H2Ohio Technology Assessment Program (TAP)

Final Report

Assessment of Minimizing Nutrient Discharge from Decentralized Communities Technology Submission

Intermittent Baffled Bioreactor (iBBR)

January 2022

TETRA TECH

EXECUTIVE SUMMARY

Frontier Environmental Systems LLC (Frontier) of Rolla, Missouri has submitted a technology proposal for the Intermittent Baffled Bioreactor (iBBR) to Ohio Environmental Protection Agency's (Ohio EPA's) H2Ohio Technology Assessment Program (TAP) for the purpose of addressing the Lake Erie algal blooms and associated nutrient loading. The TAP objectives addressed by iBBR are (1) reduction of nutrient loading to rivers, streams, and lakes and (2) improvement of nutrient removal in wastewater treatment systems.

iBBR is designed to minimize nutrient discharge from decentralized communities. The iBBR technology employs biological processes to remove organic pollutants, particles, and nutrients (total nitrogen [TN], and total phosphorous [TP]). Key features of this technology are that it:

- Is suited to remove nutrients from smaller, decentralized community wastewater flows;
- Removes nutrients at a relatively low cost; and
- Offers high nutrient removal efficiency with low energy use, no external carbon addition, low sludge production, and low maintenance requirements.

Frontier suggests and Tetra Tech concurs that the iBBR technology accomplishes two main objectives: high nutrient removal efficiency and low treatment cost. It removes approximately 90% of TN and 90% of TP from wastewater, at a cost significantly lower than average municipal sewage bills. Past studies of the iBBR technology have indicated that final effluent TN and TP concentrations, less than 5 and 0.5 milligrams per liter (mg/L) respectively, are readily achievable.

iBBR is a modification and improvement to a proven and mature wastewater treatment technology (the baffled bioreactor or BBR). The iBBR technology combines a BBR technology employing a Modified Ludzack Ettinger (MLE) aeration process. The iBBR process applies the aeration intermittently. The intermittent aeration significantly enhances TN and phosphorous (P) removal from the wastewater treatment plant effluent. The enhanced nutrient removal (ENR) available with the iBBR process allows system effluents to meet current regulatory levels for TN and TP; whereas the BBR process alone may not be capable of meeting this goal.

Although it may be operated at lower flows, the relatively low infrastructure cost and maintenance requirements make iBBR well suited for smaller community systems treating flows ranging from 12,000 to 300,000 gallons per day (GPD), or the approximate equivalent of systems serving 40 to 1,000 homes, respectively. Thus the iBBR process may be an effective enhancement to management of wastewater from smaller, decentralized Ohio communities in rural areas of the Lake Erie Watershed, where infrastructure and Operation and Maintenance (O&M) costs associated with developing and operating effective conventional wastewater plants capable of meeting goals for ENR can prove to be prohibitive.

Frontier provided studies and example pilot projects that demonstrated how the iBBR technology has significantly reduced phosphorus TP and TN in multiple applications including small community systems and municipal wastewater treatment plants. In addition, Frontier has fabricated and tested iBBR systems for deployment in forward operations bases (FOBs) for the United States (U.S.) Military.

An iBBR system demonstrated at the Rolla, Missouri Southeast Wastewater Treatment Plant (WWTP), with a capacity of up to 12,000 GPD (equivalent to 40 homes) yielded the following results:

- The effluent ammonia, TN, and TP were generally less than 0.5 milligrams of N per liter (mg-N/L), 5 mg-N/L, and 0.5 milligrams of P per liter (mg-P/L), respectively.
- The removal efficiencies of both TN and TP were approximately 90%.
- Under extremely low temperature of 9.3 C and low C/N ratio of 1.6 conditions, this process still removed 76% of TN and 56% of TP.
- Compared to the conventional MLE process, the implementation of intermittent aeration significantly improved TN and TP removal and also saved aeration energy by 10%.

According to Frontier, existing MLE plants can be easily upgraded to this intermittent aeration mode to achieve enhanced nutrient removal while saving energy. This system treats wastewater from a 15-home subdivision. The total operator time for this system averages between 4-5 hours per month (including sample collection).

For a fixed installation of iBBR, designed and constructed in a manner compatible with the northern Ohio/ Lake Erie watershed climate, operating at 11,000 GPD for 30 years, Frontier estimates at total lifecycle cost of $13,333/year ([$8,333 for capital/depreciation+ $5,000 for operation and maintenance] per year. This equates to $36.53/day or $3.32/1000 gallons treated or $.003 per gallon). This compares favorably against the average cost for sewer rates in the largest U.S. cities in 2018 ($7.73/1000 gallons treated). Much of the cost savings could pass on to the customers. Assuming the influent quality is same as typical medium strength domestic wastewater, which has a TN and TP of 40 mg/L and 7 mg/L, respectively, and the treated effluent has TN and TP concentrations of 5 mg/L and 1 mg/L, respectively, the TN and TP removed per day will be 3.21 pounds (lbs.) and 0.55 lbs., respectively. When extrapolated to 1 lb. of nitrogen and based on the estimated costs for the fixed/ housed system described above, the cost to remove 1 lb. of TN is estimated to be approximately $11.38. This cost would also include the removal of a proportional amount (0.17 lbs.) of TP. Overall the cost per gallon treated compares favorably to other technologies available for nutrient removal in wastewater.

This report evaluates iBBR against a suite of criteria identified by the TAP using information provided by Frontier and obtained elsewhere. Tetra Tech determines that iBBR is very likely to be effective at reducing nutrient loading to Lake Erie, in direct proportion to the number of wastewater treatment systems to which it is applied. Tetra Tech did not identify any negative impacts associated with environmental risks, supply chain limitations, or community perception. A demonstration project targeting adoption of iBBR at locations within the Lake Erie Watershed could provide more detailed data regarding the technology's performance and costs and increase awareness among smaller communities that would potentially comprise the largest and most immediate market for this technology.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACRONYMS/ABBREVIATIONS

Acronyms/Abbreviations	Definition
A/O	Anoxic/Oxic
A2O	Anaerobic-anoxic-oxic
BBR	Baffled bioreactor
BOD-5	Biological oxygen demand-5 Day
CCDC	U.S. Army Combat Capabilities Development Command
COD	Chemical oxygen demand
dBBR	Deployable baffled bioreactor
DoD	United States Department of Defense
DoD	Dissolved Oxygen
DWM	Drainage Water Management
ENR	Enhanced nutrient removal
FOB	Forward Operations Base
Frontier	Frontier Environmental Systems LLC
GPD	gallons per day
GVSC	Ground Vehicle Systems Center
HABs	Harmful algal blooms
HRT	Hydraulic retention time
iBBR	Intermittent baffled bioreactor
iMLE	Intermittent Modified Ludzack-Ettinger
kg	kilogram
kg/day	kilograms per day
kPa	Kilopascal
lb.	pound
lbs.	pounds
lpd	Liters per day
lpm	liters per minute
m^3	cubic meters
m^3/d	cubic meters per day
MBBR	Moving bed biofilm reactor

Acronyms/Abbreviations	Definition
MBR	Membrane bioreactors
MDNR	Missouri Department of Natural Resources
mg/L	Milligrams per liter
MGD	Million gallons per day
mg-N/L	Milligrams of nitrogen per liter
mg-P/L	Milligrams of phosphorus per liter
MLE	Modified Ludzack-Ettinger
MLSS	Mixed liquor suspended solids
N	Nitrogen
NAVSEA	Naval Sea Systems Command
NH3-N	Ammoniacal nitrogen
NH4+-N	Ammonia-nitrogen
NOAA	National Oceanic and Atmospheric Administration
NPS	Non-point source
O&M	Operation and maintenance
O2	Oxygen
Ohio EPA	Ohio Environmental Protection Agency
PAO	Phosphorous accumulating organism
PPE	Personal Protective Equipment
QA/QC	Quality Assurance/Quality Control
QAPP	Quality Assurance Project Plan
RAS	Return activated sludge
RFT	Request for Technology
RL	Readiness Level
RT	Retention time
SLR	Solids loading rate
SOR	Surface overflow rate
SRT	Solids retention time
SS	Suspended solids
SVI	Sludge volume index

Acronyms/Abbreviations	Definition
TAP	Technology Assessment Program
TARDEC	U.S. Army Tank Automotive Research, Development, and Engineering Center
Tetra Tech	Tetra Tech, Inc.
TKN	Total Kjeldahl nitrogen
TN	Total nitrogen
TP	Total phosphorous
TSS	Total suspended solids
U.S.	United States
U.S. EPA	United States Environmental Protection Agency
USD	U.S. Dollars
VFD	Variable frequency drive
WLR	Weir loading rate
WWTP	Wastewater treatment plant

1.0 INTRODUCTION AND BACKGROUND

H2Ohio (http://h2.ohio.gov) is Ohio Governor Mike DeWine's comprehensive, data-driven water quality plan to reduce Harmful Algal Blooms (HABs), improve wastewater infrastructure, and prevent lead contamination. Governor DeWine's H2Ohio plan is an investment in targeted solutions such as :

- Reducing phosphorus runoff through increased implementation of agricultural best management practices and the restoration of wetlands;
- Improving wastewater infrastructure;
- Replacing failing home septic systems; and
- Preventing lead contamination in high-risk daycare centers and schools.

HABs have been a concern in Lake Erie for decades, and the State of Ohio has a long history of developing solutions to address them. In support of these efforts, state agencies are often presented with new approaches for addressing HABs. These approaches often involve technologies and products that are typically innovative, can be proprietary, and span multiple scientific disciplines. To evaluate these proposals for their efficacy and feasibility, the Ohio Environmental Protection Agency (Ohio EPA) worked with the Ohio Lake Erie Commission to create a public advisory council—the Technology Assessment Program (TAP) Team. The H2Ohio TAP Team is comprised of representatives from the private sector, public sector, trade associations, and non-profit companies. The H2Ohio TAP team is conducting an evaluation of technologies designed to treat, control, and reduce HABs in the Lake Erie watershed. H2Ohio initiated the TAP to solicit and evaluate technologies that support one or more of the following five goals:

1. Reduction of nutrient loading to rivers, streams, and lakes;
2. Removal of nutrients from rivers, streams, and lakes;
3. Reduction of the intensity or toxicity of algal blooms;
4. Recovery of nutrients from animal waste; and
5. Improvement of nutrient removal in wastewater treatment systems.

The H2Ohio TAP Team worked to solicit and prioritize technology proposals for further review. A Request for Technologies (RFT) was developed and issued by the Ohio EPA in November 2020 (H2Ohio TAP, 2020). The H2Ohio TAP conducted a thorough evaluation of the 40+ proposals received in response to the RFT and selected 10 technologies for further evaluation. The developers of these 10 technologies were given an opportunity to provide additional information and supporting data to allow an independent evaluation of their technology by a third party, Tetra Tech, Inc. (Tetra Tech).

As a contractor to the Ohio EPA, Tetra Tech conducted an independent third-party evaluation of the 10 technologies selected by the H2Ohio TAP team. The goal of the evaluation was to provide a general assessment of the potential effectiveness, implementability, readiness, and cost of deploying each technology. Select technologies may eventually be demonstrated in the field under future H2Ohio programs.

