CIE4485
Wastewater Treatment

Dr.ir. Tommaso Lotti

2. New perspective for N removal: The anammox process

TU Delft

New perspective for N removal: the anammox process

CITG TU-Delft

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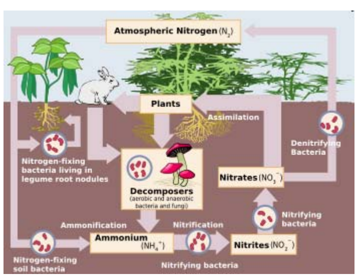
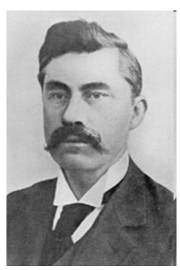
Sergei Winogradski
1856-1953

Nitrogen Cycle

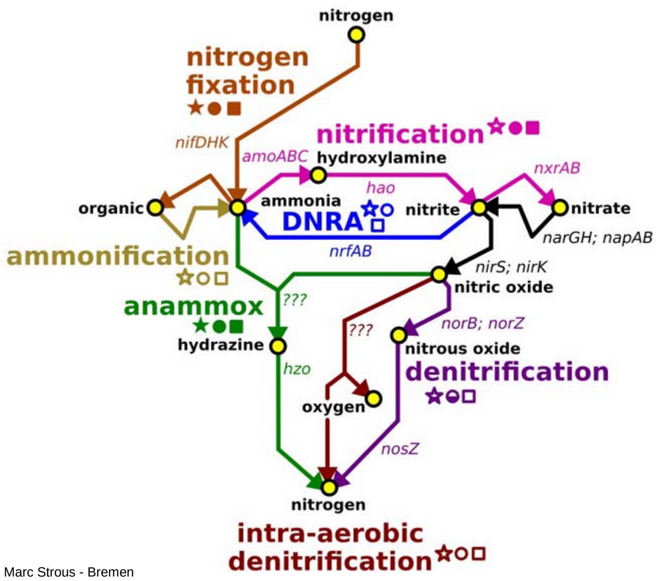
- 1880: Winogradski - Zurich
  - ➔ Nitrifying bacteria
- ± 1900: Beijerinck - Delft
  - ➔ Denitrifying bacteria
  - ➔ Nitrogen fixing bacteria



Martinus Willem Beijerinck
1951-1931



Nitrogen cycle has become a Nitrogen Web



Anammox history

- 60s to 80s

Regular reports of “unexpected nitrogen loss”

Usually interpreted as: Nitrogen removal by nitrifiers or aerobic deammonification

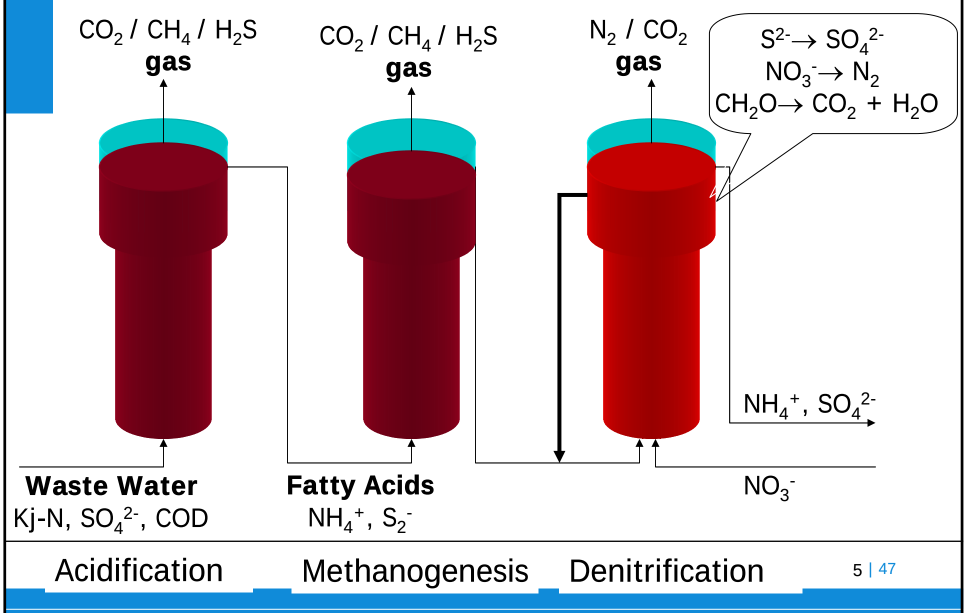
Likely often due to diffusion limitation and Anammox Bacteria

