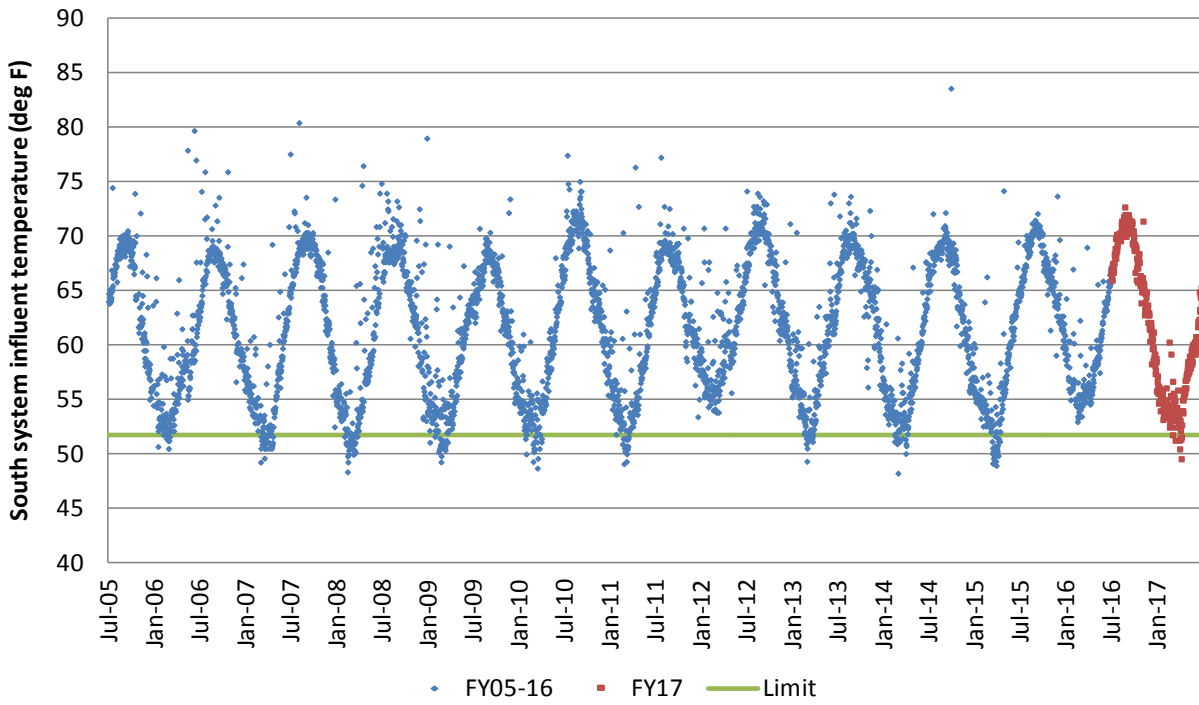
Figure 10. South System Influent Temperatures
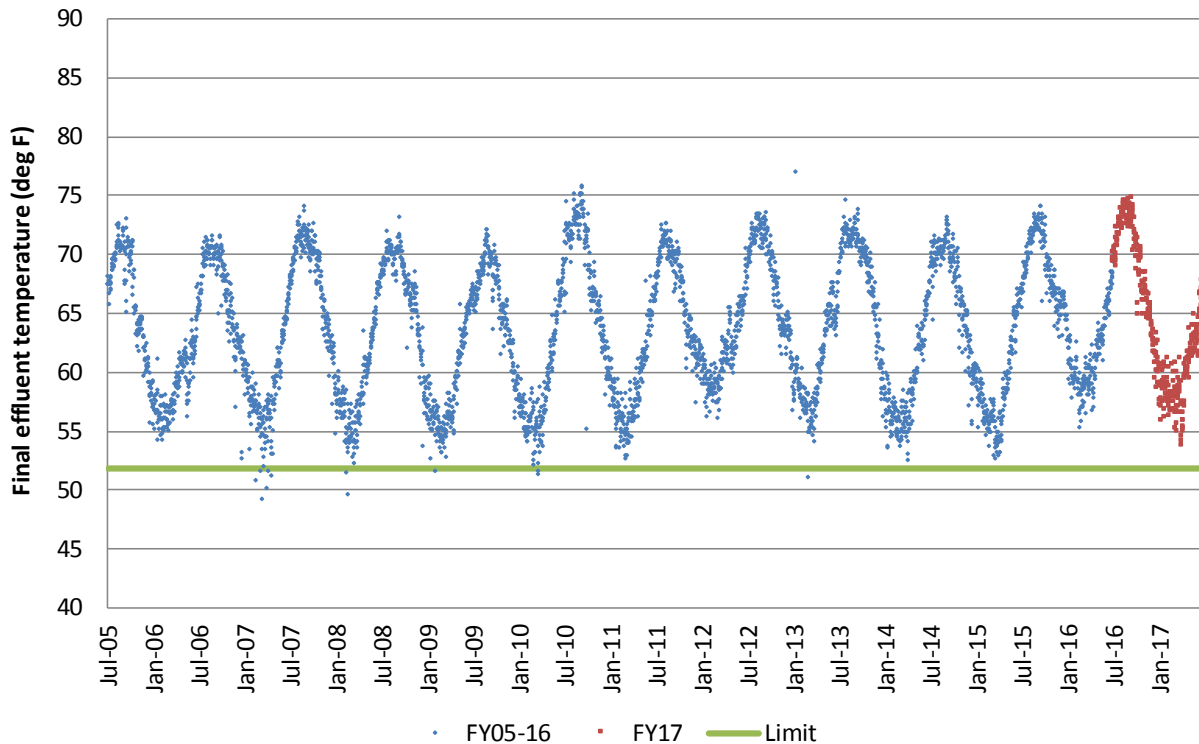
Figure 11. Final Effluent Temperatures

Table 3. Flows and Nitrogen Loads

	Design Flow (MGD)	Primary Effluent Nitrogen Load (lb/d)		Secondary Effluent Nitrogen Load (lb/d)	
		2001*	FY06-FY17	2001*	FY06-FY17
Average – Day	361	80,600	98,300	66,200	76,600
Max – Month	700	104,700†	134,200	86,000†	105,000

* Based on limited monitoring data (July-December 1999) and estimated total nitrogen
   loads from residuals processing recycle flows.

† Estimated.

2.4.3   Required Effluent Quality

Limits for nitrogen in effluent from Deer Island have not been set. This evaluation considers two levels of effluent quality: 4 mg/L and 8 mg/L of total nitrogen, both year-round. These concentrations reflect typical effluent standards for nitrogen, though some recent permits have given effluent limits as low as 2 or 3 mg/L total nitrogen. Other recent permits have given seasonal effluent limits, with limits in place during the warm months, and reporting only during colder months. Conceptual land requirements and

site layouts are conservatively based on a year-round effluent limit of 4 mg/L because a year-round limit requires more space for nitrogen removal.

Section 3. Screening of Alternatives

This section identifies processes available to remove nitrogen from wastewater and screens them to generate a list of alternatives appropriate for further evaluation. Table 4 summarizes the alternatives, and Section 4 examines them in detail.

Nitrogen removal technologies fall into three basic categories: physical/chemical processes, biological processes, and hybrids of the two.

3.1   Physical/Chemical Processes

Physical/chemical processes rely on basic chemical reactions to remove nitrogen species. Physical/chemical processes employed for nitrogen removal include:

- Reverse osmosis
- Ammonia stripping
- Ion exchange
- Breakpoint chlorination.

Reverse osmosis Reverse osmosis (RO) is expensive and requires a high degree of pretreatment. Additionally, the permeability of ammonium through RO filters has not been extensively studied. Its use is not necessary to achieve potential nitrogen standards at Deer Island.