2.0 PURPOSE

The primary purpose of the technology assessment and evaluations was to conduct a comprehensive scientific evaluation of the selected technologies to determine if and how they could be utilized to address HABs in Lake Erie.

Based on input from Ohio EPA and the H2Ohio TAP team, Tetra Tech established primary (P1 & P2) and secondary (S1 & S2) objectives for the third-party evaluation program. The primary objectives are critical to the technology evaluation and involve conclusions regarding technology performance that are based on quantitative and semi-quantitative data. The primary objectives for the evaluations of the participating technologies are as follows:

- P1: Effectively assess the performance, cost-effectiveness, and reliability data gathered from each vendor with regard to one or more of the 5 H2Ohio goals:
  - Reduce nutrient loading to rivers, streams, and lakes:
  - Remove nutrients from rivers, streams, and lakes:
  - Reduce the intensity or toxicity of algal blooms
  - Recover nutrients from animal waste:
  - Improve nutrient removal in wastewater treatment systems, specifically with small (e.g. lagoon) and decentralized systems
- P2: Ensure that the evaluations are completed by appropriate personnel using a documented, consistent approach and level of detail, to include:
  - Proof of concept review
  - Fatal flaw analysis
  - Review of previous implementation of the technology or similar technologies
  - Review of data quality objectives
  - Review of quality assurance/quality control procedures and reports
  - Evaluation of scalability
  - Information gap evaluation
  - Evaluation of cost; both total and by unit, such as nutrient reduced/removed
  - Feasibility review for a proposed demonstration project
  - Feasibility review for full scale implementation
  - Statement of probability of success

The secondary objectives pertain to Tetra Tech's approach to assessing and presenting the information and thus support the primary objectives.

The secondary objectives for Tetra Tech's evaluation are as follows:

- S1: Prepare Comprehensive Scientific Assessment and Recommendations Reports for each technology that will support potential users' ability to make sound judgements on the applicability of the technology to a specific site and to compare the technology to alternatives.

- S2: Ensure that project deliverables follow consistent format and similar levels of detail. Each report will contain:
  - A summary of the technology and results of past uses of the technology;
  - Results of conceptual model review, fatal flaw analysis, and information gap evaluation;
  - A statement of probability of success and scalability of the project;
  - Verification of cost estimates at various implementation levels;
  - Results of the feasibility review for a potential demonstration project and full-scale implementation of the technology;
  - Verification of claims made by applicants.

The technology evaluation consisted of the (1) collection; (2) evaluation; and (3) summarizing and reporting of data on the performance and cost of each technology. These data provided the basis for meeting the primary objectives.

Most data supporting these evaluations were provided by the technology developers and Tetra Tech attempted to verify it using independent sources, when available. Tetra Tech focused its verification efforts on key aspects of the technology (e.g., effectiveness, cost) as well as any claims that seemed questionable. Otherwise, Tetra Tech assumed information provided by the vendor to be accurate. Instances where Tetra Tech is unsure of a claim being made by the vendor are noted in the report. In some cases, information was also obtained from the peer-reviewed scientific literature. Tetra Tech worked with each developer to obtain the data necessary to meet the primary and secondary evaluation objectives.

Tetra Tech then completed an independent evaluation of the data provided by each developer and prepared separate reports for each technology evaluation, following a consistent report format. This report provides a summary of our review of iBBR.

3.0 TECHNOLOGY OVERVIEW

Frontier Environmental Systems LLC (Frontier) of Rolla, Missouri has submitted a technology proposal for the Intermittent Baffled Bioreactor (iBBR). Frontier's iBBR technology is designed to remove total nitrogen (TN) and total phosphorus (TP) nutrients from wastewater systems serving decentralized communities at a relatively low cost. It features low energy use, no external carbon addition, low sludge production, very low maintenance, and high nutrient removal efficiency. It employs biological processes to remove organic pollutants, particles, TN, and TP. The technology may be deployed in new construction, as a mobile unit, or retrofitted to an existing wastewater treatment plant (WWTP) system to enhance nutrient removal.

Baffled bioreactors (BBR) are an established technology designed to achieve denitrification of wastewater by maintaining a highly active microorganism culture based on hydraulic principles. The BBR employs a standard Ludzack-Ettinger (MLE) process for advanced wastewater treatment, for complete nitrification and partial denitrification.

Studies have shown that an intermittent Modified Ludzack-Ettinger (iMLE) process can achieve better denitrification than the MLE process, to achieve enhanced nutrient removal (ENR). iBBR combines the BBR technology and iMLE process and enhances the BBR process by applying intermittent aeration . It is an advancement from the existing BBR technology. iBBR is designed for small flow wastewater treatment to meet present standards. The upgrade enables it to achieve ENR.

The iBBR integrates two components: (a) the BBR structure and the (b) iMLE process. The iMLE process alone has been proved in 13 million gallons per day (MGD) capacity (two parallel 6.5 MGD trains), using an existing pre-anoxic plant structure. However, the BBR has an upper capacity limit of 300,000 GPD, due to the need of a large internal settler. For this reason, the combined iBBR process is suited for systems in operating at 300,000 GPD or less. At flows greater than 300,000 GPD, the regular pre-anoxic process, integrated with intermittent aeration (e.g., iMLE process), is more appropriate. Based on these considerations and the need to make enhanced nutrient removal technically and economically feasible for small community systems, iBBR is a technology ideally suited to smaller, decentralized sewer systems treating approximately 12,000-300,000 GPD, the equivalent of approximately 40 – 1,000 homes.

The iBBR technology accomplishes two objectives: high nutrient removal efficiency and low treatment cost. Data provided by Frontier indicates that it can remove approximately 90% of TN and 90% of TP from wastewater at a relatively low cost. The final effluent TN and TP concentrations are typically less than 5 and 0.5 milligrams per liter (mg/L), respectively. (Frontier, 2021a & 2021b.)

4.0 TECHNOLOGY EVALUATION

This section of the report addresses each of the criteria identified by Ohio EPA to be included in the independent evaluation process.

4.1 CONCEPTUAL MODEL REVIEW

iBBR is a treatment method for wastewater/ sanitary sewage . iBBR is an upgraded version of BBR designed with the intent of improving nutrient removal performance and offering a more cost effective treatment option for small, decentralized communities than a conventional WWTP. Conceptually, the BBR technology allows the cost-effective adaptation of activated sludge processes to the scale of a small-flow system; the iBBR innovation offers the added benefit of enhanced nutrient removal, supporting the goal of limiting TN and TP discharge to the effluent-receiving water bodies in the Lake Erie watershed. The technology was initially developed for FOB applications.

Biological methods typically used for municipal wastewater treatment due to their low costs compared to physical and chemical methods. Biological processes include activated sludge processes, fixed film processes, and membrane bioreactors (MBRs). Conventional activated sludge processes employ sludge return (“return activated sludge” or “RAS”) from the final clarifier. Fixed film processes use media to which microorganisms attach. MBRs employ membrane filtration. The principal difference among these biological processes is how to maintain microorganisms for contaminant degradation. Each of these common methods has limitations with regard to application to smaller systems and/ or the goal of ENR.

Activated sludge processes are most widely used in centralized treatment plants serving larger communities because they are less expensive to build and produce very good effluent with reasonable maintenance requirements. However, because they rely on sludge return from the secondary clarifier to maintain microorganisms in the aeration tank, the maintenance needs are significant and render these processes uneconomical for small systems when viewed on a cost per GPD capacity.

Fixed film processes (Ex: recirculating sand filters, moving bed biofilm reactor (MBBR), etc.) do not need sludge return and therefore, are very simple to operate. They are widely used for small flow wastewater treatment. However, their effluents typically contain high Total Suspended Solids (TSS) concentration and they are not effective for ENR.

Recently developed MBRs provide the best effluent quality in terms of 5-day biological oxygen demand (BOD-5) and TSS removal due to the physical filtration process. Nevertheless, the equipment, controls, maintenance and energy needs are significant and expensive to operate. These disadvantages made it very difficult to adopt by small communities.

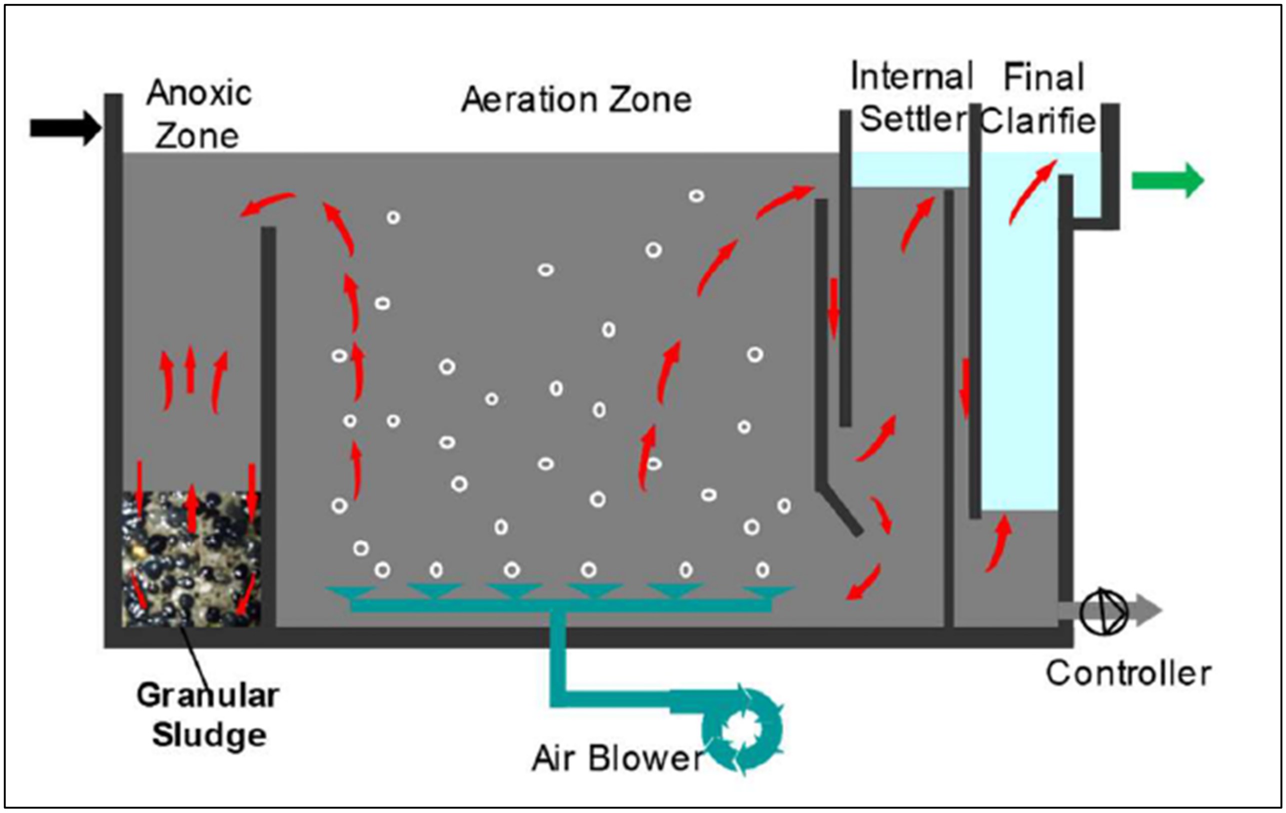
Overall, the activated sludge process is typically the most cost-effective method for municipal wastewater treatment; however, the controlled sludge return requires significant operating costs and makes its use in systems serving small, decentralized communities – such as subdivisions in rural areas – not cost effective. The BBR innovation eliminates the controlled sludge return requirement. It is essentially a pre-anoxic process without controlled RAS operation because it returns settled sludge from an internal settler to the aeration zone by itself, through naturally occurring flow streams between baffles during aeration. Because of this innovation, the activated sludge process can be applied in the form of a BBR, greatly reducing the operation and maintenance costs and rendering this option cost-effective for small-flow wastewater treatment. The key advantage of the BBR is the ease of operation, so that it can be operated without continual operator attention. The BBR employs a pre-anoxic MLE process for advanced wastewater treatment.

