SECTION 5.0
NITRIFICATION/BNR TECHNOLOGY REVIEW

5.1 INTRODUCTION

The section details the theory of the biochemical mechanisms involved in biological nitrogen removal and biological excess phosphorus removal (BEPR) from municipal wastewater treatment plant effluents. Details are presented of the more common biological nitrogen and phosphorus process configurations, with a particular emphasis on suspended growth processes that may have future application at Winnipeg's three wastewater treatment plants.

5.2 BIOLOGICAL NITROGEN REMOVAL

Wastewater treatment processes designed for biological nitrogen removal normally achieve this removal through the sequential processes of nitrification and denitrification. Denitrification is the biological reduction of nitrate or nitrite to nitrogen gas, which escapes to the atmosphere. In denitrification, nitrate and nitrite serve the same function as oxygen in the process, i.e., as the terminal electron acceptor. From the stoichiometry of denitrification, it can be seen that when nitrate serves as the terminal electron acceptor, 1 mg NO_3^- (as N) is equivalent to 2.86 mg O (as O). Further, it can be shown that for every mg of NO_3^-N denitrified:

- 2.9 grams of O_2 are recovered
- 3.6 grams of alkalinity (as $CaCO_3$) are produced
- Between 3 and 4 mg of substrate (as COD) are required

In addition to being a critical element in biological nitrogen removal, approximately 63% of the oxygen consumed in the nitrification reaction can be recovered by denitrification assuming that complete denitrification is achieved. Furthermore, approximately 50% of the alkalinity destroyed in the nitrification reaction is also recovered. Consequently, denitrification can play an important role in reducing the process energy requirements and maintaining the process pH within the optimal range for nitrification, even in plants that are not required to achieve biological nitrogen removal.

Denitrification has a slightly lower biomass yield than normal aerobic respiration, with approximately 0.5 grams of VSS being produced from every gram of NO_3^-N denitrified.

For denitrification to occur, the following conditions are necessary:

- Presence of nitrate or nitrate. These compounds are normally produced by nitrification and serve as the terminal electron acceptor in denitrification.
- Absence of dissolved oxygen. The presence of oxygen prevents the formation of the enzyme necessary for the substitution of nitrate for oxygen as the terminal electron acceptor.
- A facultative bacterial mass, i.e., a mass of organisms with the necessary enzyme system to use nitrate instead of oxygen as the terminal electron acceptor.
- Presence of a suitable electron donor, or energy source. The carbonaceous energy source for denitrification can either be internal (organic material naturally present in the wastewater), external (e.g. methanol added to the denitrification stage of the process), or self generated (nutrients released though the death of organisms in the process).

Assuming that anoxic conditions are maintained and there is no measurable dissolved oxygen in the system, the denitrification rate is primarily a function of the amount and nature of available carbon, with rates being significantly higher in the presence of readily biodegradable organic material. In general, organisms responsible for denitrification are much less sensitive to temperature, pH and inhibitory substances than nitrification organisms.

5.3 BIOLOGICAL NITROGEN REMOVAL PROCESSES

The majority of suspended growth, biological nitrogen removal processes in operation worldwide are single sludge activated sludge processes with aerobic zones for carbon removal and nitrification, and anoxic zones for denitrification. Process schematics of several commonly used nitrogen removal configurations are presented in Figure 5.1. These processes normally use a predenitrification zone (i.e., denitrification zone is upstream of the nitrification zone) in order to make optimal use of the incoming wastewater as the carbon source for denitrification. In processes such as the Modified Ludzack Ettinger Process, nitrified mixed liquor is recycled from the aerobic zone to the anoxic zone, where it is denitrified using the incoming wastewater as a carbon source. In processes with a postdenitrification zone (e.g. the Wuhrmann Process, in which the denitrification zone is downstream of the nitrification zone), the denitrification rates are significantly lower as they rely on a self-generated carbon source for denitrification. If high denitrification rates are required in the post denitrification zones, an external carbon source is required. Processes such as the 4-Stage Bardenpho process are used to achieve extremely low effluent nitrate concentrations, and have both preanoxic and postanoxic zones. Some activated sludge processes, particularly those with surface aeration systems, are designed to have anoxic pockets within the aerobic zone of the bioreactor. These anoxic pockets promote additional nitrogen removal through simultaneous nitrification-denitrification in the aerobic zone of the process.