Ammonia stripping

Ammonia stripping requires addition of lime or another softening chemical to raise the pH of wastewater to about 11. At this pH, ammonia is present as a gas, rather than as the ammonium ion. The limed wastewater is sprayed over a packing material, with air added counter-current to the liquid flow to strip the ammonia gas. A problem with this alternative is that power requirements and ammonia emissions are high, and the calcium carbonate scale that forms on the packing requires a high level of maintenance. Very few WWTPs use ammonia stripping today.

Ion exchange

In ion exchange, wastewater is passed through a bed of material that exchanges sodium or potassium in the exchange material for the ammonium ion in wastewater. When the ion-exchange material becomes exhausted, passing a caustic solution through the bed regenerates it. Regeneration releases the adsorbed ammonium ions, which are collected in the exhaust solution. This regeneration solution must then be treated as well. Ammonia in the exhaust can be recovered for use as a fertilizer. Problems with ion exchange include high operation and maintenance costs and head loss resulting from suspended solids build-up on the resin.

Breakpoint chlorination

With breakpoint chlorination, chlorine at high doses oxidizes ammonia nitrogen to nitrogen gas. Dechlorination is needed after breakpoint chlorination, and volatile organic compounds such as

chloroform and other trihalomethanes are formed. Breakpoint chlorination must be preceded by treatment beyond secondary treatment, typically coagulation, settling, and filtration, thus making it most effective on polished effluents. There are few large-scale applications of ion exchange for nitrogen removal. A problem with this alternative is that the chlorine demand will be too great to allow for cost-effective implementation. It is estimated that 10 pounds of chlorine are required to remove one pound of ammonia.

Physical/chemical processes remove nitrogen only in the ammonia form. Although ammonia contributes the most to the total nitrogen load of the plant, these methods do not remove organic nitrogen or nitrite and nitrate. They have never been used extensively, and their use is declining, so there are few plants now using physical/chemical processes for nitrogen removal. Physical/chemical processes are judged to be inappropriate for use at Deer Island.

3.2   Biological Processes

Biological nitrogen removal generally involves two processes in sequence: nitrification in an aerobic environment and denitrification in the absence of oxygen. In nitrification, ammonia is oxidized to nitrite by *Nitrosomona* bacteria and then to nitrate by *Nitrobacter* bacteria. Nitrification can typically be achieved in one step. In denitrification, nitrate is reduced to nitrogen gas by various groups of bacteria. For denitrification to occur at an appreciable rate, suitable concentrations of organic material must be present. In some configurations, the organic matter present in the wastewater is sufficient for denitrification to occur. For other configurations, a supplementary source, such as methanol, must be provided. Direct conversion of ammonia to nitrogen gas (annamox) is described in section 3.2.4.

Processes available for biological nitrification and denitrification include suspended-growth systems, fixed-film systems, and hybrid systems. In hybrid systems, fixed-film material is added to the aeration tank of suspended-growth systems.

3.2.1   Suspended Growth Systems

Deer Island uses a high purity oxygen activated-sludge process to provide secondary treatment. The activated sludge units at Deer Island include aeration tanks and secondary clarifiers. Options for use of the activated sludge process for nitrogen removal at Deer Island include:

- Sequencing batch reactors
- Membrane activated sludge systems
- Two-stage activated sludge
- Single-stage activated sludge

Sequencing Batch Reactors
Sequencing batch reactors combine biological activity and settling in a single tank by cycling between two phases, rather than separating these functions in an aeration tank and a clarifier. They do not save

space, however, and control and piping become complicated for large facilities. They are not evaluated further in this report.

Membrane Activated Sludge Systems

Membrane activated sludge systems use membranes instead of clarifiers, to separate effluent from biomass. Their advantage is that the concentration of mixed liquor in aeration tanks can be much higher than with conventional activated sludge. With higher concentrations, the volume of aeration tanks can be decreased. Membrane activated sludge systems have not been used at plants larger than about one MGD, however. Membrane activated sludge systems are not further evaluated in this report.

Two-Stage Activated Sludge

When activated sludge systems were first used for nitrification, they were designed and built as two-stage systems, with the first stage designed to remove biochemical oxygen demand and the second stage designed to oxidize ammonia.   It is now recognized that single-stage nitrification is feasible, and, except for special cases, today's treatment plants feature single-stage nitrification.

At Deer Island, two-stage nitrification would require construction of aeration tanks and clarifiers after the existing units. There is not enough space remaining to build these units, and two-stage nitrification is thus impractical.

Single-Stage Activated Sludge

Nitrification and denitrification can be obtained in a single-stage system, such as the Modified Ludzack-Ettinger (MLE) process and step feed variation of the activated-sludge process. The MLE process modifies an aeration tank of an activated sludge system by incorporating an anoxic zone ahead of an aeration section designed to provide nitrification. Mixed liquor, which contains nitrate, is returned to the anoxic zone, and nitrate is reduced to nitrogen gas. The step-feed process can achieve denitrification by providing alternating anoxic and aerobic zones. This process has been used successfully in many WWTPs in the United States.

Temperature is the controlling factor in single-stage activated sludge nitrification/denitrification. To provide nitrification in cold weather (when the wastewater temperature can be 51.8°F [11°C] or colder), the solids retention time (SRT) would have to be increased to about 11 days. Current design provides for an SRT of less than 3 days. However, the wastewater temperature rarely drops below 51.8°F. If nitrification in cold weather were required, more aeration tanks would be needed. An aeration volume equal to about seven of the existing three aeration batteries would be required. The area required (about ten acres) exceeds the space available with reasonable geometry and this option is dropped from further evaluation. Addition of an anoxic zone would require even more area. No additional clarifiers would need to be constructed, however, because flows would not increase.

3.2.2   Fixed Growth Systems

In fixed-film systems, the biological organisms grow on a supporting surface, in contrast to suspended-growth systems, where the organisms grow in a liquid phase and then have to be separated from effluent in clarifiers. Fixed-film systems provide a greater surface area for biological growth than suspended growth systems and thus can operate more efficiently at the same volume. Fixed-film

systems include rotating biological contactors, nitrifying trickling filters, biological aerated filters and submerged packed-bed reactors, fluidized bed reactors, and moving bed biofilm reactors.

Rotating Biological Contactors

Rotating biological contactors (RBCs) consist of disks rotating on shafts arranged so that all or part of the disks are submerged. Excessive growth sloughs from the disks and is captured in clarifiers. For aerobic treatment, the disks are submerged to about 40% of their diameter. For denitrification, the disks are completely submerged. The rotation of the disk allows for bulk mixing, and thus no aeration is required. Mechanical reliability of RBCs due to microbiologically introduced corrosion and excess stress due to biomass growth can be a problem and RBCs are not often used at large treatment plants. Therefore, RBCs will not be reviewed further in this report.

Nitrifying Trickling Filters

Trickling filters can be used for nitrification after BOD removal, sometimes without the need for settling tanks. Additional odor control may be required for trickling filters. Some plants operating trickling filters have had problems with flies and other organisms consuming the biofilm, leading to reduced performance. A preliminary comparison of the area required for trickling filters and of space available at Deer Island showed that space is insufficient. Nitrifying trickling filters will not be reviewed further.

Biological Aerated Filters

Biological aerated filters (BAFs) consist of fully submerged, stationary beds of medium about 3 or 4 mm in diameter. Flow through the system is usually upward (although there are some downflow systems), and air diffusers are placed at the bottom of the filter. Periodically, the filters are backwashed to remove accumulated solids. The backwash water requires treatment and is usually returned to the main wastewater flow after settling. BAFs are used primarily for nitrification, though they can also be used anaerobically for denitrification. They are retained in this report for further evaluation of nitrification only.