Three basic types of activated sludge processes are widely used: pre-anoxic , post-anoxic, and anaerobic-anoxic-oxic (A2O) . The pre-anoxic process (where the mature BBR is based) has fast denitrification rates in the pre-anoxic zone, recovers oxygen from nitrate, and produces alkalinity for nitrification, but it can only provide partial denitrification and minimal phosphorus removal. The post-anoxic process can achieve very low effluent nitrate, but the process is extremely slow and often needs external carbon source for denitrification. The A2O process adds phosphorus removal capability to the pre-anoxic process, but still achieves only partial TN removal.

Figure 1 illustrates the BBR working principle. It uses baffles to create unique flow patterns within the treatment tank, and air to drive all process functions. It has a pre-anoxic zone to perform denitrification, an aerobic zone to perform organic matter degradation and ammonia oxidation, an internal settler to concentrate and return highly active microorganisms to the aeration zone without using pumps, and a final clarifier to remove aged sludge that is no longer active. It has only four mechanical moving parts: one influent pump, two alternatively operated air blowers, and one solenoid valve. Because the BBR does not have any media inside the tank, and uses only air to drive all process functions through maintenance-free surge lifting devices (patent pending) rather than motor-driven pumps and impellers, it is extremely simple to operate and maintain. The unique process configuration also allows highly active granular sludge to form to facilitate process performance.

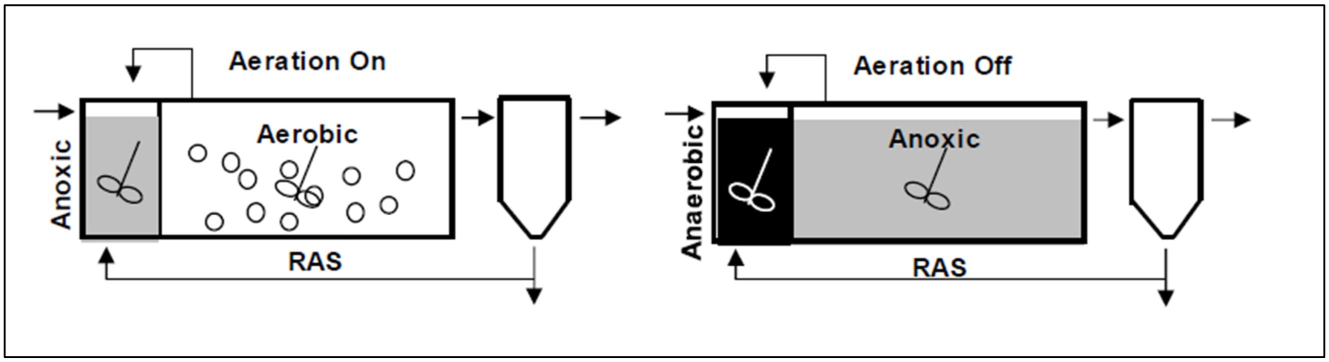
Ease of operation was the major consideration in the development of BBR. Simplicity of operation results in minimal operational cost as well, which is the major consideration for small community applications. The BBR removes BOD-5, TSS, and ammonia, making the effluent significantly better than present permit requirements where ENR is not required. However, it only partially removes TN and TP, not meeting ENR requirements.

Figure 1 - Schematic of the Baffled Bioreactor



The iBBR innovation applies intermittent aeration to BBR and thus retains all advantages of the BBR (very low maintenance needs and low sludge production), the pre-anoxic process (fast denitrification in the pre-anoxic zone, oxygen recovery from nitrate, and alkalinity production for nitrification), the post-anoxic process (low effluent nitrate), and the A2O process (biological phosphorus removal). Figure 2 illustrates the process principle behind the iBBR. It is an intermittently aerated pre-anoxic process. When the aeration is on, the process works as a conventional pre-anoxic process – the ammonia is oxidized to nitrate in the aerobic zone and the nitrate is reduced to nitrogen gas in the pre-anoxic zone. However, when the aeration is off, the previous aerobic zone turns to anoxic to denitrify the residual nitrate. The resulting reduced nitrate and dissolved oxygen in the return mixed liquor causes the previously pre-anoxic zone to become anaerobic, and these anaerobic conditions cultivate phosphorus-accumulating organisms (PAOs) that accomplish biological phosphorus removal. Therefore, the iBBR keeps all advantages of the BBR (simple operation and RAS low sludge production) but with the additional benefit of extensive removal of TN and TP. Use of intermittent aeration (rather than continual) reduces energy use by approximately 10% . (Liu and Wang 2017).

Figure 2 - iBBR Process Principle (Modified iMLE Process)



The BBR has been field-demonstrated in various military bases at different times, including Fort Leonard Wood Missouri, Fort Bliss, Texas, Naval Sea Systems Command (NAVSEA), Maryland, and The U.S. Army Combat Capabilities Development Command (CCDC) Ground Vehicle Systems Center (GVSC), Michigan (Tucker et al., 2016, 2018). It has also been installed in a 15-home Southwood II Subdivision in Rolla, Missouri since 2017 (Campbell et al., 2021). The total time the operator spent for the field BBR is between 4 to 5 hours per month, and most of this time was used for sample collection and analysis per compliance requirements. The operation and maintenance time for BBR itself was nearly negligible.

The iBBR process principle shown in Figure 2 can also be applied to large, centralized wastewater treatment plants to improve nutrient removal and simultaneously reduce chemical and electricity costs. iBBR may also be applied as a pilot-scale system to upgrade centralized wastewater treatment plants in the Lake Erie region. Frontier is currently demonstrating iMLE process in a 13 MGD full-scale wastewater treatment plant to enhance nutrient removal performance without external carbon addition and with 30% aeration energy reduction. Similarly, this iBBR technology may be downsized for individual or clustered home applications at an affordable cost to replace traditional septic tanks. This will be useful in regions where wastewater collection is difficult due to terrain or infrastructure availability. However, as iBBR integrates the BBR structure with the iMLE process, application of the iBBR technology is limited by the upper end capacity limit of 300,000 GPD for the BBR due to the need of a large internal settler. For this reason, iBBR is a technology ideally suited to smaller, decentralized sewer systems treating approximately 12,000-300,000 GPD, the equivalent of approximately 40 – 1,000 homes. (Frontier, 2021a & 2021b.)

4.2 FATAL FLAW ANALYSIS

A formal fatal flaw analysis was not submitted by Frontier as part of their response to this evaluation, so a limited fatal flaw screening was completed based upon review of the information submitted and presented in this report. No obvious fatal flaws were identified with regard to the iBBR, as it is essentially a modification to an existing technology.

The iBBR technology has two main requirements for successful implementation and performance. The construction must be appropriate to address local climatic conditions (extremely cold climates require more involved design and construction considerations) and system flows must remain within design parameters to ensure consistent performance and cost effectiveness. No pre-existing infrastructure is required for construction of new systems and existing wastewater treatment plants can be retrofitted with this technology. The equipment and the supplies are items that are commonly available. Studies to date have focused on application of this technology to wastewater flows in the range of 12,000 to 300,000 GPD (the equivalent of approximately 40 to 1,000 homes).

While mobile / "deployable" iBBR units are ideally suited for less severe cold temperatures, the technology can be successfully implemented in colder climates as experienced northern Ohio, given that appropriate design and construction considerations are incorporated. (Frontier, 2021a & 2021b.)

4.2.1 Barriers to Adoption

There is limited published information that focuses on barriers to use of iBBR and no known U.S.-specific surveys of producers' intentions regarding the adoption of iBBR.

One concern regarding widespread adoption may be the emphasis on controlling non-point sources (NPS) (agricultural runoff) rather than traditional point-source discharges such as WWTPs. Point-source discharges as sources of nutrients in the Lake Erie watershed have decreased significantly from historical levels and comprise a much smaller portion of the total nutrient load to Lake Erie. While agricultural/ non-point sources have become the primary focus of efforts to reduce nutrient loading, WWTP's nonetheless remain consistent and ongoing contributors of TP and TN to the watershed.

iBBR can overcome the limited ability of BBR alone to consistently meet low discharge standards for nutrients as either a stand-alone system for small communities or an improvement to larger systems. iBBR also offers the low-maintenance benefits of BBR combined with enhanced nutrient removal. Based on these considerations, perception of iBBR among regulating agencies is anticipated to be positive as the technology offers improved nutrient removal to meet current and future discharge standards and can contribute to Ohio EPA's mission of reducing the potential for formation of HABs.

Construction and startup of new systems is not anticipated to present a significant barrier as the technology is constructed with standard "off the shelf" components and is currently in a state of readiness to deploy.

Perception among potential users is anticipated to be positive as iBBR offers effective reduction in nutrients at a lower cost than some technologies and is built upon a proven, existing technology. General public perception is also anticipated to be positive as the technology is consistent with the goals of improvement in the environmental health of receiving water bodies that serve as sources of drinking water and recreational opportunities, and thus may offer an indirect economic benefit as well.

Given the anticipated positive perception of the technology, Frontier identified the general challenge of marketing the technology and matching it to the appropriate users as the greatest barrier to widespread adoption at this time. Identifying and matching community systems of appropriate scale and need, yet having sufficient financial resources for implementation will be critical. Potential users ideally suited for this technology include some if not all of the following criteria:

- New or existing systems serving *non-centralized communities in the size range of 40 to 1,000 households (12,000 to 300,000 GPD)*;
- Regulated municipal, institutional or private entities having *legal/ statutory responsibility for management of wastewater and compliance with discharge limits*
- Communities (or developers) facing the need to include wastewater collection and treatment to support *new development or enhance the performance of existing systems* to meet current and future regulatory limits; and,
- Entities having *access to sufficient capital resources* (tax base, bond funding, service fees, grants and other resources) to invest in new or improved wastewater treatment infrastructure.

Based on these considerations, the greatest challenge to adoption of iBBR will likely be making potential users who are in need, best suited and financially well-positioned for installation of new or improved wastewater systems, aware of the potential benefits and relatively low operating cost of the iBBR technology and matching them to Frontier.

4.3 REVIEW OF PREVIOUS IMPLEMENTATION OF IBBR

iBBR is currently available for implementation via Frontier. Frontier provided summaries of previous deployments of iBBR, BBR and iMLE, operated at varying scales. Information regarding other evaluations of BBR was obtained via published sources. Tetra Tech believes these studies demonstrate the feasibility and viability of this technology for use in Ohio to help reduce TP and TN in effluent from WWTPs and prevent them from entering the Lake Erie watershed. Full copies of these reports can be provided by Frontier and are only summarized for the purposes of the evaluation. The following sections summarize the results of four past evaluations of the BBR, iBBR and iMLE technologies.