- 80s: Pilot at Gist brocades Delft with “unexpected nitrogen loss”

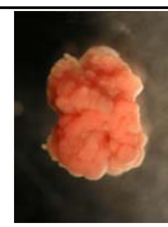
Arnold Mulder/Gijs Kuenen: must be different organism

- 90s: Recognition of Anammox bacteria made Anammox processes possible to design and reliable operate

Origin of Anammox – Pilot Gist-brocades



Anammox



ANaerobic AMMonium OXidation

Predicted in 1979 (based on thermodynamics + evolution)

Discovered by Mulder/Kuenen in 1988/1995 in Delft

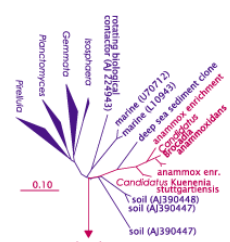
Order: Planctomycetales

Characteristic feature: internal compartment, ladderanes

Genetic Diversity:

-*Brocadia*, *Kuenenia* (fresh water: several WWTP's)

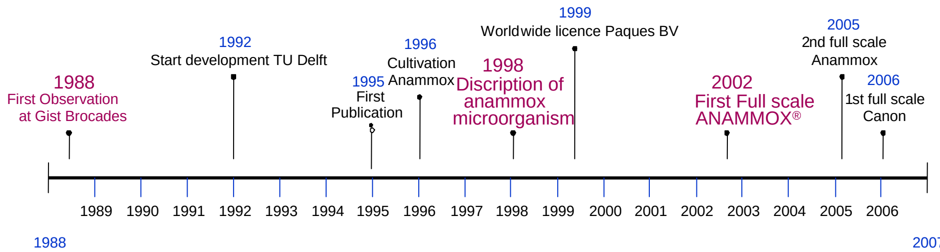
-*Scalindua* (marine conditions: Black sea, Golfo dulce)

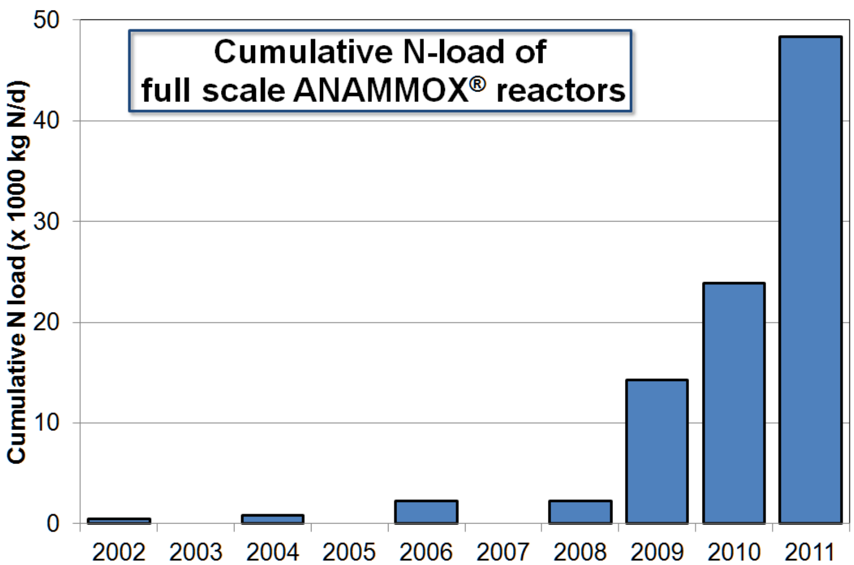


Autotrophic (CO_2 as carbon source, extremely low growth rate)