Submerged Packed-Bed Reactors

Submerged packed-bed reactors are similar in configuration to biological aerated filters. However, they are not aerated and methanol is usually added to the feed stream to provide a carbon source for denitrification. Like biological aerated filters, submerged packed-bed reactors require backwashing to remove trapped solids and excess biological growth. In both cases, this backwash stream must be treated and is pumped to the head of the plant to be treated as primary influent. Submerged packed beds are further evaluated in this report.

Nitrification and denitrification can be achieved in a single packed-bed that combines the features of a biological aerated filter and of a submerged packed-bed reactor. In this type of reactor, the packed-bed is about three meters deep. The air diffusers are set at about two meters beneath the surface, so that the lower section is not aerated and denitrification takes place in the lower section. Methanol is required with secondary effluent because secondary effluent does not contain enough carbon for denitrification to proceed. This combined nitrification/denitrification process has not been attempted at

large plants and is not retained for further evaluation, though it is worth considering in the future for space-saving reasons if its feasibility at large scale is demonstrated.

Fluidized-Bed Reactors

Fluidized-bed reactors are tanks filled with 4 to 10 feet of sand or other granular medium to support the growth of biomass. Wastewater is fed from the bottom of the reactor at a velocity high enough to fluidize the bed. (This contrasts with biological aerated filters, where the bed is not fluidized during normal operation.) Excessive growth shears from the medium and is separated from treated effluent in an upper zone of the reactor. The system supplier believes that other options are preferred for nitrification, and fluidized-bed reactors are not retained for further study for nitrification. Fluidized-bed reactors are retained, however, for denitrification.

Moving-Bed Biofilm Reactors

The moving-bed biofilm reactor (MBBR) process consists of a tank filled with small plastic elements. The hollow cylindrical elements are about 1 cm in all dimensions and have ridges on the exterior and a crosspiece on the inside. These carriers are specially designed to maximize surface area to allow for the most biofilm growth. A clarifier is required to separate excess growth.   With air addition, MBBR can be used for nitrification. With methanol addition, the process can be used for denitrification. This process is recommended for further evaluation.

3.2.3   Hybrid Systems

Hybrid systems are sometimes called integrated fixed-film activated sludge systems (IFAS). The fixed-film material placed in the suspended-growth tanks includes ropes, sponges, trickling filter media, RBCs, and the media used for MBBR. These materials could be placed in the existing aeration tanks and increase their capacity. This report does not further evaluate hybrid systems, but they should be considered if MWRA decides to conduct pilot tests of alternative nitrification systems. Pilot testing could be used to determine appropriate design criteria.

3.2.4   Sidestream Treatment

Several other processes for nitrogen removal have been developed based on the partial nitrification of ammonium to nitrite combined with anaerobic ammonium oxidation. However, these processes target the removal of nitrogen from wastewater containing significant quantities of ammonium, such as sludge.

Although none of the processes described in this section are feasible for mainstream treatment, some have been retained as possible sidestream treatment alternatives. Sidestreams are typically composed almost entirely of nitrogen as ammonia and some organic nitrogen. Possible applications include use on gravity thickener sludge centrate from primary, the sludge centrifuge centrate from secondary treatment, or the centrate from residuals dewatering. All of these streams are highly concentrated in ammonia and contribute significantly to the overall nitrogen load of Deer Island, while accounting for a small fraction of the overall flow. Sidestream treatment would not be sufficient to achieve a target effluent concentration of 4 mg/L, but would aid in reducing the total nitrogen load to the plant. This

would lower the footprint of mainstream treatment processes to be installed, and reduce the supplemental carbon requirements and overall sludge production.

The previous fixed-film nitrogen removal technologies are better suited for mainstream treatment at Deer Island, while those discussed below are better suited for sidestream treatment.

Single Reactor System for High Ammonia Removal Over Nitrite (SHARON)
In the single reactor system for high ammonia removal over nitrite (SHARON), ammonium is oxidized in a one reactor system under aerobic conditions to nitrite (nitrification), which in turn is reduced to nitrogen gas (denitrification) under anoxic conditions using an external carbon source.

Anaerobic Ammonium Oxidation (Anammox)/Deammonification (DEMON)
In the Anaerobic Ammonium Oxidation (Anammox) process, nitrite and ammonium are converted into nitrogen gas under anaerobic conditions by unique annamox bacteria without the need for an external carbon source. Sludge production is significantly reduced as compared to other sidestream treatment processes. One disadvantage is the significant acclimation period for the bacteria; it has taken up to two years for the process to operate at full capacity in some installations. This process requires no supplemental methanol or aeration, though the system can be intermittently aerated to increase ammonia removal.

Specifically evaluated in this report is Veolia's ANITA™ Mox Process. One single reactor is filled with polyethylene carriers with a density slightly less than water for biogrowth. However, in an anammox system, nitrification and denitrification take place in the same reactor. This simultaneous nitrification and denitrification is the result of unique anammox bacteria. The two steps take place in different layers of the biofilm. The aerobic nitrification reaction occurs in the outer layer, where approximately 55% of the influent ammonia is oxidized to nitrite. In the inner layer, anoxic ammonia oxidation (anammox) takes place, producing nitrite and converting the remaining ammonia directly to nitrogen gas and a negligible amount of nitrate. No supplemental methanol is required for this process. Since the anammox bacteria growth rate is very slow as compared to conventional wastewater bacteria growth rates, biomass retention is crucial. Media screens and sufficient aeration to keep the carriers in suspension aids in biomass retention.

ANITA Mox has been retained for sidestream treatment, and is discussed further in Section 4.6.1.

SHARON-Anammox Process
The Anammox process provides an alternative to nitrification with no requirement for an external carbon source. When combined with the SHARON process, the total aeration costs are greatly reduced when compared to the conventional nitrogen removal by nitrification-denitrification.

Completely Autotrophic Nitrogen Removal Over Nitrite (CANON)
The Completely Autotrophic Nitrogen Removal Over Nitrite (CANON) is a two-step, one reactor process that involves the removal of nitrogen under oxygen limited conditions. An alternative to the two-reactor SHARON-Anammox process, the ammonium oxidizing organisms coexist with the organisms performing the Anammox process. Nitrite oxidizers, performing the unwanted reaction to nitrate, are

24

outcompeted on two fronts: competing for ammonium with Anammox, and competing with oxygen with the aerobic ammonium oxidizers.

Membrane Bioreactors (MBR)

Membrane bioreactors combine a membrane process (like ultrafiltration) with a suspended growth bioreactor. MBRs in an aerobic zone have proven to be effective ammonia and nitrite oxidizers, though they most successfully remove organic nitrogen. When followed by an anoxic post-denitrification process, MBRs can be very effective for total nitrogen removal. The membrane can be either submerged in the existing reactor, or external, where the membranes are a separate process and require additional pumping. Submerged MBRs require aeration to keep solids in suspension and to help prevent fouling. Aeration also has the added benefit of aiding in nitrification. MBR efficacy decreases significantly with fouling, and as a result must be chemically backwashed daily. MBRs have few current applications in large municipal wastewater facilities.

Post Aerobic Digestion (PAD)

Post Aerobic Digestion is used to treat activated sludge, and involves implementing aerobic digestion after anaerobic digestion. Although sludge itself is not a sidestream, the centrate from sludge dewatering is, and by reducing the nitrogen load in sludge, the influent nitrogen load to the plant can ultimately be reduced as well. Sludge holding tanks can be retrofitted to PADs in order to see a reduction of TN, as well as volatile suspended solids, and phosphorus. PADs can be fitted with intermittent aerators in order to achieve nitrification and denitrification in the same reactor, or sludge can be recycled from aerobic to anaerobic digester as in an MLE process No supplemental carbon or alkalinity is required. A cooling system is necessary in order to regulate temperature and foaming.