4.3.1 Southwood II BBR

Most rural communities in the United States are facing increasingly rigorous effluent discharge limits, especially for ammonia, for their wastewater treatment facilities. A new baffled bioreactor (BBR) technology, which employs a pre-anoxic activated sludge process operated with a long solids retention time (SRT), was installed in a small community in Missouri to address the more stringent effluent limits. Frontier installed the BBR system at the Southwood II Subdivision in Rolla, Missouri in 2017. (Information in this section was obtained primarily from (Campbell et al., 2020)).

The Southwood II Subdivision has 15 homes. Previously this community used a recirculating sand filter to treat its wastewater. Due to a new requirement for ammonia reduction, the recirculating sand filter no longer met this new requirement, and had to be replaced with a different technology for advanced ammonia removal.

Several possible improvement alternatives for this facility included regionalization, land application, and the upgrade of the original facility with new technology capable of meeting the more stringent limits. The goals for assessing improvement alternatives were to minimize life cycle costs, maintain ease of operation, and meet existing and anticipated future effluent limits with minimal process modifications. Due to prohibitive capital and O&M costs associated with connection to the regional WWTP, regionalization was ruled out as an option. Local soil and climate conditions, and the cost of land acquisition to support a spray field, were unfavorable to adopting the land application option as well. Given the cost constraints and other considerations, evaluation of new treatment technology was selected as the preferred path forward.

Based on an assessment of the probable project costs, it was determined that the implementation of the Frontier dBBR process at the original WWTP site would be the most cost-effective option for the community. Furthermore, this alternative had an added benefit of removing some nutrients, better positioning the community to meet potential future nutrient limitations on the effluent.

A deployable baffled bioreactor (dBBR) unit that was originally developed for FOB applications was refurbished and used for this project. This technology is an activated sludge process operated at a long SRT, but featured significantly reduced O&M requirements compared with conventional activated sludge processes. The process was configured with a staged metabolic selector, aerobic zone, proprietary internal settler, post-aeration zone, and a polishing clarifier. Given the similarities of the United States Department of Defense (DoD) application to the Southwood II community application in terms of treatment quality and O&M preferences, it was determined that the dBBR technology might provide a viable solution for Southwood II community.

The total wastewater flow of the Southwood II community is approximately 4,000 – 5,000 GPD. The BBR was built using a 20-foot shipping container (Figure 3). The capacity of the BBR was approximately double the anticipated wastewater flow.

Figure 3 - Deployable BBR Used for Southwood II Evaluation (Frontier 2021)

Modifications and improvements to the site were made to afford the implementation of the dBBR process. The original recirculation tanks were repurposed as inline equalization/sludge storage tanks. The equalization tank was also sized to accommodate sludge storage. Sludge production in the dBBR process was estimated to be 408 kg annually. In order to minimize BOD oxidation in the storage tank and dissolved oxygen carryover to the metabolic selector chambers, no aeration or mixing capability for the equalization/storage tanks was installed. A sludge depth probe was installed in the equalization/storage tank to provide the operator feedback regarding an excessive sludge blanket depth.

Influent wastewater was pumped from equalization/storage tanks to the pre-anoxic zone of the dBBR unit. The influent pump for the dBBR is a submersible pump controlled by a variable frequency drive (VFD). A standby constant speed submersible pump is used for emergency situations. The influent pumps are located at the downstream end of the equalization/ storage tank, within a screened wet well vault designed to keep sludge and other particulate matter from entering and binding the pumps. The pumps have capacity to handle the anticipated peak flow received at the facility.

During the normal operation period, wastewater enters the pre-anoxic zone and blends with the nitrate-rich mixed liquor from the aerobic zone. The pre-anoxic zone hydraulic retention time is approximately 1.9 hours. The organic material within the influent is rapidly utilized for denitrification. When there is no wastewater flow entering the process, the pre-anoxic zone hydraulic retention time (HRT) is 5.6 hours and the aeration system transitions to maintenance modes. Discharge from the pre-anoxic zone enters into the aerobic zone for polishing of BOD and nitrification. Air is introduced into the aerobic zone via fine bubble membrane diffusers. When the influent pump is operating, air is delivered to the aerobic zone via a regenerative blower capable of providing 2,124 liters per minute (lpm) of air at a pressure of 27.6 kilopascal (kPa). When the influent pump is not in operation, the dBBR automatically switches to a maintenance mode and air is delivered to the aerobic zone via a small positive-displacement-style diaphragm blower. The maintenance mode operation is designed to maintain the activated sludge activity and mixing when there is no influent to the dBBR, reducing unnecessary aeration and energy wasting.

Flow passes from the aeration zone to the internal settler that comprises a proprietary stilling baffle. The baffle creates a quiescent zone immediately after the aerobic zone, allowing flocculated mixed liquor to settle back into the aeration zone. The internal settler was designed to accommodate conservative surface overflow rate (SOR), solids loading rate (SLR), and weir loading rate (WLR) to promote settling of fine discrete particles and bulking sludge typically associated with long SRT processes.

Overflow from the internal settler passes into a post-aeration chamber to allow re-aeration prior to entering a final polishing clarifier. Post-aeration was performed via diffused aeration. The sludge settled in the final polishing clarifier is discharged via an airlift pump to the equalization/storage tank. Overflow from the polishing clarifier passes a SANITRON UV disinfection unit and discharges to the receiving stream.

The rated treatment capacity of the dBBR is 50,000– 55,000 liters per day (lpd). For this application, the estimated operational flow rate was 21,560 lpd (about 5,700 GPD). At this flow rate, the aggregate HRT, incorporating both anoxic and aerobic zones, is 25.8 hours. The resulting operational SRT is 76 days with a design mixed liquor suspended solids (MLSS) of 5,000 mg/L. These parameters are representative of long SRT process. Design sludge production calculated based on traditional activated sludge modeling (e.g., ASM1) is 1.2 kg/day. Air delivery capacity is capable of meeting MDNR requirements for extended aeration processes, resulting in an applied oxygen delivery of 1.8 kilograms (kg) of oxygen (O2) per kg of BOD and 4.5 kg O2 per kg of Total Kjeldahl nitrogen (TKN). BOD and TKN loadings utilized for the design were representative of maximum day loadings projected for the facility over the planning period. The final oxygen requirements were reduced based on the anticipated oxygen recovery associated with denitrification in the pre-anoxic zones. Table 3 provides a summary of key design parameters associated with the dBBR at the Southwood II WWTP.

Table 1 - Summary Of Design Criteria for the DBBR Unit At The Southwood II WWTP Site

Effluent Parameter	Value
Design average daily flow	21,558 lpd (5,700 GPD)
Design peak hour flow	78.6 lpm
BOD loading	4.1 kg/day
TSS loading	2.1 kg/day
TKN-N loading	0.9 kg/day

The Missouri Department of Natural Resources (MDNR) classifies the dBBR as a new and innovative technology, which requires a two-year demonstration period before final adoption. As a consequence, an elevated testing regimen was implemented. For example, testing of the influent and effluent quality parameters such as BOD-5, TSS, and Ammoniacal nitrogen (NH3-N) was performed twice a month. BOD-5 was measured in conformance with Standard Method 5210 B. TSS was determined in conformance with Standard Method 2540 D. Ammonia-nitrogen was tested utilizing an United States Environmental Protection Agency (U.S.EPA) Method 530.3.

Other supplemental testing was performed periodically. The MLSS was determined utilizing gravimetric methods referenced above. The settleability was measured and sludge volume index was calculated based on Standard Method 2540 F.

Data collected to date indicates that the BBR technology produces an effluent with quality that meets permitting requirements. For example, in 2018 the average values of effluent BOD-5, TSS, and NH3-N were 3.2, 2.2, and 0.5 mg/L, respectively. In comparison, the permit requirements for both BOD-5 and TSS are 45/30 (weekly avg./monthly avg.). For NH3-N, it is 3.6/1.4 (daily max./monthly avg.) for warm months and 7.5/2.9 for cold months. Currently there are no TN and TP removal requirements for this community. In a recent full-year normal operation cycle (2018), the average effluent concentrations of BOD-5, TSS, and ammonia-nitrogen were 3.2, 2.2, and 0.5 mg/L, respectively, with removal efficiencies of 96%, 85%, and 98%, respectively. All these parameters were significantly better than their respective permit limits. The long SRT afforded an enhanced factor of safety for the process, conferring the ability to nitrify at sustained ambient temperatures as low as −22°C. Long SRT also resulted in significant reductions in waste sludge production, resulting in dramatically reduced operational costs for sludge handling. Ultimately, the long SRT activated sludge process afforded the ability to meet stringent effluent quality standards including ammonia and the numerous unique challenges that are inherent to small flows. Additional key observations of the evaluation included:

- Small community hydraulic and mass loadings are highly variable and difficult to quantify during facility design.
- A long SRT activated sludge process results in superior performance and enhanced factor of safety.
- The long SRT process with pre-anoxic zones generated no excess sludge during the extended operation period, significantly simplifying plant operation.
- A long SRT process is well suited to accommodate wastewater variability associated with small communities while maintaining superior treatment quality.

4.3.2 Rolla WWTP iBBR

The iBBR (BBR + iMLE) technology was tested in a wastewater treatment plant in Rolla, Missouri at a pilot-scale (in reference to a centralized treatment plant), which is equivalent to the full-scale system of a 40-home community. A peer-reviewed journal paper from the data of this testing was published in Journal of Cleaner Production. Most information in this section was obtained from this publication (Liu and Wang, 2017).

While the present version of the BBR (as previously tested in the nearby Southwood BBR evaluation) is designed to meet present permit requirements, the proposed iBBR is designed to meet future permit requirements when ENR is required. It retains all benefits of the BBR, plus additional TN and TP removal and energy saving.

The study was carried out with a continuous-flow intermittent aeration anoxic/oxic (A/O) bioreactor for small-flowrate decentralized wastewater treatment. In the conventional pre-anoxic MLE process, the nitrified mixed liquor cannot be completely returned to the pre-anoxic zone for denitrification. In this study, Frontier applied intermittent aeration to the MLE process to enhance denitrification and total phosphorus (TP) removal.

The Rolla Southeast Wastewater treatment plant was fed with the raw wastewater that has a normal BOD-5-to-TN ratio of 4.6 (phase II data), the average values of effluent chemical oxygen demand (COD), TSS, NH3-N, TN, and TP were, respectively, 20, 4.7, 0.3, 3.2, and 0.5 mg/l (Liu and Wang, 2017a). Importantly, the average removal efficiencies for both TN and TP were approximately 90%. It was also demonstrated in China to treat an influent that has a very low BOD-5-to-TN ratio (approximately 2.5), resulting in effluent TN and TP of approximately 10 and 1 mg/l, respectively (Qang et al., 2018). Note that the influent BOD-5-to-TN ratio is critical for the removal of both TN and TP, and a higher value results in better TN and TP removal. Municipal wastewater in the U.S. typically has a BOD-5-to-TN ratio of greater than 4, which will result in effluent TN and TP concentrations of less than 5 and 0.5 mg/l, respectively.