Attached growth processes are more commonly used for tertiary nitrification than for denitrification. However, separate stage denitrification has been well proven in downflow packed bed gravity filters, and upflow fluidized beds, using methanol as the carbon source for denitrification. These processes have been successfully applied in Florida to meet a stringent effluent total N limits of 3.0 to 5 mg/L. With proper controls, the methanol requirements are close to the stoichiometric range. Attached growth nitrogen removal processes are under development in Europe in which the nitrification stage effluent is recirculated to an anoxic reactor in order to use the incoming wastewater as a carbon source for denitrification. Several configurations, operating modes and media have been tested. Full scale nitrogen removal facilities under the trade names of Biocarbone and Biostyr have recently been commissioned.

5.4 BIOLOGICAL PHOSPHORUS REMOVAL

Biological excess phosphorus removal (BEPR) is a phenomenon in which organisms in the activated sludge microbial mass remove and intracellularly store a greater mass of phosphorus from the wastewater than that which they require for basic metabolic purposes. The following two conditions must be satisfied for reliable BEPR to take place:

- At some stage in the process, the activated sludge mass must be subjected to a truly anaerobic state, defined as the absence of both dissolved oxygen and/or nitrate/nitrite.
- While in the above anaerobic state, a certain minimum quantity of simple carbonaceous substrate, or readily biodegradable COD, must be available to the organisms for storage. The most important substrates for BEPR are short chain volatile fatty acids (VFAs), principally acetic and propionic acid.

The key bacterial species involved in the BEPR mechanisms has been identified as *Acinetobacter* ssp (especially the strain Lwoffi), although other organisms have also been found to have this capability. Bio-P organisms have the ability to store phosphorus within the cells as long chains of inorganic polyphosphate, commonly known as volutin granules. Under anaerobic conditions, the energy associated with the polyphosphate bonds can be used to take up short chain VFAs, especially acetic acid. By breaking the phosphate energy bonds, stored phosphorus is released to the liquid phase. The SCVFA taken up in this way is stored as poly-ß-hydroxybutyrate

(PHB) until the organisms reach the aerobic zone of the process. In the aerobic zone, the organisms metabolize the PHB and use the energy to take up all available phosphorus, which in turn facilitates the uptake of VFA in the anaerobic zone. In this way, organisms capable of BEPR have an advantage in the highly competitive activated sludge environment. Removal of the phosphorus-rich biomass from the process via the waste activated sludge effectively removes the phosphorus from the wastewater.

Short chain VFAs required for BEPR can either be:

- Naturally present in the wastewater as a result of acid fermentation in the collection system.
- Added directly to the anaerobic zone of the process, e.g. as acetic acid.
- Generated on-site at the wastewater treatment plant through primary sludge fermentation.

5.5 BIOLOGICAL PHOSPHORUS REMOVAL PROCESSES

Biological phosphorus removal processes subject the activated sludge biomass to anaerobic conditions in the presence of readily biodegradable carbon to initiate P release and VFA uptake, followed by aerobic conditions in which P uptake occurs. Process schematics of the key biological phosphorus removal configurations are presented in Figure 5.2. The non-nitrifying Phoredox process consists of an anaerobic zone and an aerobic zone in series. The sequential anaerobic and aerobic conditions can also be created in a sequencing batch reactor process. The Phostrip process is a combined process that employs both biological and physical chemical methods to achieve phosphorus removal. Phosphorus released from a portion of the return activated sludge in the anaerobic "stripper" reactor is chemically precipitated using lime and removed from the process as waste sludge.