3.2.5   Treatment Innovations

OpenCel Focused Pulse

OpenCel uses electrical pulses to disrupt waste activated sludge cell structures causing the cells to lyse. Once ruptured, waste activated sludge is more readily degradable by active microorganisms. If the waste activated sludge is fed to a digester, it degrades more completely, giving higher volatile solids destruction (therefore less biosolids yield) and generating more digester gas (if anaerobic). If fed to an anoxic zone, the ruptured cells become a source of readily biodegradable carbon for denitrification. OpenCel can also aid in foaming mitigation and odor reduction. There are only two full-scale applications of OpenCel in North America due to its prohibitively expensive capital and operating costs.

Microbial Fuel Cells (MFC)

Microbial fuel cells operate essentially as large galvanic cells, using an anode and a cathode to convert organic matter to electricity. MFCs take advantage of the electrons released during ammonia and nitrate oxidation and harvest them on carbon-based biodes. The use of algae or bacteria based biocathodes can aid in nitrogen removal. MFCs require no aeration, no supplemental carbon, and produce low volumes of sludge. However, they are very pH sensitive and difficult to maintain. Presently, MFCs are still in their infancy and are used primarily for agricultural and food wastewaters with no applications larger than 100,000 MGD.

Table 4. Alternatives for Controlling Nitrogen at the Deer Island Treatment Plant

	Total Nitrogen Removal
Physical/Chemical Processes	
Reverse Osmosis	X
Ammonia Stripping	X
Ion Exchange	X
Breakpoint Chlorination	X

	Nitrification	Denitrification
Biological Processes		
Suspended Growth		
Sequencing Batch Reactors	X	X
Membrane Activated Sludge	X	X
Single Stage and Two Stage	X	X
Fixed Film		
Rotating Biological Contactor	X	X
Nitrifying Trickling Filter	X	
Biological Aerated Filters	X	
Submerged Packed-Bed Reactor		X
Fluidized-Bed Reactors		X
Moving-Bed Biological Reactor	X	X
Treatment Innovation		
OpenCel Focused Pulse		X
MFC	X	X
	Nitrification	**Denitrification**
Sidestream Treatment		
SHARON	X	X
Anammox/DEMON		X
SHARON-Anammox	X	X
CANON	X	X
MBR	X	X
PAD	X	X

3.3   Systems Retained for Further Evaluation

Table 5 shows systems retained for further evaluation. These systems were chosen based on ability to handle the flows and nitrogen loads at Deer Island, as well as experience with cost, reliability, and ability to fit into the available land at the treatment plant.

Table 5. Systems Retained for Further Evaluation

	Nitrification	Denitrification
Biological Aerated Filters	X	
Submerged Packed Bed Reactors		X
Fluidized-Bed Reactors		X
Moving Bed Biofilm Reactor	X	X
Integrated Fixed Film Activated Sludge	X	X
Anammox (ANITA Mox) for Sidestream	X	X

Section 4. Evaluation of Alternatives

This section investigates the alternatives proposed in Section 3 for further evaluation. They are grouped into these process alternatives:

- Biological aerated filters for nitrification with submerged packed-bed reactors for denitrification
- Biological aerated filters for nitrification with fluidized-bed reactors for denitrification
- Moving-bed biofilm reactors for nitrification and denitrification
- Integrated Fixed Film Activated Sludge MLE for nitrification and denitrification

Development of the alternatives includes selection of criteria for sizing units and preliminary sizing of components. Alternatives are developed to meet hypothetical permit limits of 4 mg/L and 8 mg/L of effluent nitrogen, but are designed conservatively to meet effluent levels of 3 mg/L and 6 mg/L, respectively.

Based on information provided, MWRA's consultant was able to obtain information about proprietary equipment and processes from system suppliers. Recommendations from the suppliers were reviewed, and professional judgment and experience were applied to select design criteria. The units provided allow for standby, such as for backwashing or other maintenance and for repair.

Oxygen requirements, chemical requirements, and sludge production for each alternative would be about equal. Those needs are covered in Section 4.4.

4.1   Biological Aerated Filters and Submerged Packed-Bed Reactors

Design criteria for nitrification in biological aerated filters (BAFs) and denitrification in submerged packed-bed reactors (SPBRs) are shown on Table 6. Two major suppliers provided recommendations for the criteria: Infilco Degremont, Inc., and Kruger, Inc. In the table, the number of units needed to meet nitrogen loads is calculated, based on loading criteria and on unit dimensions.

The table shows that 119 BAFs and 32 SPBRs would be required. These include standby units. To fit on the space available, the units would have to be constructed on two levels. Each level would include half of the units, plus blowers and other ancillary facilities.

To reach the new facilities, secondary effluent, which now flows to an effluent channel south of the secondary clarifiers, would be diverted to a new effluent channel north of the clarifiers and to a new pumping station to lift flow to the new facilities. Effluent from the new facilities would enter a new tunnel discharging to the chlorine contact tanks.

Blowers would provide aeration. The air would be injected at the base of each biological aerated filter and flow upward, co-current with the wastewater flow.

The BAFs and SPBRs both need to be backwashed approximately every two days, using final effluent for backwashing. Backwash waste would be returned to the head of the secondary system or to the head

of the plant. Backwash rate is about 25 gpm/ft^2, for about eight minutes. Air required for backwashing is approximately 5000 standard cubic feet per minute per cell (scfm/cell).

The gross area required for siting the BAF and SPBR system, including blowers, a pump station and galleries would be about 5.7 acres, the entire available space in the area of secondary Battery D. Figure 12 shows the proposed BAF and SPBR layout.

4.2   Biological Aerated Filters and Fluidized-Bed Reactors

The BAF design for this treatment combination would be identical to that described in Section 4.1. Table 7 summarizes sizing information for the fluidized bed reactors (FBRs) for denitrification. The FBR design is based on information provided by US Filter. The effluent from the fluidized beds would flow to the chlorine disinfection basin and then be discharged from the facility. Table 7 shows that 119 BAFs and 56 FBRs would be required; these include standby units.

The area requirements for the BAF/FBR system would be approximately seven acres. This area exceeds the space available in Battery D, but the proposed layout can be incorporated as shown in Figure 13.

Table 6. Biological Aerated Filter for Nitrification and Submerged Packed-Bed Reactors for Denitrification

	BAF Nitrification	SPBR Denitrification
TKN Load (lb/d)		
Maximum Month	101,600	101,600
Nitrogen Loading Rate Allowed (lb/d/1,000ft^3)	40*	190*
Hydraulic Loading Rate Allowed (gpm/ft^2)	4	15
Unit Dimensions		
Depth (ft)	12.1	9.5
Surface Area (ft^2)	1,940	1,940
Volume (ft^3)	23,500	18,430
Active Units	108	29
Units Provided	119	32
*These estimates for loading rate were provided in 2002. Since then, significant process improvements have been made, and much higher nitrogen loading rates are possible.		