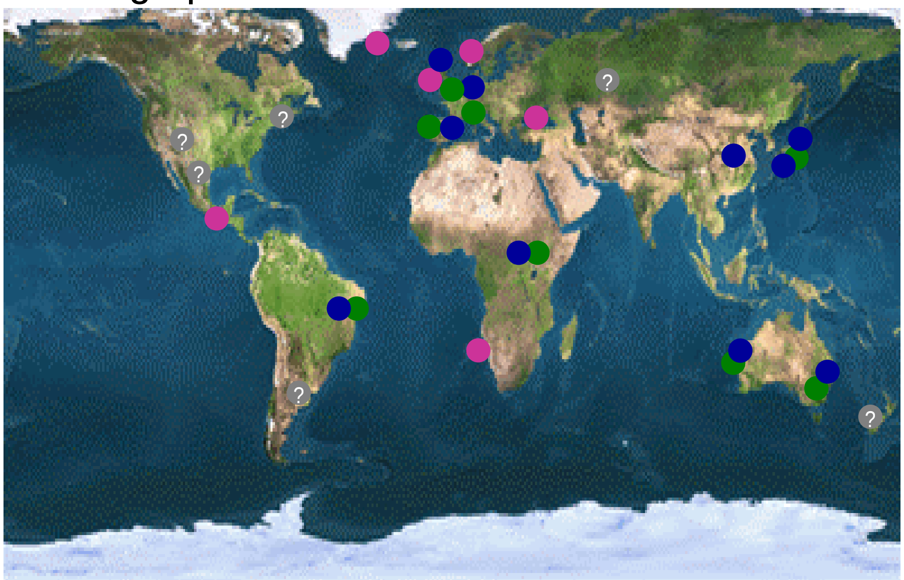
Minimal doubling time = 1 week

HISTORY AND STATUS ANAMMOX - 2007



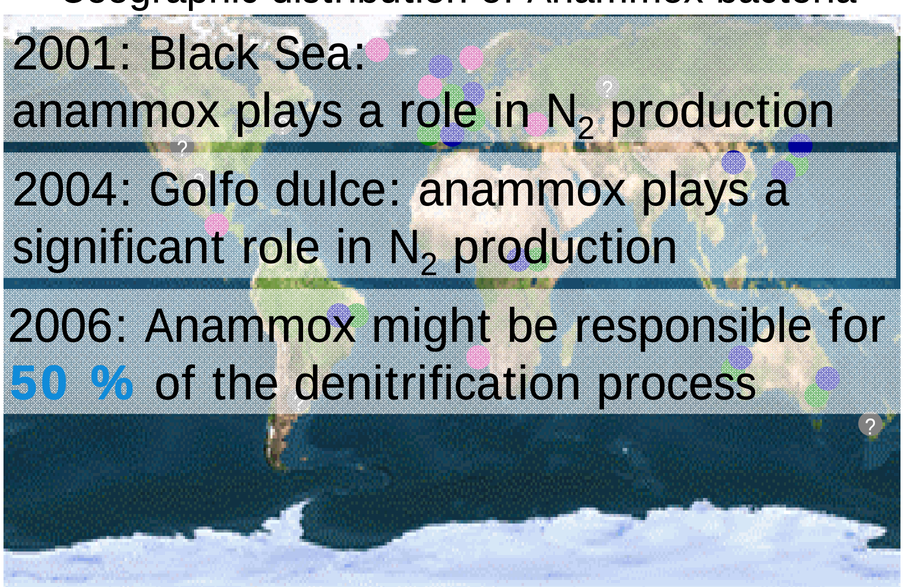


Geographic distribution of Anammox bacteria



Not confirmed “Kuenenia” “Brocadia” “Scalindua”