Most plants designed for BEPR in temperate and cold climates require primary sludge fermentation to generate the short chain VFAs needed for biological phosphorus removal. The key primary sludge fermenter configurations are presented in Figure 5.3. Two of the fermenter configurations (single stage fermenter/thickener and the two stage complete mix/thickener fermenter) have integral liquid-solids separation and therefore provide the ability to discharge the VFA-rich fermenter supernatant directly to the anaerobic zone of the BEPR process. In both of these processes the waste primary sludge is withdrawn in a thickened state.

5.6 BIOLOGICAL PHOSPHORUS AND NITROGEN REMOVAL PROCESSES

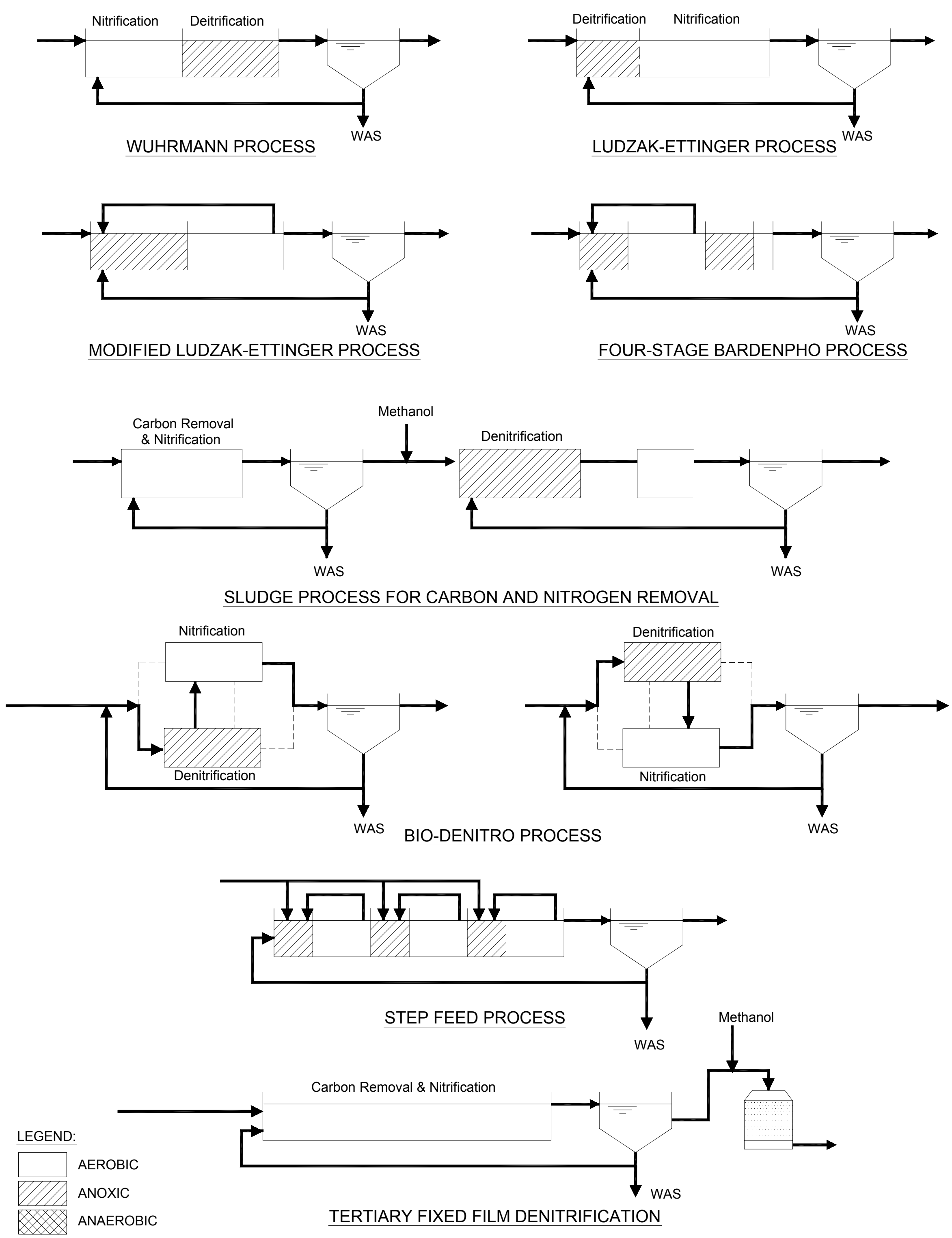
There are several single sludge process configurations designed for simultaneous biological nitrogen and phosphorus removal. These are commonly termed biological nutrient removal, or BNR, processes. Process schematics of the key BNR process configurations are presented in Figure 5.4. In general, these processes are similar to the biological nitrogen removal processes, except that they have an anaerobic zone at or near the head end of the process train to satisfy the requirements for biological phosphorus removal.