Figure 12. Proposed BAF and SPBR Layout

Table 7. Biological Aerated Filter for Nitrification and Fluidized Bed Reactors for Denitrification

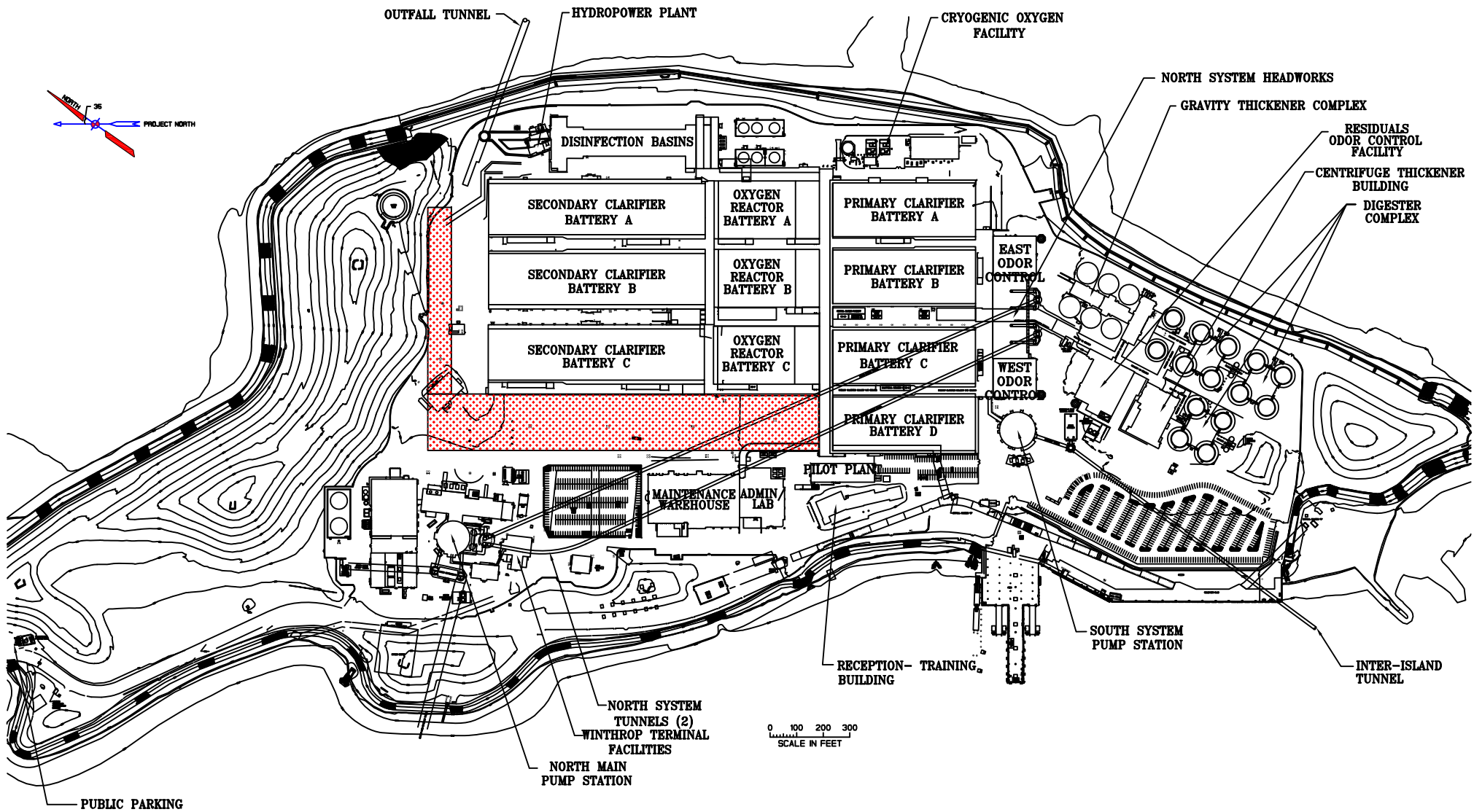|	BAF Nitrification	FBR Denitrification
TKN Load (lb/d)		
Maximum Month	101,600	101,600
Nitrogen Loading Rate Allowed (lb/d/1,000ft^3)	40*	250**
Hydraulic Loading Rate Allowed (gpm/ft^2)	4	18
Unit Dimensions		
Depth (ft)	12.1	10
Surface Area (ft^2)	1,940	800
Volume (ft^3)	23,500	8,000
Active Units	108	51
Units Provided	119	56
*These estimates for loading rate were provided in 2002. Since then, significant process improvements have been made, and much higher nitrogen loading rates are possible. ** There is little information available on FBRs and nitrogen loading rates.		

NORTH
35
PROJECT NORTH

OUTFALL TUNNEL

HYDROPOWER PLANT

CRYOGENIC OXYGEN
FACILITY

NORTH SYSTEM HEADWORKS

GRAVITY THICKENER COMPLEX

RESIDUALS
ODOR CONTROL
FACILITY

CENTRIFUGE THICKENER
BUILDING

DIGESTER
COMPLEX

DISINFECTION BASINS

SECONDARY CLARIFIER
BATTERY A

OXYGEN
REACTOR
BATTERY A

PRIMARY CLARIFIER
BATTERY A

EAST
ODOR
CONTROL

SECONDARY CLARIFIER
BATTERY B

OXYGEN
REACTOR
BATTERY B

PRIMARY CLARIFIER
BATTERY B

SECONDARY CLARIFIER
BATTERY C

OXYGEN
REACTOR
BATTERY C

PRIMARY CLARIFIER
BATTERY C

WEST
ODOR
CONTROL

PRIMARY CLARIFIER
BATTERY D

PILOT PLANT

MAINTENANCE
WAREHOUSE

ADMIN
LAB

SOUTH SYSTEM
PUMP STATION

RECEPTION- TRAINING
BUILDING

INTER-ISLAND
TUNNEL

NORTH SYSTEM
TUNNELS (2)
WINTHROP TERMINAL
FACILITIES

NORTH MAIN
PUMP STATION

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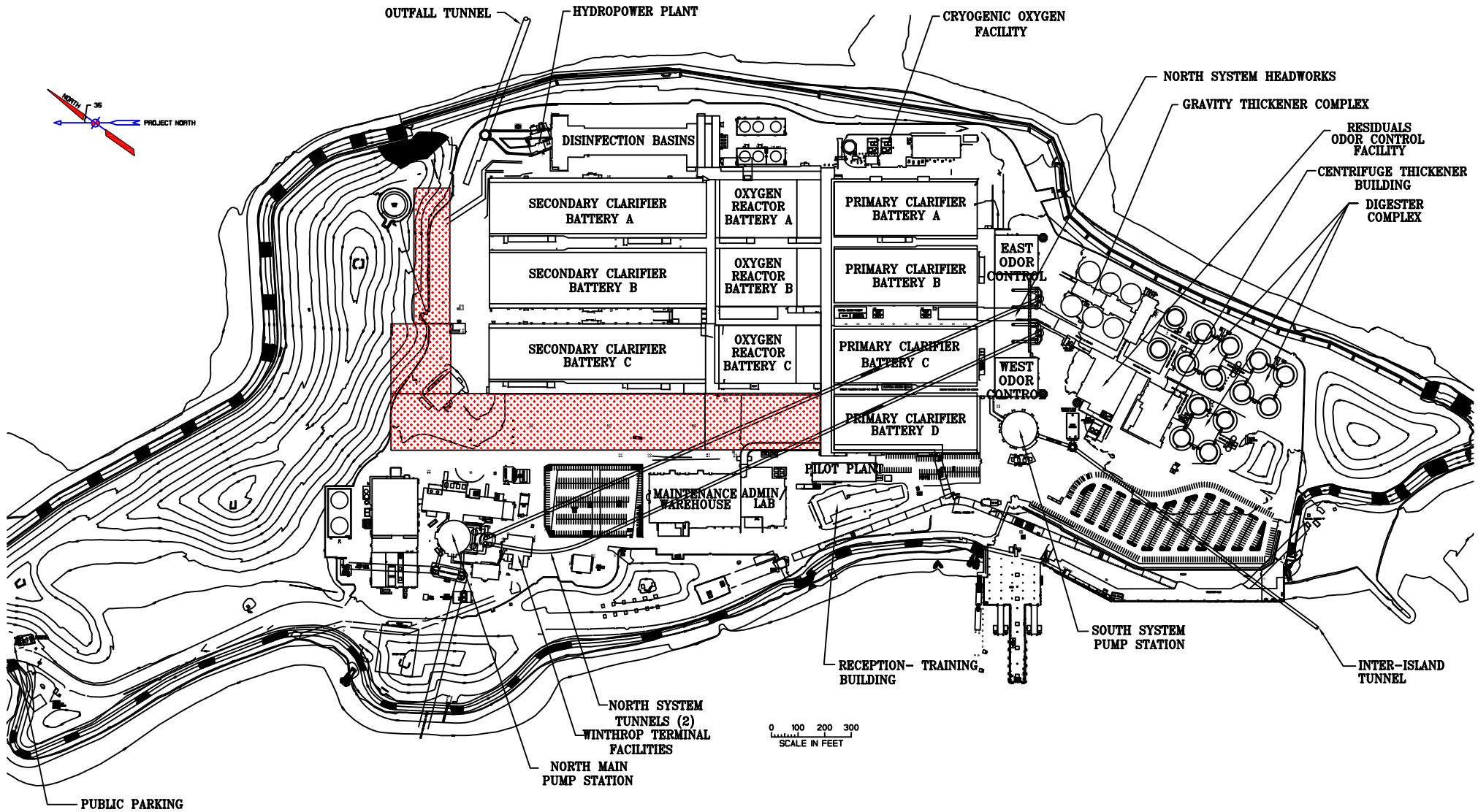SCALE IN FEET