Geographic distribution of Anammox bacteria



Not confirmed “Kuenenia” “Brocadia” “Scalindua”

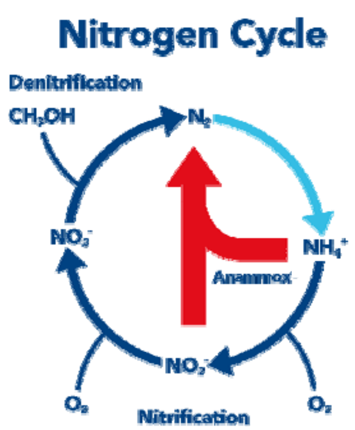
GROWTH STOICHIOMETRY

Catabolism: $NH_4^+ + NO_2^- \rightarrow N_2 + 2\ H_2O$
Anabolism: $CO_2 + 2\ NO_2^- \rightarrow CH_2O + 2\ NO_3^-$

$$\mathbf{NH_4^+ + 1.3\ NO_2^- + 0.066\ HCO_3^- + 0.15\ H^+ \rightarrow}$$
$$\mathbf{1\ N_2 + 0.3\ NO_3^- + 2\ H_2O + \quad 0.066\ CH_2O_{0,5}N_{0,15}}$$

Nitrate Production is Measure for Growth

ANAMMOX PRINCIPLE



Short cut in N-removal

Less Oxygen ➔ less Energy
No Organic Carbon ➔ more Biogas

BUT:
Need for preventing nitrite (NO_2^-) oxidation

Very slow growing organism
(approx. 10 times slower)
➔ Need for good biomass retention

CONVENTIONAL AMMONIUM REMOVAL

Nitrification: $2\ NH_3 + (3+1)\ O_2 \rightarrow 2\ NO_3^- + 2\ H^+ + 2\ H_2O$

Denitrification: $2\ NO_3^- + 8g\ COD + 2\ H^+ \rightarrow N_2 + 3g\ SLUDGE$

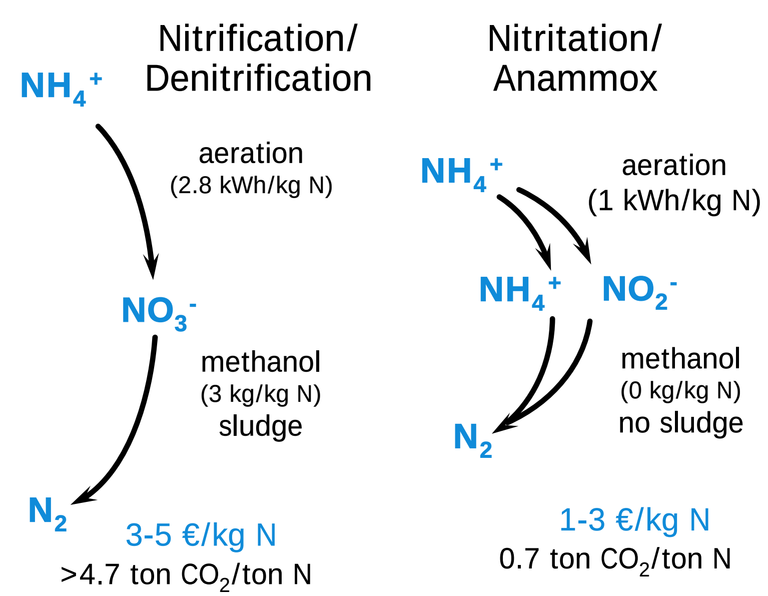
➡ $2\ NH_3^- + 4\ O_2 + 8g\ COD \rightarrow N_2 + 3g\ SLUDGE$