The pilot-scale unit was installed at the Southeast Wastewater Treatment Plant in Rolla, Missouri, and fed with raw wastewater after the screening. A pilot-scale iMLE process was constructed using a standard 20- ft shipping container (Figure 3 shows a typical unit constructed in a shipping container). The effective volumes of the mixing zone and the intermittent aeration zone were 6.3 and 14.3 cubic meters (m^3), respectively, and the post-aeration zone was 1.25 m^3. The aeration on/off operation in the intermittent aeration zone was controlled by a timer. Table 2 below presents conditions for different phases.

Table 2 - Operating Conditions for Phases I-VI. iBBR Rolla MO

Experimental setup (note: the hydraulic retention time (HRT) for the treatment zones, including the mixing zone, intermittent aeration zone, and post-aeration zone).

Phase	Duration (day)	Mode	Aeration: Mixing (min)	Flow (m^3/d)	T (℃)	HRT (h)	SRT (d)	Wastewater
I	1–36	iMLE	51:45	57	23.6	9.2		Natural start-up with regular wastewater
II	37–98	iMLE	51:55	57	24.1	9.2	~10	Feeding with regular wastewater with C/N = 4.6
III	99–132	MLE	100% aeration	57	20.2	9.2	~10	
IV	133–152	iMLE	51:45	57-48-37	14	9.2–14.2	~18	Feeding with limited C/N = 2.4 wastewater
V	153–186	MLE	100% aeration	30	9.9	17.5	~35	Feeding with very low C/N = 1.6 wastewater
VI	187–223	iMLE	60:60	30	9.3	17.5	~45	

In Phase I, the process was started up naturally with raw wastewater, without adding any seeding sludge. It was operated using the intermittent aeration mode (iMLE mode). After approximately 5 weeks (Fig. 3(b)), complete nitrification was achieved (effluent ammonia <1 mg-N/L). Then, the performance of the iMLE process was evaluated using regular wastewater for 2 months (Phase II). In Phase III, the process was operated using the continuous aeration mode (MLE mode) for approximately one month, to compare the nutrient removal performance and energy consumption between the iMLE and MLE operations. During the MLE mode operation, the internal mixed liquor return rate was not changed. In Phase IV, the TN removal performance of the iMLE process was tested at a reduced C/N ratio to evaluate the process performance under carbon limited conditions. Tap water and ammonium bicarbonate were added to the influent, to decrease the BOD concentration while maintaining a similar TN concentration as before.

Because the temperature dropped significantly during Phase IV testing, the sludge wasting rate was reduced to increase the SRT to compensate for the low temperature effect. In Phases V and VI, the temperature of the reactor dropped to less than 10°C. The C/N ratio was further reduced to 1.6, to test the reactor performance under extremely unfavorable conditions (both temperature and C/N ratio). Because the raw wastewater was very much diluted during these phases, only ammonium bicarbonate was added to the raw wastewater to decrease the C/N ratio. To quickly accumulate nitrifiers in the low temperature, the process was operated using the MLE mode first (Phase V). During Phase V, the added ammonia concentration was about 7 mg/L at the beginning, and finally reached 24 mg/L at the 170th day. When complete nitrification was achieved (effluent ammonia <1 mg-N/L), the operation changed into iMLE mode, marked as Phase VI. In Phases V and VI, the reactor temperature decreased to less than 10°C and the SRT was increased to 35-45 days to compensate for the low temperature impact. To maintain a long SRT of 35-45 days, the inflow rate was reduced to decrease the hydraulic loading and increase the MLSS concentration in the reactor.

During all phases, the internal mixed liquor return ratio (mixed liquor return/inflow) was maintained at approximately 2, that is, the mixed liquor return flow was approximately 200% of the inflow rate. Different SRTs were maintained to compensate for varying reactor temperatures. The Dissolved Oxygen (DO) concentration in the intermittent aeration zone was controlled in the range of 0.2-3.0 mg/L during the aeration-on period using a DO controller.

During the aeration-off period, a mixing device was turned on to provide necessary mixing within the intermittent aeration zone. The aeration time vs. the mixing time was 51 min vs. 45 min during the tests in Phases II and IV. In Phase VI, the aeration time vs. the mixing time was 60 min vs. 60 min. During the performance test, the MLSS concentration and the sludge settling characteristics, as indicated by sludge volume index (SVI), were monitored. Composite influent and effluent samples were collected for water quality analysis. The concentrations of COD, suspended solids (SS), TN, and TP in the influent and effluent, and the effluent concentrations of ammonia and nitrate, were measured three times a week. The effluent nitrite was monitored during Phases IV and VI with external ammonium addition.

During a nearly one-year operation monitoring and optimization period, different operation parameters including aeration time fraction, mixed liquor recycle ratio and HRT were examined for the removal efficiencies of COD, N and P. Results indicate that the bioreactor could maintain a high concentration of mixed liquor SS, thus achieving a high COD removal. Nitrogen removal could be enhanced in the following ways: decreasing the aeration time fraction (i.e., increasing the non-aeration time) at a fixed influent flowrate; decreasing the mixed liquor recycle ratio at a fixed aeration intensity; or increasing both the aeration time fraction and cycle time for an increased influent flowrate. When the bioreactor reached steady-state conditions (wastewater temperature 17.4~28.6˚C, aeration time fraction 0.5, mean DO concentration in the aeration stage about 1.0 mg· L-1, HRT 16.6 h, and mixed liquor recycle ratio 1.5), the removal efficiencies of COD, ammonia-nitrogen (NH4+-N), TN and TP could reach > 90%, > 90%, 70%~80% and > 80%, respectively. The effluent COD, NH4+-N and TN concentrations could meet Level 1A standard while the effluent TP concentration could meet Level 1B standard, according to the Discharge Standard of Pollutants for Municipal WWTP (GB18918-2002). The performance of the iBBR system with regard to nitrogen and phosphorous removal is summarized in Table 3.

Table 3 - Summary of Treatment Performance for Phases I-VI. iBBR, Rolla MO

Summary of the treatment performance at steady condition in different phases.

Phase	COD (mg/L)			TN (mg-N/L)			Ef-NH_3 (mg-N/L)	Ef-NO_3^- (mg-N/L)	TP (mg-P/L)		
	In.	Ef.	% Rem.	In.	Ef.	% Rem.			In.	Ef.	% Rem.
II	458 ± 140	20 ± 10	96	28.0 ± 7.3	3.2 ± 0.6	89	0.3 ± 0.2	1.2 ± 0.5	4.3 ± 0.8	0.5 ± 0.2	90
III	451 ± 108	13 ± 5	97	27.0 ± 6.2	6.4 ± 1.5	76	0.1 ± 0.2	5.2 ± 1.5	4.2 ± 1.2	0.4 ± 0.3	91
IV	369 ± 107	11 ± 5	97	44.7 ± 9.8	4.8 ± 1.8	89	0.3 ± 0.1	2.7 ± 1.1	4.5 ± 1.2	0.3 ± 0.1	93
V	349 ± 140	18 ± 10	95	48.6 ± 7.1	22.6 ± 5.0	54	2.8 ± 3.7	16.7 ± 3.4	3.1 ± 0.9	1.4 ± 0.7	56
VI	279 ± 130	16 ± 7	94	47.9 ± 7.3	11.5 ± 1.9	76	0.3 ± 0.3	9.3 ± 1.7	2.7 ± 0.8	1.2 ± 0.4	56

The study indicated that, when treating municipal wastewater with a carbon (represented by BOD-5) to TN ratio (e.g. C/N ratio) of 2.4 or greater:

- The effluent ammonia, TN, and TP were generally less than 0.5 mg-N/L, 5 mg-N/L, and 0.5 mg-P/L, respectively
- The removal efficiencies of both TN and TP were approximately 90%.
- Under extremely low temperature of 9.3℃ and low C/N ratio of 1.6 conditions, this process still removed 76% of TN and 56% of TP.
- Compared to the conventional MLE process, the implementation of intermittent aeration significantly improved TN and TP removal and also saved aeration energy by 10%.

According to Frontier, existing MLE plants can be easily upgraded to this intermittent aeration mode to achieve enhanced nutrient removal while saving energy.

4.3.3 Fort Leonard Wood “Deployable Baffled Bioreactor (dBBR)” Demonstration

Additional evaluations completed by Frontier that have potential relevance to the use of iBBR technology in Ohio involved the additional potential benefits of ”deployable” systems to support nonconventional or seasonal wastewater management needs, and the potential for reuse of treated water for non-potable purposes at these sites. Although these tests were conducted for the U.S. Military with the main objective of support to FOB areas, such temporary or seasonal sites could conceptually include non-military deployments in support of disaster management and relief, or seasonal support to campgrounds, state parks, marinas or other recreational facilities that experience high usage for only a portion of the year.

The Frontier dBBR has been successfully tested by the DoD at Fort Leonard Wood, Missouri; Naval Surface Warfare Center-Carderock, Maryland; and Fort Bliss, Texas, for use in FOBs located in combat zones. The dBBR has further been recommended for use in water harvesting applications for non-potable water productions, with an eye toward minimizing the DoD water demand in combat zones (Tucker et al., 2016; Frontier, 2021a & 2021b). In all applications, the dBBR has exceeded the design criteria established by the DoD and has routinely demonstrated a capability to minimize sludge production (Tucker et al,. 2016).

The Tricon dBBR system was developed by Frontier in response to a call for proposals from the U.S. Army Tank Automotive Research, Development, and Engineering Center (TARDEC), Warren, Michigan. The system takes its name from the Tricon shipping container that holds the water being treated. The intent was to develop a deployable wastewater treatment system that would treat 2,500 to 3,000 gallons per day of combined gray water, such as shower water, and black water, such as kitchen and toilet discharge, so that it could be safely discharged into the environment. With the reduction of N, P and other parameters, the dBBR evaluation suggests that treated effluent water could potentially be reused for non-potable purposes (flushing toilets, watering vegetation, etc.).

One of the field trials took place at Fort Leonard Wood, Missouri in 2015, using raw sewage from the installation wastewater treatment plant. The system exceeded the performance requirements set for the operational experiment. The very low effluent levels of BOD, SS, N and P attained by the system indicated that sustainable water recycling and reuse possibilities are within reach for future base camps. The performance of the system indicated that the technology was robust enough to be employed with elements of almost any size in austere conditions.

Figure 4 - Deployable BBR Developed for Military Operations (Frontier 2021a)

Frontier set up the dBBR system with a maximum influent rate of 3,000 gallons per day at the Fort Leonard Wood wastewater treatment plant. A program of extensive monitoring and testing began within days. The Army established several parameters that would demonstrate the effectiveness of a wastewater treatment system:

- ***Reduced amount of solids***. The first parameter considered for the dBBR system was the ability to reduce the amount of solids. It was determined that sludge wasting could not exceed 10 percent. This standard was established to reduce the amount of solids that would ultimately require disposal. During the entire operational testing of the dBBR, sludge wasting did not exceed 6% at any given time.

- ***Reduced use of energy***. The second operational parameter considered was the reduction of energy used for system operations. The maximum amount of energy permitted to treat a gallon of water was set at 20 watt-hours. Several different influent flow rates were used during the operational tests, with energy use rates ranging from only 3.23 watt-hours per gallon to 4.76 watt-hours per gallon.