The 3-Stage Bardenpho process forms the basis of all BNR processes. Carbon removal, nitrification and phosphorus uptake take place in the aerobic zone. The requirements for biological phosphorus removal are satisfied in the anaerobic zone. Some carbon removal and most of the denitrification takes place in the anoxic zone. The 5-Stage Bardenpho Process is used when a low effluent total N concentration is required.

A key feature in the design and operation of BNR processes is the need to protect the anaerobic zone from incoming nitrate. Nitrates preferentially consume the VFAs needed for BEPR, thereby inhibiting the phosphorus removal mechanism. In the UCT and Modified UCT processes, the return activated sludge is denitrified in an anoxic zone, and denitrified mixed liquor is conveyed to the anaerobic zone via a dedicated recycle. In the Johannesburg modification of the 3-Stage Bardenpho process, the return activated sludge is passed through an anoxic reactor to remove any dissolved oxygen or nitrate from the stream. In the Westbank process, the RAS is denitrified in a pre-anoxic zone using a portion of the incoming wastewater as a carbon source for denitrification. The VFA-rich fermenter supernatant is discharged directly to the anaerobic zone of the process.

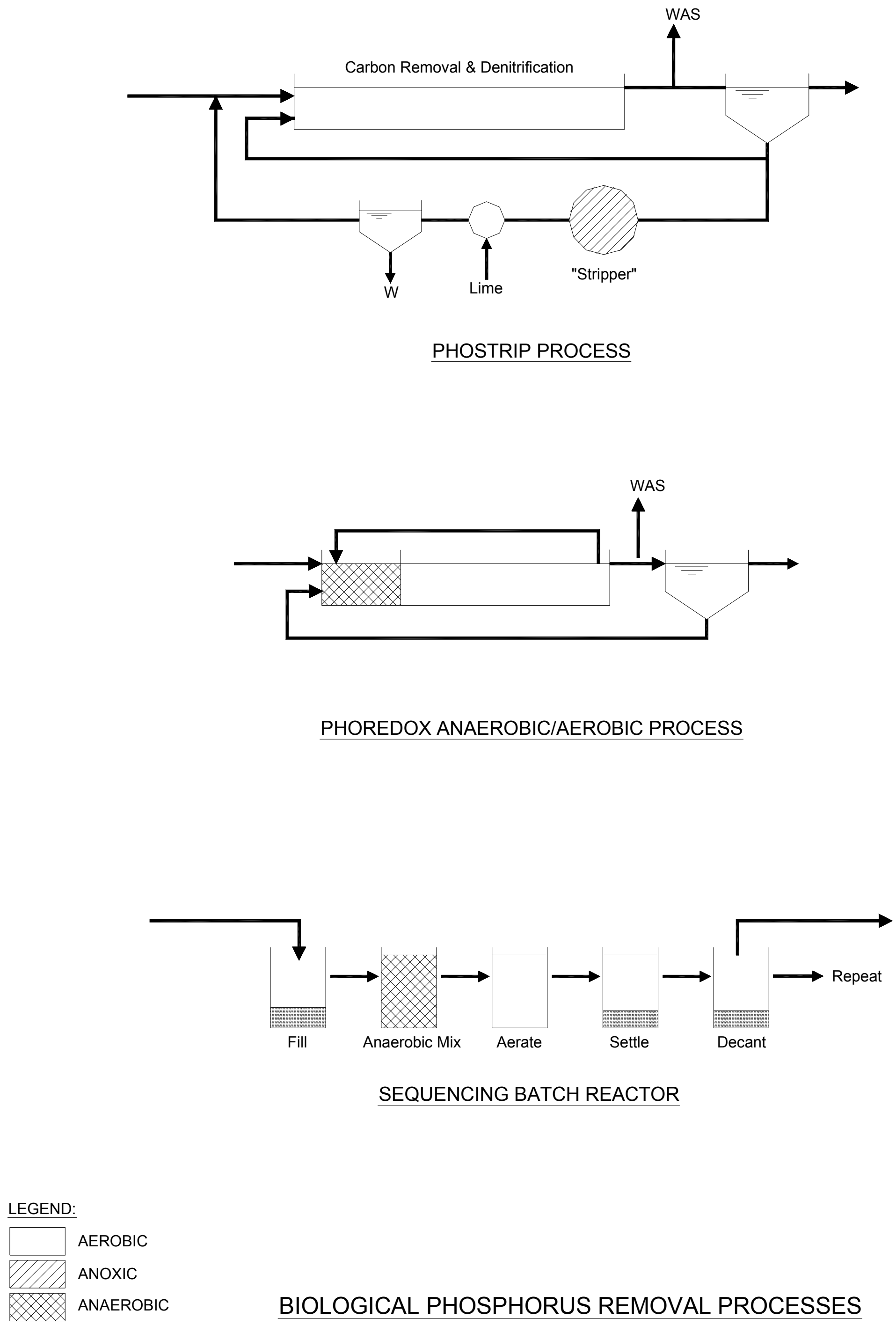
5.7 SUMMARY

In the event that the Winnipeg wastewater treatment plants are required to be upgraded to include biological nutrient removal at some future date, the process technology used in the plant upgrading for nitrification will have a significant impact on the availability of a suitable BNR process. This factor must be taken into consideration in the selection of nitrification technology to be used. For example, if a single stage nitrification process is used, the incorporation of denitrification offers several process benefits over and above the ability to achieve nitrogen removal. These benefits include the recovery of a significant fraction of the oxygen and alkalinity consumed in the nitrification reaction. If, however, a single sludge nitrification process must be upgraded to biological phosphorus removal in the future, careful attention must be paid to protect the anaerobic zone from incoming nitrate. Further, it is likely that primary sludge fermentation will be required to provide the necessary quantity of short chain VFAs for reliable BEPR. If a second stage nitrification process is used at any of the three plants, a tertiary denitrification stage with methanol addition will be the only way of achieving biological nitrogen removal as it will be difficult to use the incoming wastewater as a carbon source for denitrification. It will also not be possible to use the denitrification stage to recover a portion of the oxygen and alkalinity consumed in the nitrification stage.