AUTOTROPHIC AMMONIUM REMOVAL

Nitritation: $NH_3 + 1.5\ O_2 \rightarrow NO_2^- + H^+ + H_2O$

Anammox: $NO_2^- + NH_3 + H^+ \rightarrow N_2 + 2\ H_2O$

➡ $2\ NH_3^- + 1.5\ O_2 \rightarrow N_2$



Why Nitrogen Removal?
Eutrophication

- Bad Water
- Smell
- Toxic compounds
- Danger for drinking water




GENERAL PROBLEM for WATER TREATMENT:

Increasing standards for nutrient removal

POTENTIAL SOLUTION:

Treatment of NUTRIENTS in flows from SLUDGE TREATMENT (side stream)

→ 10-30% of N-load (in a small flow)

NITROGEN REMOVAL IN SIDE STREAMS

SIDE STREAM CHARACTERISTICS:

HIGH concentration → SMALL tank volume

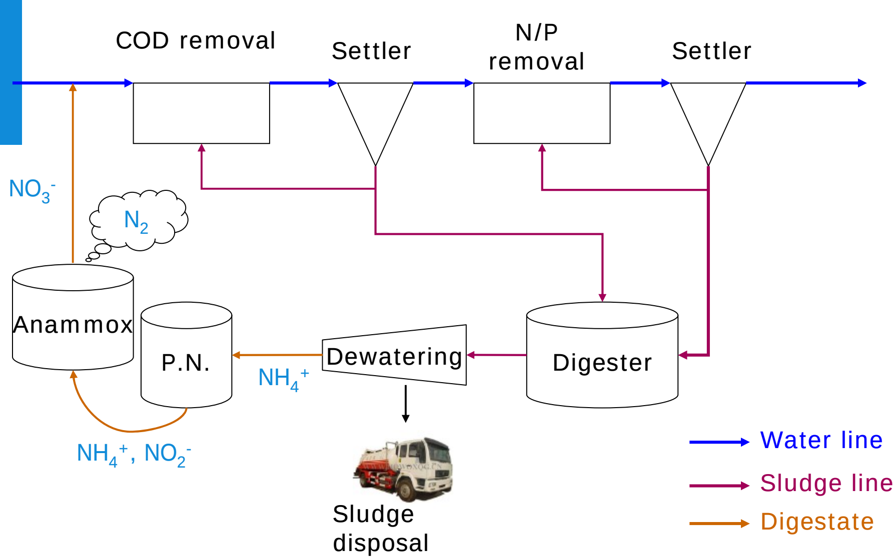
HIGH temperature → SHORT SRT possible

No absolute need for good effluent

POTENTIALITY:

→ Remove Nitrogen in compact reactor

APPLICATION IN SIDE STREAM TREATMENT

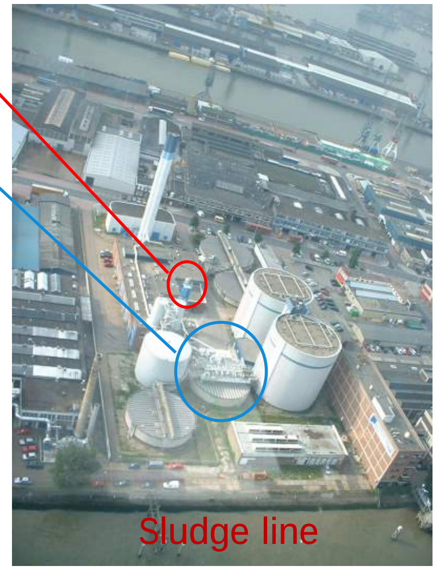


Sluisjesdijk-Dokhaven, Rotterdam

2-stage system
- ANAMMOX
- PARTIAL NITRITATION

Water line

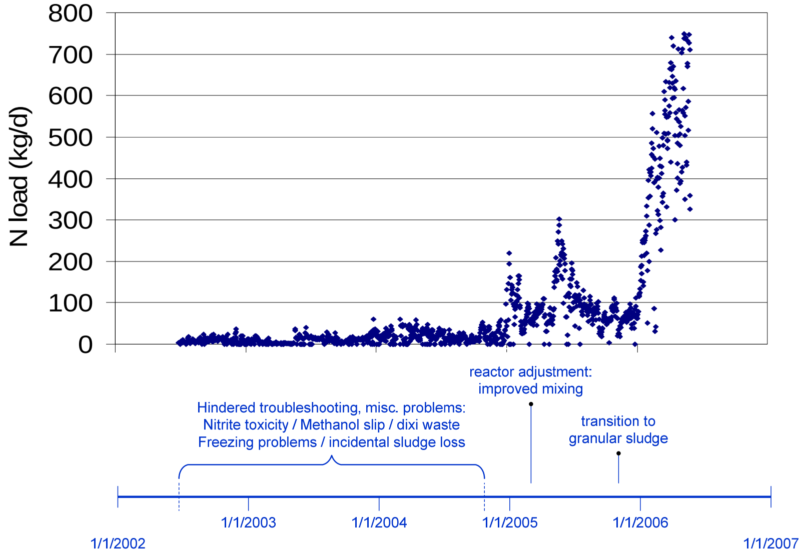
Sludge line



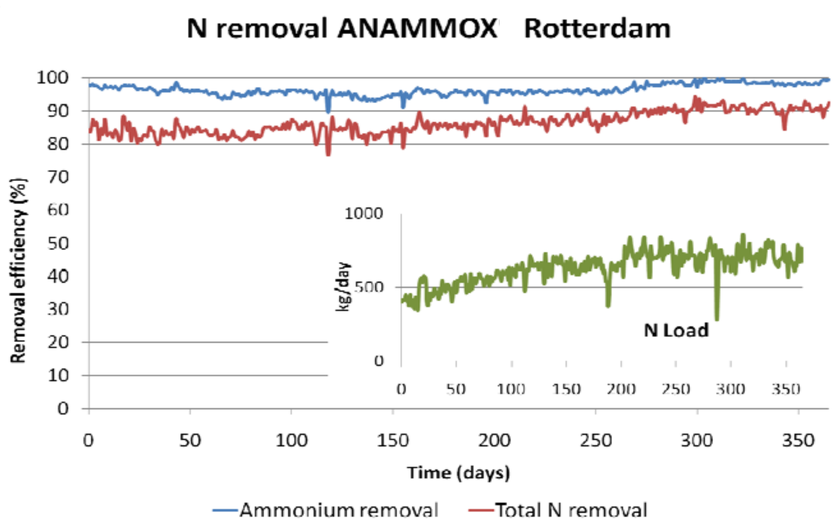
Anammox® Scale-up

- First application in IC®-reactor ➔ Known
- No sludge available
- Cost of pilot operation relatively high
- Decided to build directly full scale (from 15 litres to 70 m^3)