PUBLIC PARKING

Figure 13. Proposed BAF and FBR Layout

4.3   Moving-Bed Biofilm Reactors

For this option, Kaldnes provided the design concept criteria. Media would be added to the existing aeration tanks, where nitrification would occur.

Table 8 summarizes design criteria for the MBBR nitrification system and Table 9 summarizes the MBBR denitrification system. Because the MBBRs would be treating primary effluent, the analysis for MBBRs accounted for nitrogen removed via assimilation into the biomass produced during BOD removal. In the proposed MBBR systems, polyethylene media would be added to the existing aeration tanks. The biomass for biological treatment would grow on the media, thus eliminating the need for recycling solids from the secondary clarifiers. Stainless steel sieves would be installed at the outlets of the aeration basins to retain the media.

The existing on-site pure oxygen aeration system would provide oxygen and mixing. Because the aeration basins would now provide nitrification as well as oxidation of BOD, additional tankage, as described in Table 8, would be required to handle the design flows. Additional facilities for producing oxygen would also be required.

Effluent from the aeration basins would be deaerated before flowing to additional MBBRs for denitrification. Deaeration can be accomplished by nitrogen stripping, which drives dissolved oxygen from the wastewater. Nitrogen gas is a by-product of the cryogenic pure-oxygen generation system. This excess nitrogen can possibly be used as the nitrogen stripping source.

New effluent channels would be required to divert flow from the aeration basins to the denitrification MBBRs and then to the existing secondary settling basins for clarification.

For aeration, approximately 6,500,000 ft^3 of total volume would be required. The existing aeration basins provide 4,321,800 ft^3. However, with the need to construct two new channels, 485,100 ft^3 of aeration volume would be lost from the existing basins. The total new volume required (2,630,000 ft^3) could be located in the space previously allotted for aeration Battery D.

Denitrification would require between 2,430,000 to 3,225,000 ft^3 of new construction depending on the level of effluent nitrogen concentration to be met. Prior to denitrification, 152,000 ft^3 of deaeration tankage is required to remove dissolved oxygen from the wastewater. Deaeration/denitrification facilities can also be sited in the space previously allocated for secondary clarifier Battery D. Methanol facilities for denitrification would be located between the vehicle maintenance building and the dry storage warehouse.

The proposed MBBR nitrification/denitrification system would require about 6.3 acres. Figure 14 shows the conceptual layout of the MBBR nitrification/ denitrification system.

Table 8. Moving Bed Biofilm Reactor for Nitrification

	MBBR for Nitrification
Nitrogen Load in Primary Effluent (lb/d)	
Maximum Month	134,000
Nitrogen Assimilated Plus Ammonia Nitrogen in Effluent (lb/d)	13,600
Nitrogen Nitrified (lb/d)	121,000
Nitrification Rate (g/m^2·d)	0.931
Specific Surface Area (m^2/m^3)	500
Total Media Required (ft^3)	4,200,000
% Fill of Carrier Elements	65%
Total Volume Required (ft^3)	6,500,000
Total Existing Aerobic Tank Volume (ft^3)	4,321,800
Volume Lost to New Channel (ft^3)	485,100
New Volume Provided (ft^3)	2,630,000
Unit Dimensions of New Basins	
Depth (ft)	24.5
Surface Area (ft^2)	4,900
Number of Basins	12

Table 9. Moving Bed Biofilm Reactor for Denitrification

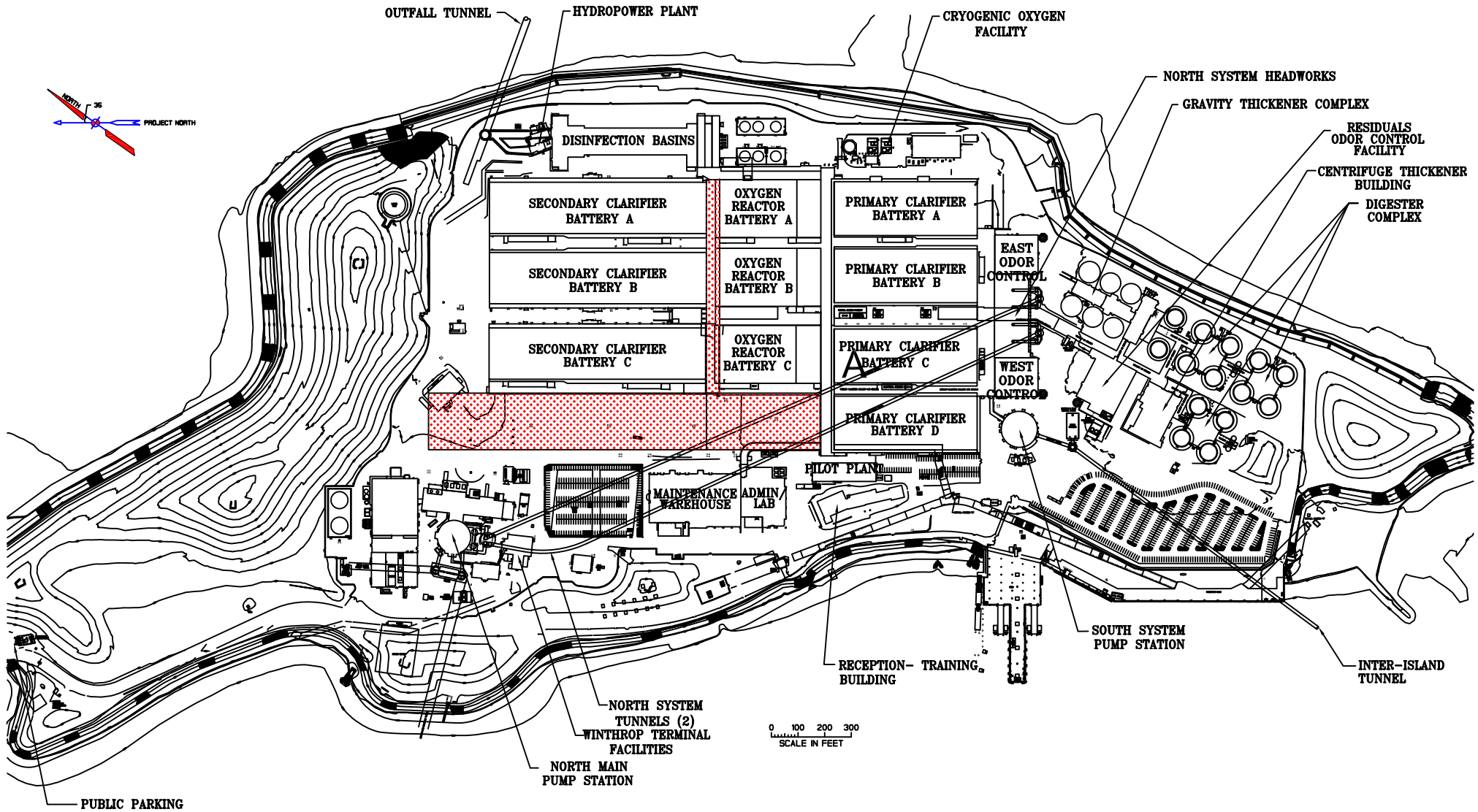|	MBBR for Denitrification	
	4 mg/L Total Nitrogen	**8 mg/L Total Nitrogen**
Total Nitrate Nitrogen Reduced (lb/d)	98,000	74,300
Loading Rate (g/m^2·d)	2.45	2.45
Specific Surface Area (m^2/m^3)	500	500
Media Required (ft^3)	1,290,000	972,000
% Fill of Carrier Elements	40%	40%
Total Tank Volume (ft^3)	3,225,500	2,430,000
Deaeration Volume	152,000	152,000
Tank Dimensions		
Surface Area (ft^2)	4,900	4,900
Depth (ft)	24.5	24.5
Number of Reactors	27	21