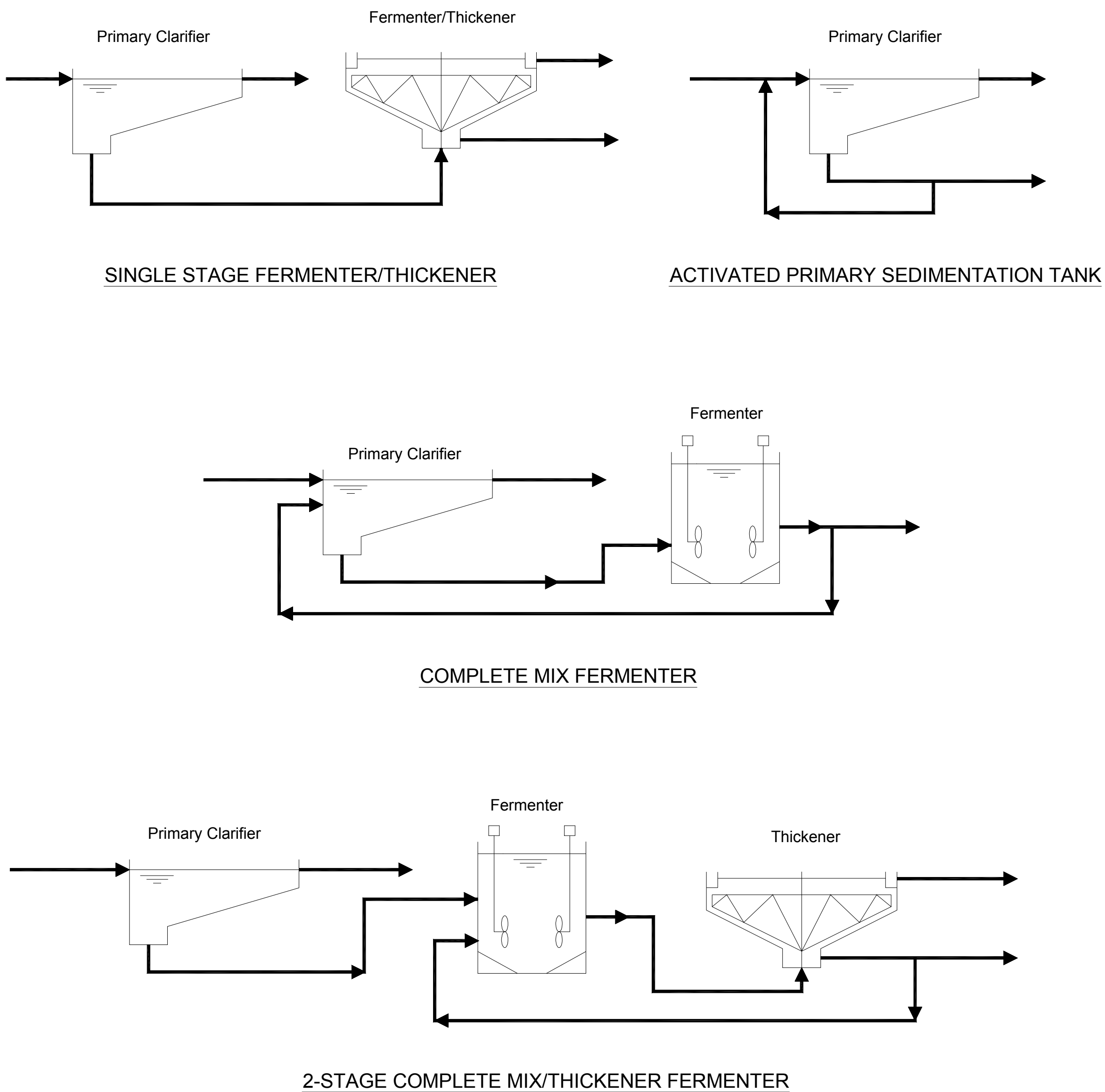
BIOLOGICAL NITROGEN REMOVAL PROCESSES

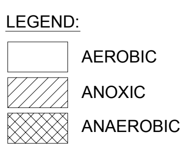
Figure 5.1



BIOLOGICAL PHOSPHORUS REMOVAL PROCESSES