Sluisjesdijk-Dokhaven, Rotterdam



Sluisjesdijk-Dokhaven, Rotterdam



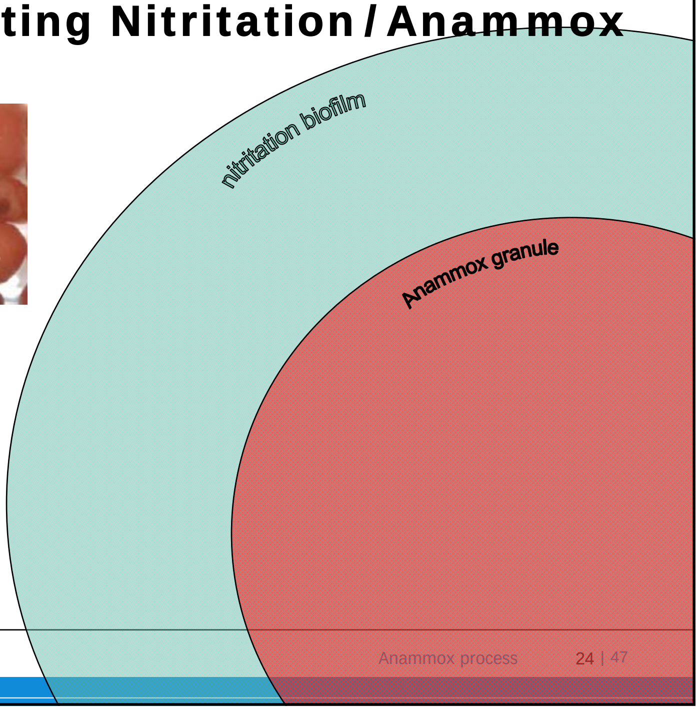
Sluisjesdijk-Dokhaven, Rotterdam

Stable operation since early 2006

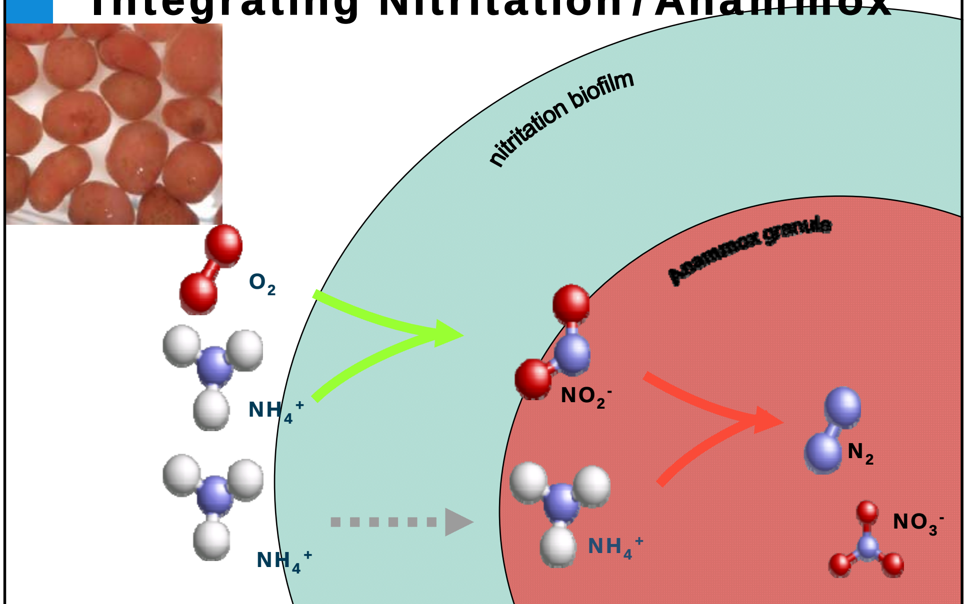
7 kgN/m^3.day
800 kg/day

Integrating Nitritation / Anammox

1 mm



Integrating Nitritation / Anammox



$2\ NH_3 + 1.7\ O_2 \rightarrow 1.14\ NO_2^- + 0.86\ NH_3 \rightarrow 0.88\ N_2 + 0.24\ NO_3$

One Reactor Anammox systems

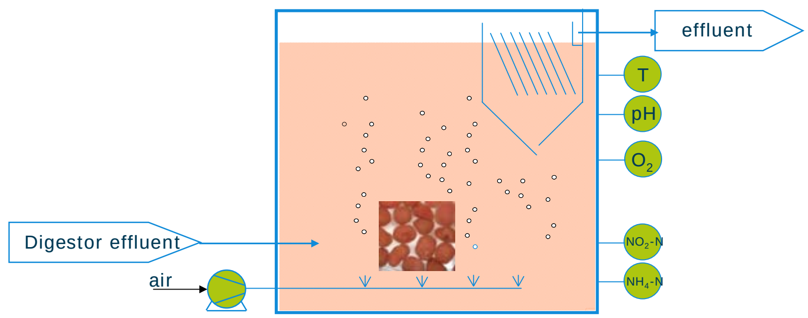
(1-stage partial nitritation-anammox)

Essentially based on UASB technology with:
- Fine bubble aeration
- Simple tilted plate settlers (TPS)
- No need for influent distribution