Figure 14. Proposed MBBR Nitrification/Denitrification Layout

4.4   Common Elements

Elements common to the three alternatives include oxygen required for nitrification, chemical required for denitrification and additional capacity for processing sludge produced from both nitrification and denitrification systems.

4.4.1   Oxygen Requirement

Nitrification will increase the requirement for oxygen. This section examines two alternatives for providing oxygen.

The first case is for the BAF system, which would process secondary effluent from the existing activated-sludge system and for which air from the atmosphere would be used to provide oxygen. In that case, blowers provided by the system supplier would provide diffused air. The blowers would be housed in the BAF building. During the maximum day, about 280 tons/day of oxygen would be needed. Air use would be about 150,000 cfm at the maximum rate, and connected power for the blowers would be about 7,500 horsepower.

The second case is for the MBBR system, which would process primary effluent. With the MBBR system, high-purity oxygen would be used. Two new 150-ton units would have to be added, to supplement the two 150-ton/day units existing at Deer Island's cryogenic plant.

4.4.2   Chemical Requirements

Denitrification would require addition of methanol. The methanol requirement assumed for all of the denitrification systems is 3 lb methanol per lb of nitrate-nitrogen reduced. Methanol consumption for denitrification would average about 220,000 lb/d for less than 8 mg/L effluent TN concentration and 320,000 lb/d for an effluent TN concentration of less than 4 mg/L at maximum month flows. This would require bringing in six additional 30 ton trucks of methanol every day. Alternatively, two 243,000 gallon methanol storage tanks could be constructed. Each tank would provide about 14 days of storage.

4.4.3   Sludge Production

Methanol addition would increase sludge production at the rate of about 0.6 lb/lb of nitrate nitrogen reduced. For example, using MBBR, about 97,600 lbs/d of nitrogen would be reduced to achieve 4 mg/L of total nitrogen during the maximum month, and about 58,560 lb/d of additional sludge would thus be produced.

The additional sludge produced would impact thickening of biological sludge and sludge digestion. At a concentration of about 0.6%, additional sludge to be thickened would amount to about 640 gpm. The design concentration of thickened biological sludge is 5% and the digesters are sized to provide 15 days of storage at the maximum month. Under these conditions, about 2 million gallons of digestion capacity would be needed. Based on current operating practices, the digesters have enough capacity to handle the additional sludge flow. However, if necessary the volume of additional sludge produced could be lowered with sidestream treatment.

4.5 Sidestream Treatment and Additional Considerations

Biological nitrogen removal technologies appear to be the most cost-effective method of nitrogen removal at this time. In the spring of 2003, the Water Environment Research Foundation (WERF) embarked on a research project, *Sustainable Technology for Achieving Very Low Nitrogen and Phosphorus Effluent Levels* (WERF, 2003). This 2-year project assessed a variety of technologies to develop information about the feasibility and cost benefits of nutrient reduction. WERF determined that among advanced treatment processes, membrane separation technology in the form of membrane bioreactors and SHARON/Anammox applications have emerged as promising alternatives to conventional nutrient removal processes. Additional considerations in the selection of alternative options include separate treatment of residual processing return flows at the Residuals Processing Plant in Quincy, decreasing methanol requirements, and decreasing sludge production.

4.5.1 Separate Treatment at the Residuals Processing Plant

Since April 2005, digested sludge has been sent to the Residuals Processing Plant in Quincy via the inter-island tunnel. With all processing of digested sludge taking place at the Processing Plant, sidestreams from dewatering the digested sludge contain high concentrations of ammonia, and it might be economical to treat the sidestreams for nitrogen removal at the Processing Plant. An unused land area of approximately 54,800 ft^2 could be utilized for additional reactor construction. Treatment at the Residuals Processing Plant therefore may decrease the size of facilities needed at Deer Island.

The centrate from the dewatering process at the Processing Plant flows to the Intermediate Pump Station in Quincy at an average of 1.2 MGD and is on average 1400 mg/L ammonia nitrogen. This accounts for over 16,600 lb/day of ammonia or 16% of the total influent nitrogen to Deer Island. This centrate stream accounts for only 0.354% of the total flow. An 80% reduction of ammonia in the centrate would account for a 13% reduction of the TN load to the entire plant. This TN load reduction would in turn reduce the number of main stream reactors required to meet effluent limits (see Table 13 below). Either a DEMON or ANITA Mox anammox installation would be able to achieve this desired reduction (see preliminary design criteria below).

4.5.1.1 Anammox ANITA™ Mox

Veolia provided the design criteria for their ANITA Mox anammox system. A total suspended solids (TSS) concentration of 800 mg/L was assumed. However, the centrate from the dewatering process has an average concentration of total suspended solids over 5,000 mg/L, which could pose operational issues. Although most annamox systems aren't affected by TSS since flow in is equal to flow out, it could lead to reduced DO. Larger blowers could help to increase DO and dish filters upstream of the reactors could help to reduce TSS concentration. Both of these solutions would require additional space beyond what is already proposed.

The proposed ANITA Mox system predicts up to 90 percent ammonia nitrogen removal, and up to 80 percent total inorganic nitrogen removal. The total footprint of the reactors required for this system is approximately 17,000 ft^2, which fits well within the available space at the Processing Plant. However, aerators would be required to provide the necessary aeration. Veolia recommended the installation of four blowers, each rated at 3500 scfm, and one for standby. The operating temperature for optimal

performance ranges between 25°C and 35°C, with a maximum operating temperature of 37°C. This wide range accounts for the fluctuations in the digester sludge effluent temperatures while still maintaining optimal performance. The remaining design criteria for this system is summarized on the following page in Table 10.