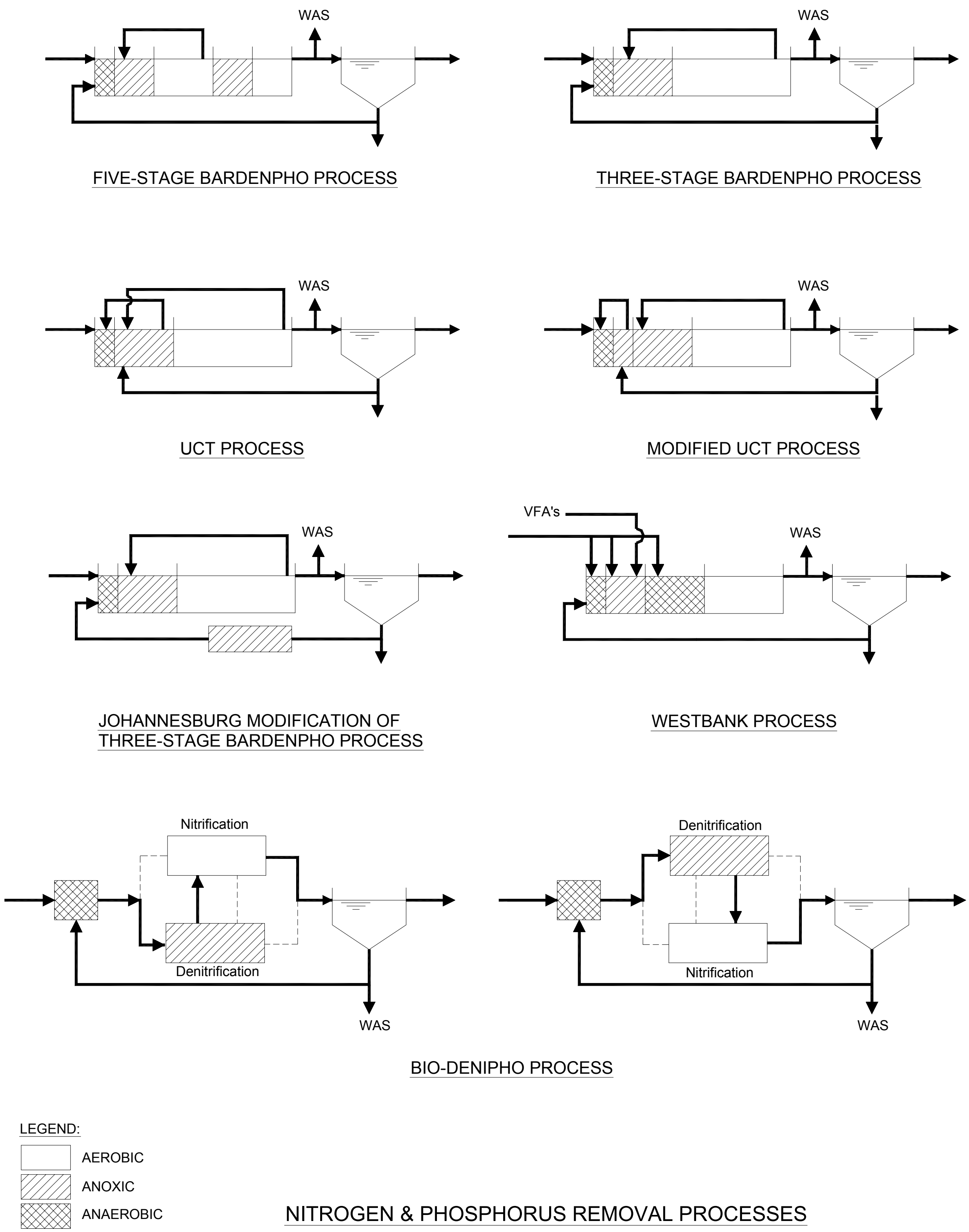
Figure 5.2





PRIMARY SLUDGE FERMENTER CONFIGURATIONS

Figure 5.3



NITROGEN & PHOSPHORUS REMOVAL PROCESSES

Figure 5.4