- ***Reduced organic pollutants.*** The third parameter considered was a reduction in pollutants, as measured by the amount of BOD and by the levels of SS in the water. BOD is the amount of DO needed by aerobic organisms to break down organic material in water. This amount was typically kept below one-third of the maximum allowable, while the levels of SS were typically less than half the maximum allowable.

- ***Reduced levels of nitrogen and phosphorus***. The fourth parameter considered was the efficiency of the system in removing significant amounts of N and P. N and P are typical wastewater nutrients. For water to be reused, these two nutrients must be removed. If they are not, they will accumulate after several reuse cycles rendering it unusable. Furthermore, for wastewater to be discharged into surface water, nitrogen and phosphorus must be removed to avoid the explosive growth of algae. The demonstration test indicated that the dBBR effectively removed nitrogen and phosphorus compounds from the wastewater. (Tucker et al., 2016; Frontier, 2021a & 2021b).

4.3.4 Shenzhen Guangming Wastewater Treatment Plant

The iMLE process that iBBR combines with BBR has also been evaluated for enhancing the cost efficiency for nitrogen removal in a larger-capacity municipal WWTP. The study was conducted in the Shenzhen Guangming WWTP in China at approximately 6.6 MGD on two parallel treatment trains of the 12-train plant. Results were compared to those achieved by the original two-stage Anoxic/Oxic (A/O) process with continuous aeration with external carbon addition operated on the plant's other 10 trains (Zhang et al., 2021).

This study involved the application of a modified iMLE process to achieve reduction of N in wastewater at a large capacity WWTP in China. In a previous study, Frontier had integrated pre-anoxic denitrification and intermittent-aeration denitrification into one process to form a new process of iMLE. The iMLE process combines the advantages of the two types of denitrification approaches, which can reduce the "overflow" of nitrate and improve the utilization of original organics in the wastewater. The previous pilot-scale study indicated that the effluent TN concentration could be reduced to approximately 3.0 mg-N/L with a removal efficiency of 90% when the wastewater contained sufficient organics .

When the wastewater contained insufficient organics (BOD-5/TN = 2.4), the average effluent ammonia and TN were 0.3 and 4.8 mg-N/L, respectively . In addition, this process could reduce approximately 10% of aeration needs compared to the regular pre-anoxic process . However, whether iMLE process can be applied in full-scale wastewater treatment plants to improve TN removal and reduce aeration energy or not has not been demonstrated. Shenzhen Guangming WWTP used a two-stage A/O process and the effluent TN had met the Class I A discharge standard of 15 mg-N/L. However, starting from April 2019, the plant was required to meet a new local TN discharge limit of less than 10 mg-N/L. In order to consistently meet this new requirement, an external carbon source was added into the 2nd anoxic zone to improve the TN removal. However, the operation cost increased significantly since then. In this study, two trains of the biological treatment system in Guangming WWTP that treated 25,000 m3/d (i.e. each train treats approximately 3 million GPD for the plant) of flow were upgraded to the iMLE process. The TN removal efficiency and aeration energy consumption were monitored in the new process.

The Following conclusions were drawn from the field study of iMLE process in Shenzhen Guangming WWTP.

- When the iMLE process was operated with DO control mode, its effluent COD and ammonia concentrations were consistently less than 30 mg/L and 1.5 mg/L, respectively, which were equivalent to the two-stage A/O process with continuous aeration.

- When using iMLE process (DO based control mode) to treat the organic insufficient wastewater (BOD-5/TN = 2.5), the effluent TN concentration was consistently below 10 mg/L with an average value and removal efficiency of 6.1 ± 1.0 mg-N/L and 78%, respectively. This performance was similar to that of the two-stage A/O process equipped with addition of external carbon source. The elimination of the external carbon addition of the iMLE process saved approximately 0.16 Chinese yuan for treating one cubic meter of wastewater. (Equivalent to a savings of approximately $234,000 United States Dollars [USD] per year if extrapolated to 25,000 m^3 or 6.6 MGD.)

- Compared to the two-stage A/O process, the iMLE process reduced the air consumption by 20–30%. Therefore, the iMLE process operated with DO based-control mode could synergistically improve TN removal and reduce aeration energy, which provides a new approach of WWTP upgrade.

The resultant energy and carbon cost savings saved approximately 0.16 Chinese Yuan for one m^3 of wastewater treated while still meeting the discharge limits. The iMLE process decreased the air consumption by 20–30%. The results suggest that the iMLE process operated with appropriate DO control could reduce chemical cost and aeration energy use synergistically in a large plant, which provides a cost-effective approach for WWTP upgrade.

4.4 COST EVALUATION

According to Frontier, one of the key beneficial aspects of the iBBR technology is that the iBBR process offers cost-effective wastewater treatment capable of ENR for small-community systems due to the minimal operator time and O&M requirements, making it viable and less expensive on a per-unit-treated basis than conventional activated sludge processes associated with larger scale WWTP operations. Frontier provided estimated costs for a deployable/ mobile unit and for an iBBR system in a permanent concrete sub-grade structure. Both estimates are for systems that would be "full scale" in the context of applicability to a small, decentralized community of 40 homes or less, with a capacity up to 12,000 GPD. However, the deployable unit would be recommended for an initial or "pilot" study, whereas the fixed, concrete structure housed construction would be the recommended approach for a permanent facility in the Lake Erie watershed region of (northern) Ohio due to the cold winters.

All cost estimates herein are provided by Frontier (Frontier, 2021a & 2021b). Where available, Tetra Tech reviewed online sources of cost information to correlate Frontier's cost estimates or cost comparisons. Real cost data regarding permanent installations of this or similar technologies is limited to only a few installations or demonstrations. Frontier claims that the technology's best "target" range is for systems serving the range of 40 to 1000 homes (12,000 to 300,000 GPD); however, additional evaluations of long-term or larger scale implementations in Ohio would allow more refined and documentable cost estimates.

4.4.1 Deployable System iBBR Cost Evaluation

For a pilot scale evaluation of the iBBR technology, Frontier would use a deployable version of the iBBR for easy deployment to Ohio. The capacity of the system would be 10,000 - 12,000 GPD in Ohio. The pilot scale test would essentially also assume an iBBR unit for a decentralized community that has approximately 40 homes. As previously discussed, this system would also be considered "full" scale for a small, decentralized wastewater treatment system serving a community of up to 40 homes. However, for a permanent installation in Ohio subject to year-round operation, Frontier recommends that a system housed in a more permanent concrete sub-grade structure be used. For this reason, the deployable iBBR cost estimate is considered "pilot" scale. Such an installation could also be appropriate for a seasonal or temporary use application.

The deployable iBBR would be built using a 20-ft shipping container based on Frontier's general existing design specification and would have a capacity up to 12,000 GPD. However, this unit can also be installed in a community that has as little as 10 homes requiring wastewater treatment (less than 5,000 GPD) because it does not have a lower flow limit (Frontier, 2021a &2021b).

4.4.1.1 Capital Costs

The estimated construction costs for a 40-home community, 12,000 GPD unit in the following table.

Table 4 - Deployable iBBR Construction Cost Estimate

Cost Item	Frontier Cost Estimate
iBBR Equipment	$180,000
Engineering and Permitting	10,000
Site preparation (gravel bed; influent collection tank):	20,000
Delivery, installation, travel, startup and operator training	15,000
Total estimated construction cost:	**US $225,000 ($20.45 / GPD capacity)**

Additional costs for completing a pilot-scale evaluation would be highly dependent on the duration of the project, flow rates and specific sampling and analytical requirements.

The deployable system could theoretically be used as a permanent system following the demonstration. However, deployable systems with relatively low treatment capacities are less suited to colder climates than those housed in permanent structures constructed at least partially below grade. If the unit were put into continued use after the demonstration, this iBBR unit could be donated to the small community where this demonstration project is conducted. Therefore, no demolition cost is assumed.

4.4.1.2 O&M Costs

After the iBBR is set up, the maintenance cost is reported by Frontier to be very minimal. According to Frontier, it will take approximately 4 - 5 hours per month to collect and analyze samples (assuming monthly sampling is required) and make minor adjustments, so the total labor cost should be approximately $100/month (the average salary cost per hour for a municipal wastewater operator in Ohio is reportedly $20.90 per hour – [Indeed, 2021]). The electrical power cost is estimated by Frontier as approximately $100/month based on Frontier's experience with other installations. Therefore the total annual cost of labor and electricity is estimated at $2,400. Overhead rates of the partner who is responsible for O&M will vary highly; for estimating purposes, Frontier assumes a total O&M cost of $4,400/year including operator company overhead. These costs do not account for inflation.

During the lifespan of the equipment (assuming 25 years), parts like UV bulbs, blowers, influent pump, and the DO probe will need to be replaced, and excess sludge will need to be hauled away every few years. Assuming the UV bulb needs to be replaced once per year, and that the influent pump, blowers, DO probe need to be replaced every 10 years, and the sludge needs to be hauled away every 3 years, the total replacement cost for these parts and sludge hauling during the lifespan of the iBBR is estimated at approximately $15,000, or $600/year.

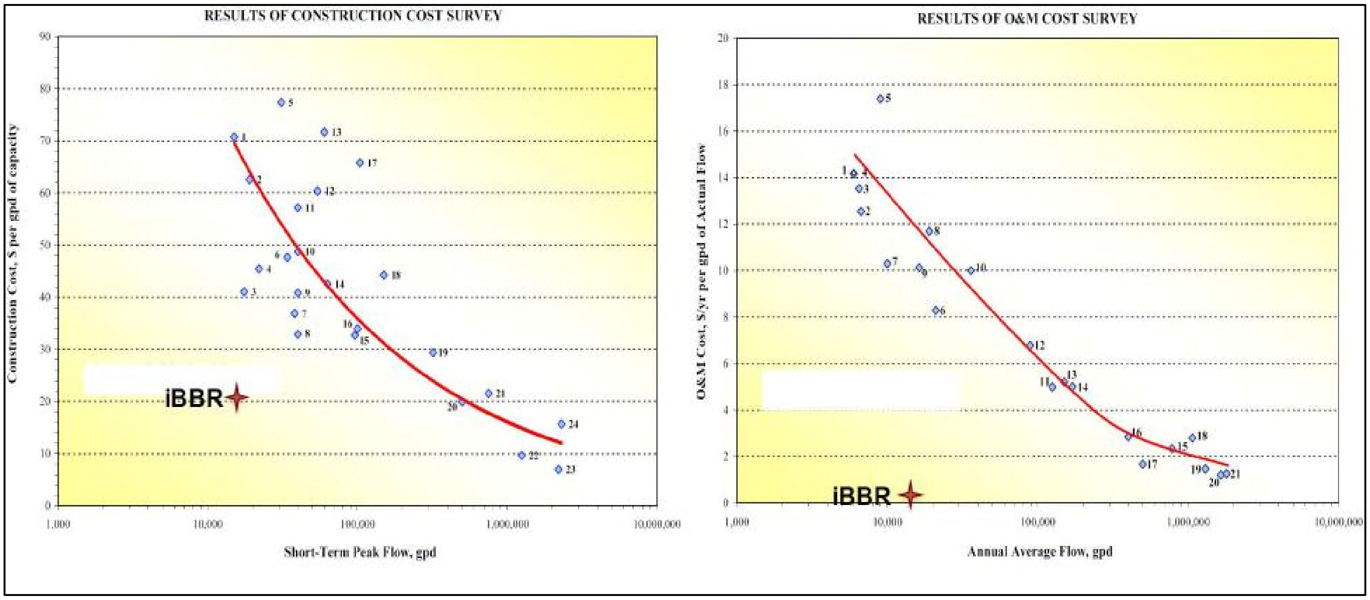
If a deployable system were operated for 25 years, at an assumed 11,000 GPD, the total volume treated would be approximately 100 MG. Therefore, total expenses for operation (including labor, electricity, parts replacement, and sludge hauling) is $3,000/year (= 2,400 + 600), or $0.75/1,000 gallons treated. The annual expenses per GPD capacity is calculated to be $0.27/yr-GPD capacity [($3,000/yr)/(11,000 GPD) = $0.27/yr-GPD capacity].