Table 10. ANITA Mox Design Criteria

Residuals Centrifuge Centrate Flow (MGD)	1.2
Number of Process Trains	4
Number of ANITA Mox Reactors per Train	1
Dimensions, each (ft – L x W x D)	65 x 65 x 16
Volume, each (ft^3)	67,600
Total Volume (ft^3)	270,400
Media Type Effective Surface Area (m^2/m^3)	K5 500
Volumetric Loading Rate (kg-N/day/m^3)	.0582
Surface Area Loading Rate (g-N/day/m^2)	1.25
Fill of Biofilm Carriers in each Reactor (%)	46
Media Volume, total (ft^3)	124,800
Total Effective Surface area (ft^2)	62,400,000
Aeration Rate (scfm)	13,220
Design Temperature (°C)	35

4.5.2   Sidestream Treatment at Deer Island Treatment Plant

The combined gravity thickener overflow and the waste activated sludge recycle streams are about 12.0 MGD and contain about 10,200 pounds of total nitrogen, about 10% of the total load to the plant. However, most sidestream treatment processes are able to treat only ammonia nitrogen and small amounts of nitrate, and at a smaller scale (the largest sidestream treatment installations are up to 8 MGD). The total ammonia load in both of these streams is roughly 3,000 pounds per day, or less than 3% of the total load to the plant. Pretreatment of these streams would reduce the load to the activated

sludge process but it is unlikely that the resulting nitrogen concentrations could meet the effluent quality levels of 4 mg/L and 8 mg/L evaluated in this report. Sidestream treatment at Deer Island would serve as a supplement to mainstream nitrogen removal processes to help reduce the footprint and number of reactors required (see Table 11 below).

The gravity thickener overflow flow rate varies more day to day than the waste activated sludge recycle streams (standard deviation of 1.66 MGD vs. 1.06 MGD), making it difficult to accurately design a reactor. The waste activated sludge recycle stream also has a higher ammonia nitrogen concentration than the gravity thickener overflow and would be more economical to treat. The daily ammonia load from the recycle stream is approximately 1650 pounds. An 80% reduction of ammonia in this stream would account for a 1.3% reduction of the total nitrogen load to the plant. Therefore, it would be most economical to provide separate treatment of the waste activated sludge centrate at the Residuals Processing Plant.

Table 11. Reactors Required for Nitrogen Removal with and Without Sidestream Treatment

	No Sidestream Treatment	Residuals Processing Plant Centrate Treatment	Recycle Activated Sludge Centrate Treatment
Required BAF Reactors	108	98	103
Required SPBR Reactors	29	27	28
Required FBR Reactors	51	46	49
Additional Tankage Required for MBBR Nitrification (ft^3)	2,630,000	1,860,000	2,200,000
Required MBBR Denitrification Reactors	27	23	25

4.5.3   Decreasing Requirement for Methanol

All of the mainstream treatment alternatives considered in Section 4 would require addition of methanol as a carbon source for denitrification. With these options, purchase of methanol would be a major expense. Based upon estimates from Methanex Corporation, methanol costs approximately $0.20/lb. It would be costly (over $23 million/year) to purchase over 300,000 lb/day to achieve an effluent concentration of less than 4 mg/L. Therefore, it is imperative to find ways to reduce the methanol demand of these treatment processes.   Applying treatment processes that use wastewater to provide the carbon source would decrease use of methanol. The use of sidestream treatment systems

would help reduce the methanol demand by reducing the overall nitrogen load to the plant. See Table 12 below for methanol requirements. Annamox processes require no supplemental methanol.

Table 12. Methanol Demand for Effluent of 4 mg/L TN with and Without Sidestream Treatment

	No Sidestream Treatment	Residuals Processing Plant Centrate Treatment	Recycle Activated Sludge Centrate Treatment
SPBR/FBR Methanol Required (lb/day)	320,000	270,000	300,000
Cost per year ($)	23,360,000	19,710,000	21,900,000
MBBR Methanol Required (lb/day)	283,000	251,000	272,000
Cost per year ($)	20,659,000	18,323,000	19,856,000

Section 3.2.1 described the MLE process, which is a modification of the activated sludge process. In that section, it was stated that the MLE process and other modifications of the activated sludge process require more space than is available at Deer Island. The volume (and hence, space) required can be decreased by adding carrier material to the system, to serve as medium on which dense biological growth could be supported. Additional work would be required to assess the kinetics of these systems and to determine how to configure tanks and piping at Deer Island.

4.5.4   Decreasing Activated Sludge Production

With any of the mainstream treatment options would come an increase in activated sludge production due to the supplemental methanol. As was discussed in Section 4.5.3, the existing facilities would be able to handle and process this increase. However, treating this additional sludge would be costly and energy intensive. Sidestream treatment would reduce the amount of additional sludge produced by reducing the methanol demand. See Table 14 below for a summary of additional sludge production with various sidestream treatments.

Table 13. Additional Sludge Production with and Without Sidestream Treatment

	No Sidestream Treatment	Residuals Processing Plant Centrate Treatment	Recycle Activated Sludge Centrate Treatment
SBPR/FBR Additional Sludge Produced (lb/day)	47,000	41,000	44,000
MBBR Additional Sludge Produced (lb/day)	56,600	54,300	50,200

Section 5. Conclusions

Although MWRA's current NPDES Permit (No. MA0103284) gives no limit for effluent nitrogen, it does require that a comprehensive survey of nitrogen removal technologies be maintained and submitted every year. The outfall monitoring data shows that the nitrogen in Massachusetts Bay has had no adverse effects on algal blooms, cyanobacteria populations, or dissolved oxygen concentrations. This is not unexpected since only 3% of the total nitrogen entering Massachusetts Bay is the result of DITP effluent. However, an increasing number of wastewater treatment plants across the United States are being issued permits with nitrogen effluent limits. This survey will allow MWRA to quickly select an appropriate treatment process for nitrogen removal should an effluent limit be introduced.

Currently, there exist approximately 13 acres of usable space for nitrogen removal facilities on Deer Island. Biologically aerated filters with submerged packed bed reactors or fluidized bed reactors and moving-bed biofilm reactors were determined to be the most feasible options for implementation at Deer Island. BAFs, SPBRs, and FBRs would all require entirely new tankage and would require a large amount of land area. MBBRs could be partially retrofitted into the existing aeration basins in secondary treatment, but would require additional tankage for denitrification. All of these options would require a supplemental carbon source for complete denitrification, and would also lead to increased sludge production from denitrification.

Sidestream treatment could be beneficial in reducing the demand of some of these treatment processes. Anammox and DEMON processes were considered to be the most feasible sidestream treatment processes. It would be most economical to treat the centrate from the residuals processing plant instead of the gravity thickener overflow or the secondary treatment sludge centrifuge centrate. While none of these sidestream treatment processes would be able to achieve an effluent standard as low as 4 mg/L, they would significantly reduce the overall nitrogen load to the plant. Treating the centrate from the residuals processing plant (1.2 MGD, accounting for <1% of the total flow) would reduce the total nitrogen load to the plant by over 10%. Sidestream treatment processes have a small footprint, are relatively inexpensive, and could aid in reducing the overall footprint, methanol requirement, and additional sludge production of the mainstream treatment processes.

All of the evaluated processes would fit within the limited footprint on Deer Island, though all have their drawbacks as well. Regardless of which mainstream treatment process is chosen, a sidestream treatment process should be considered. The technologies presented in this report are the most up to date and advanced processes for nitrogen removal used around the world. MWRA will continue to research novel nitrogen removal technologies and their possible applications at Deer Island as they emerge.

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