Because the total construction cost is $225,000, and the lifespan is 25 years, the equipment depreciation cost is estimated at: $225,000/(25 x 365 x 11,000) = $2.24/1000 gallons treated.

As a result, the total lifecycle cost for iBBR treatment is estimated at $3.00/1000 gallons treated (= $2.24 + $0.75). The average rate for city residents who send their wastewater to centralized wastewater treatment plants is $7.73/1000 gallons (Frontier 2021 [after Black & Veatch, 2019], and these centralized wastewater treatment plants may not achieve ENR. Therefore, small systems using iBBR may be capable of treating wastewater at costs up to 60 percent less than the rates charged to customers by larger systems.

Frontier provided additional information regarding comparison of costs to other available technologies. According to Frontier a survey report published in 2010 lists actual construction and operational costs for more than 20 wastewater treatment plants, most of which are small plants. Their costs are related to the size of the treatment plant. Figure 5 graphically summarizes the survey data in comparison with the estimated iBBR numbers. As indicated, the iBBR technology is less expensive to build and operate compared to many other technologies that are used for small community wastewater treatment at similar system capacities. Those systems with lower costs were generally higher capacity systems where economy of scale reduces capital expenditures when amortized over the operational lifespan of the units.

Figure 5 - Capital Cost and O&M Expense for iBBR vs. Various Other Small Plants (Frontier 2021a)



4.4.2 Housed iBBR Cost Evaluation

The deployable unit described in the previous sections was developed to meet military needs in FOBs. However, it has potential disadvantages for community applications in Ohio: (a) it is not suitable for use in regions that have very low winter temperature and (b) it has a shorter service life than the fixed units built with concrete. For applications in Ohio, a permanent (non-mobile) concrete unit that is partially or fully buried underground would be preferred. This ensures normal operation in cold winter and prolonged service life (as long as the concrete tank is not broken). Cost data herein were provided by Frontier (2021a & 2021b) unless otherwise noted.

4.4.2.1 Capital Costs

The total cost to build the concrete-housed unit is expected to increase construction costs to $250,000 (from $225,000 for the mobile unit), an 11.1% increase. Some construction costs will be higher and others lower than for a mobile system (for example, assembly will primarily occur on-site rather than prefabricated by Frontier in Missouri) and concrete tanks will be required; however, the shipping container that houses the mobile system will not be needed. The equipment and supply costs include costs for pipes; diffusers; surge mixing and lifting devices; control system; pumps, blowers, and sanitizers. Among these supplies, the components within the tank (fiberglass or polyethylene), the surge mixing and pumping devices, and the control system are propriety that have to be designed and fabricated in-house.

Table 5 - Fixed/Housed iBBR System Capital Costs

Cost Item	Frontier Cost Estimate
iBBR Equipment/Supplies	$170,000
Concrete Tanks	25,000
Engineering and Permitting, Application Fee	10,000
Site preparation (excavation, tank installation)	15,000
Delivery, installation, travel, startup and operator training	10,000
iBBR field assembly	20,000
TOTAL ESTIMATED CONSTRUCTION COST	**US $250,000 ($22.73 / GPD capacity)**

Assuming the same critical design parameters as for the mobile system (total wastewater flow is 11,000 GPD (70 - 90 GPD/person) and the unit will serve a system treating wastewater from up to 40 households, the capital costs rate are estimated at $22.73/GPD capacity.

To get the project started, Frontier would require 20% of the estimated project cost at the time of contract signing. This will allow Frontier to start the design work of the plant, and the partner to prepare documents for permit application. Additional expenses will be requested along the design and the fabrication work.

The above cost was estimated based on a community that has 40 homes. For larger communities with higher system capacities, the capital cost per gallon treated will significantly reduce due to the scale effect.

4.4.2.2 O&M Costs

After the iBBR is set up, the maintenance cost is anticipated to be minimal. Frontier estimates 4 - 5 hours per month mostly to collect/analyze samples (assuming monthly sampling is required) and make minor adjustments, so the total labor salary cost should be approximately $100/month based on average wastewater operator salaries in Ohio ($20.90 per hour) (Indeed, 2021). The power cost should also be approximately $100/month estimated based on cost data gathered from previous evaluations of the technology. Therefore the total annual cost of labor and electricity is estimated at $2,400. Overhead rates of the partner who is responsible for O&M will vary highly; for estimating purposes, Frontier assumes a total O&M cost of $4,400/year including operator company overhead. These costs do not account for inflation.

During the lifespan of the equipment (assuming 30 years), parts like UV bulb, blowers, influent pump, and the DO probe need to be replaced, and excess sludge needs to be hauled away every few years. Assuming the UV bulb needs to be replaced once per year, the influent pump, blowers, DO probe need to be replaced every 10 years, and the sludge needs to be hauled away every 2 years, the total replacement cost for these parts and sludge hauling during the 30-year lifespan of the iBBR is approximately $18,000, which is $600/year.

Therefore, total operational expenses (including labor, overhead, electricity, parts replacement, and sludge hauling) is $5,000/year (= 4,400 + 600).

Because the total construction cost is $250,000, and the lifespan of the plant is 30 years, the plant depreciation cost is calculated at: $250,000/30 year = $8,333/year.

As a result, the total lifecycle cost is estimated at $13,333/year ([$8,333+$5,000] per year. This equates to $36.53/day or $3.32/1000 gallons treated (assuming that over a 30-year operational period at 11,000 GPD, the total volume treated is approximately 120.5 MG). As previously discussed, for comparison, the average cost for sewer rates in the largest U.S. cities in 2018 was $7.73/1000 gallons treated (Frontier 2021 after Black & Veatch, 2019). Although a fraction of this saving will be used as the partner profit for long-term O&M service, much of the cost savings would pass on to the customers.

4.4.2.3 Cost Per Pound of Nutrient Removal

Assuming the influent quality is same as typical medium strength domestic wastewater, which has a total nitrogen (TN) and total phosphorus (TP) of 40 mg/L and 7 mg/L, respectively (Metcalf & Eddy, 2003), and the treated effluent has TN and TP concentrations of 5 mg/L and 1 mg/L, respectively, the TN and TP removed per day will be 3.21 lbs. and 0.55 lbs., respectively. When extrapolated to 1 lb. of nitrogen, and based on the estimated costs for the fixed/ housed system described above, the cost to remove 1 lb. of TN is estimated to be approximately $11.38. This cost would also include the removal of a proportional amount (0.17 lb.) of TP. (Frontier, 2021a & 2021b).

4.4.2.4 Other Factors Potentially Affecting Cost

When additional TP removal is needed, an alum coagulation-flocculation-clarification process may be employed. An optional upgrade package can be an add-on component to the iBBR at a price of approximately $5,000. It does not need additional tankage. Chemical treatment will add additional operational costs, mostly from the chemical use (the chemical dosage and cost need to be determined on-site). Chemical treatment will also need additional space that is protected from freezing to store chemicals and house the chemical dosing pump (Frontier, 2021a & 2021b).

4.5 SCALABILITY EVALUATION

iBBR can overcome the limited ability of BBR alone to consistently meet low discharge standards for nutrients as either a stand-alone system for small communities or an improvement to larger systems. iBBR also offers the low-maintenance benefits of BBR combined with enhanced nutrient removal.

The iBBR technology has been applied to systems serving as few as 12 homes, as well as evaluated at flows up to 12,000 GPD (equivalent of 40 homes) in a pre-existing WWTP in Rolla Missouri. While the iMLE process has been evaluated in systems at flows up to 13 MGD the iBBR technology (iMLE combined with BBR) is suited to flows up to 300,000 GPD as 300,000 GPD is the upper practical and economic limit for the BBR aspect of the technology. Assuming a typical use of 300 GPD per household, iBBR is suitable for installations serving up to 1,000 homes and thus readily scalable to larger scale deployments in Ohio. The technology is thus suitable and potentially applicable at a scale to support wastewater treatment needs at hundreds of small communities throughout the 35 Ohio counties contributing to the Lake Erie Basin in northern Ohio (Frontier, 2021a & 2021b).

Since the technology has essentially been tested in the equivalent of "full scale" implementation mode (in the context of a small community system), installation in such a small community system to demonstrate its performance under realistic community settings in the Lake Erie region would also represent a full scale implementation. Frontier indicates that such a full-scale deployment (i.e. 40 home system or 12,000 GPD) can be accomplished within 1 year and that a large-scale (maximum viable size based on the technology's current status – up to 300,000 GPD) deployment can be accomplished within 1.5 years. Once constructed, O&M is minimal (Frontier, 2021a & 2021b).

As previously discussed, assuming the influent quality is the same as typical medium strength domestic wastewater, which has a TN and TP of 40 mg/L and 7 mg/L, respectively (Metcalf & Eddy, 2003), and the treated effluent has TN and TP concentrations of 5 mg/L and 1 mg/L, respectively, the TN and TP removed per day will be 3.21 lbs. and 0.55 lbs., respectively. When extrapolated to 1 lb. of N and based on the estimated costs for a fixed system housed in concrete tanks and below grade, the cost to remove 1 lb. of TN is estimated to be approximately $11.38. This cost would also include the removal of a proportional amount (0.17 lb.) of TP (Frontier, 2021a & 2021b).The estimated cost per pound is within the range of other technologies and agricultural practices reviewed by Tetra Tech.

The challenge will be to improve awareness of the availability of iBBR, its advantages and benefits, and work with partnering agencies and organizations to foster adoption of this innovative technology. Overcoming the barriers to iBBR adoption and creating partnership commitment and momentum to support its implementation and informed active management will be critical if this conservation measure is to see widespread adoption and have a measurable impact on reducing nutrient loading in the watershed.

4.6 INFORMATION GAP EVALUATION

Based on Frontier's technology submission for iBBR, it is necessary to obtain more information about the long-term performance of iBBR and to obtain the results of larger-scale applications of the technology. Studies reviewed in support of this evaluation were based on relatively small-scale deployments of the technology (<10,000 GPD). Additional cost data from actual evaluations of larger-scale systems will be helpful in demonstrating the cost-savings aspect of the technology to potential users in the Lake Erie basin.

There is also an information gap regarding the potential market for this technology within the Lake Erie watershed as iBBR is a point-source reduction technology and emphasis has shifted to the greater nutrient load resulting from non-point sources. Nonetheless, point-source discharge remains a contributing factor to the nutrient load in the watershed, and therefore the technology could have impact on reducing P and N when matched with viable potential users in critical areas. To achieve significant impacts, a marketing strategy centered on identifying communities with the appropriate technical needs and resources will be critical to this technology being deployed widely.

4.7 FEASIBILITY FOR LARGE-SCALE TECHNOLOGY DEMONSTRATION

The Information provided by Frontier indicates that the BBR has been fully tested in multiple wastewater treatment plants using raw wastewater with different BOD-5-to-TN ratios, under different temperature conditions (Liu and Wang, 2017a; Wang et al., 2018). The enhanced iBBR has been implemented at the equivalent of "full" scale for a small system serving 12 homes in Rolla MO or "pilot scale" if considered in the context of supporting a larger capacity system. Frontier indicates that the readiness level of the iBBR is at NOAA RL 8 ("Finalized system, process, product, service or tool tested, and shown to operate or function as expected within user's environment; user training and documentation completed; operator or user approval given") and that it is ready to be evaluated through installation in a small community to demonstrate its performance under realistic community settings in Lake Erie region (Frontier, 2021a & 2021b).

A large or "full" scale technology demonstration is very feasible with iBBR. The technology has already been evaluated at a scale equivalent to full scale application in the context of a stand-alone system supporting a small community, as well as a modification / addition to a large scale municipal system. However, iBBR has not been tested in northern Ohio and thus an evaluation of its capabilities to treat wastewater and provided ENR within the Lake Erie basin would provide additional confidence on its potential applicability.

If Frontier were to receive funds for a large-scale iBBR demonstration project, the project would conceptually involve a decentralized community system serving up to approximately 40 homes. The system would be built using a 20-ft shipping container. This unit can also be installed in a community that has as little as 10 homes for wastewater treatment because it does not have a lower flow limit. Through collaboration with a local company in Ohio that would be responsible for site work, Frontier could develop the technology within 6 months for pilot-scale evaluation. This would include time for Frontier to develop the technology components and installation, assuming everything else such as the permit application and site work go smoothly (Frontier, 2021a & 2021b).

4.8 FEASIBILITY FOR FULL-SCALE IMPLEMENTATION

The Information provided by Frontier indicates that iBBR has been fully tested in multiple wastewater treatment plants using raw wastewater with different BOD-5-to-TN ratios, under different temperature conditions (Liu and Wang, 2017a; Wang et al., 2018). The system has successfully been tested in support of a small community system of the scale that is within the range of the potential targeted users for this technology in Ohio. Frontier indicates that the readiness level of the iBBR is at National Oceanic and Atmospheric Administration (NOAA) Readiness Level (RL) 8:

"Finalized system, process, product, service or tool tested, and shown to operate or function as expected within user's environment; user training and documentation completed; operator or user approval given" (NOAA 2016).

Frontier indicates that a limited full-scale deployment (i.e. 40 home system or 12,000 GPD) can be accomplished within 1 year and that a large-scale (maximum viable size based on the technology's current status – up to 300,000 GPD) deployment can be accomplished within 1.5 years (Frontier, 2021a & 2021b).

Since the technology is essentially tested in the equivalent of "full scale" implementation mode in the context of a small community system, installation in such a small community system to demonstrate its performance under realistic community settings in the Lake Erie region would also represent a full scale implementation. The challenge will be to improve awareness of the availability of iBBR, its advantages and benefits, and work with partnering agencies and organizations to foster adoption of this innovative technology. Overcoming the barriers to iBBR adoption and creating partnership commitment and momentum to support its implementation and informed active management, will be critical if this conservation measure is to see widespread adoption proportionate with the need and the scope/magnitude of the Lake Erie Basin opportunity that exists.

4.9 PROBABILITY OF SUCCESS

Previous studies of BBR and iBBR demonstrate that this technology will result in reducing point source discharges of nutrients that are contributing to the Lake Erie algal blooms. Although points-source discharges comprise a lesser portion of the P and N loading in the watershed than agricultural/ non-point sources, discharge from wastewater systems still contribute significant amounts of P and N to the watershed. Past studies of the technology have shown it to be effective at its intended purpose and when designed and operated to account for site-specific conditions (e.g. temperature extremes) and that it offers reduced O&M and operating costs in comparison with other treatment options. With appropriate design, and matched to the appropriate users, the technology has a high probability of success. Published research of the technology indicates that systems in the range of up to approximately 40 homes (approximately 12,000 GPD) to 1,000 homes (300,000 GPD) represent the ideal situations where the technology will be the most applicable and successful based on current designs and tested performance, whether deployed as "standalone" units or within an existing WWTP.

4.10 FINANCIAL VIABILITY

Frontier Environmental Systems LLC is a small business based in Rolla, MO that has been in business for 12 years. The company currently has a staff of 3 and one office location. According to Frontier annual sales are currently in the range of $0-$250,000 (Frontier, 2021a).

Frontier does not maintain an inventory of iBBR units as the systems are customized and fabricated to meet the specific needs of the project technical requirements and site conditions. Past evaluations of BBR and iBBR have been funded through government funding, university research and municipal funding. For a demonstration in Ohio or a full scale implementation, Frontier indicates that it would require 20% of the estimated project cost at the time of contract signing. Long-term plant O&M would be handled by local partners under a separate O&M contract to ensure professional care. Frontier will provide free technical support to the partner should issues occur. This will allow Frontier to start the design work of the plant and the partner to prepare documents for permit application (Frontier, 2021a & 2021b).

4.11 QAPP

Frontier did not provide any raw data to support the technology evaluation and therefore no Quality Assurance Project Plan (QAPP) was provided. Instead, information about the performance of iBBR was obtained from literature, which was peer-reviewed and provided by Frontier.

Tetra Tech recommends that a QAPP be developed for any future studies or demonstration projects.

4.12 DATA VALIDATION

Information about the performance of iBBR was obtained from literature provided by Frontier in (1) its initial proposal and in (2) its response to Tetra Tech's request for data, which included published and peer-reviewed summaries of two case studies evaluating the technology. According to Frontier, the data were generated using approved standard methods either in-house or by university research laboratories including the University of Missouri (Rolla) following standard Quality Assurance/Quality Control (QA/QC) methodology appropriate for the analytical methods and were reviewed internally for use for the intended purpose. The underlying data are therefore assumed to be of usable quality.

4.13 SUPPLY CHAIN

Frontier indicates that the components of iBBR are comprised of items that are typically "off the shelf" and readily available. The units tested have been constructed in existing plants or self-contained in shipping crates. For these reasons, Tetra Tech did not identify any specific supply-chain concerns unique to this technology.

4.14 ENVIRONMENTAL RISKS

iBBR is not anticipated to create any risks to the environment. It is an aerobic treatment method which does not release smells. It removes contaminants from wastewater and does not contaminate water and land. One of the key elements of the process is the reduced sludge solids generation, which benefits both the user (in terms of O&M) and the environment. In a typical wastewater plant, sludge management requires frequent removal and accounts for up to 30 to 60 percent of operating costs. However, iBBR requires only infrequent removal and off-site disposal of sludge (approximately every three years for a system treating up to 12,000 GPD), reducing odors and hazards associated with hauling the sludge off-site in trucks. In addition, it is a relatively quiet technology and does not produce enough noise to impact a neighborhood even at night.

4.14.1 Health & Safety

It appears unlikely that implementation of iBBR technology poses significant risks to the health and safety of those deploying the systems. Wearing personal protective equipment (PPE) is likely required when installing iBBR systems; there could also be confined space entry requirements to access portions of system, particularly if retrofitting the technology to an existing WWTP system.

4.15 COMMUNITY PERCEPTION & DISPROPORTIONATE IMPACT

Residents in decentralized communities that use iBBR will realize approximately 60% less cost for their wastewater treatment compared to their city counterparts, plus contribute less nutrients to the environment. When comparing with other small flow treatment technologies, significantly greater savings will be realized. The low maintenance of the iBBR plays the key role in the low treatment cost.

iBBR can overcome the limited ability of BBR alone to consistently meet low discharge standards for nutrients as either a stand-alone system for small communities or an improvement to larger systems. iBBR also offers the low-maintenance benefits of BBR combined with enhanced nutrient removal. Based on these considerations, perception of iBBR among regulating agencies is anticipated to be positive as the technology offers improved nutrient removal to meet current and future discharge standards and can contribute to Ohio EPA's mission of reducing the potential for formation of HABs.

Perception among potential users is anticipated to be positive as iBBR offers effective reduction in nutrients at a lower cost than some technologies and is built upon a proven, existing technology. General public perception is also anticipated to be positive as the technology is consistent with the goals of improvement in the environmental health of receiving water bodies that serve as sources of drinking water and recreational opportunities, and thus may offer an indirect economic benefit as well.

Impact of use of this technology will essentially be beneficial in all aspects. Environmental health of the region will be improved using a technology that will allow wastewater treatment at rates lower than the average municipal treatment costs. For these reasons, no adverse/ disproportionate impacts were identified.

4.15 WASTE/BY-PRODUCT MANAGEMENT REQUIREMENTS

It is unlikely that waste and/or by-product management requirements will impact the implementation of iBBR systems. According to Frontier, waste products are anticipated to include minor amounts of sludge that will require offsite disposal every three years for a system operating at approximately 12,000 GPD. (Frontier, 2021a & 2021b).

5.0 LIST OF REMAINING DATA GAPS

As explained in Section 4.6, the primary information gaps relating to iBBR are:

- The performance of iBBR in a similar climate to northern Ohio automated Drainage Water Management (DWM) compared to manual DWM
- Performance of iBBR at flows >12,000 GPD (although the BBR and iMLE components of the technology have been evaluated at significantly higher flow rates).

- Long-term performance of iBBR systems.

- The potential market for this technology; specifically identifying communities in the watershed of the sufficient scale, needs, and resources to adopt this technology.

Based on Frontier's technology submission for iBBR, it is necessary to obtain more information about the long-term performance of iBBR and to obtain the results of larger-scale applications of the technology. Studies reviewed in support of this evaluation were based on relatively small-scale deployments of the technology (<10,000 GPD). Additional cost data from actual evaluations of larger-scale systems will be helpful in demonstrating the cost-savings aspect of the technology to potential users in the Lake Erie basin. To achieve significant impacts, a marketing strategy centered on identifying communities with the appropriate technical needs and resources will be critical to this technology being deployed widely.

6.0 FINDINGS AND OPINIONS

Based on our review of the available information and discussions with Frontier, Tetra Tech has reached the following conclusions regarding iBBR:

- Agreement that the technology, iBBR, is effective at reducing point-source discharge of TN and TP from WWTPs

- Additional research is needed on how iBBR performs at controlling point-source nutrient discharges, in systems operating at higher capacity than those tested in the past. This could be a goal of a pilot project funded by H2Ohio.

- iBBR is a cost effective technology when compared to other technologies available to small community systems to treat point-source nutrient discharges. The cost per gallon treated is also lower than the average for large municipal systems.

- iBBR has strong potential for scalability to small, centralized plants in the Lake Erie watershed, however additional research and studies within Ohio are needed.

- The biggest barrier to widespread adoption of iBBR is marketing of the technology, e.g. matching to the technology to potential user systems meeting the criteria of (1) decentralized communities with a need for collective wastewater treatment and (2) having access to the economic resources to adopt the technology.

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