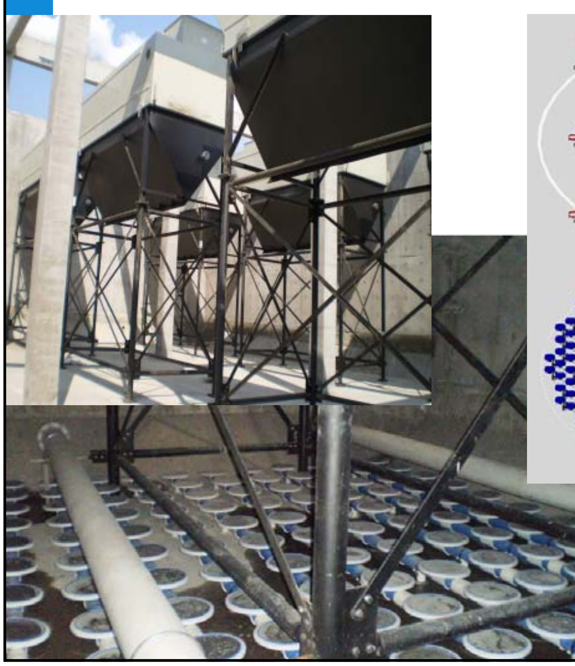
Process control based on:
- Measurement of Ammonium
- Influencing DO by variable aeration

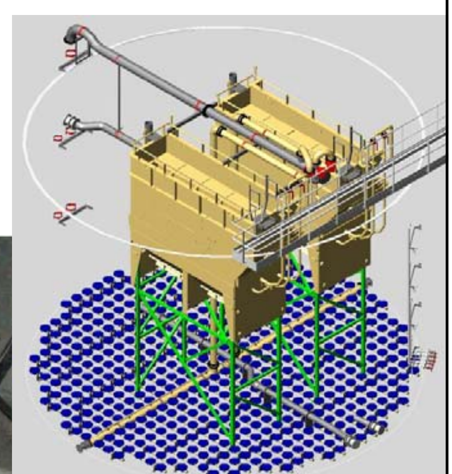
Anammox granular sludge reactor

Spec. volume load: 2 kg N/m³/d
TSS: 10 kg ds/m³



Impression of the internals



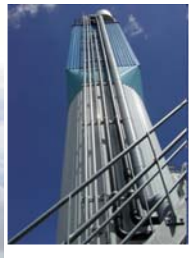


2 different configurations applied

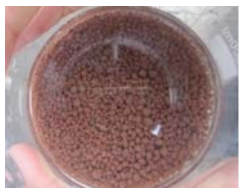
for partial nitritation - anammox

divided in 2 reactor

all in one single reactor

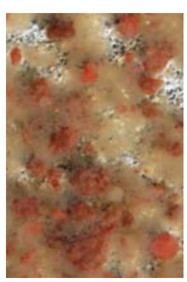



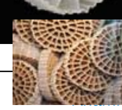

different biomass



Current Anammox Based Technologies Implemented at Full Scale

- Flocculent - SBR (Switzerland, EAWAG)
- Flocs/Granular (Austria, Bernard Wett)
- Biofilm on carrier - MBBR (Sweden, Anox-Kaldness; AnitaMOX, Veolia; DeAmmon Purac)
- Granular (Netherlands/China, Paques)


Which to chose ???

2-stage (2 distinct reactors):

• the partial nitritation and the anammox step can be optimized individually, including nitratation suppression in the first stage

• lower risk for anammox to be overgrown by heterotrophs

• smaller inoculum needed

• no risk for oxygen inhibition

1-stage (only 1 reactor):

• investment costs are significantly lower

• the process control is less complex

• lower risk for nitrite inhibition

• less N_2O emissions: 0.4-1.3 vs 2.3-6.6% of N-load

Flocs or biofilm (granules) ???

- Sludge water: Suspended COD
  ➔ Biofilm or Granular sludge to prevent accumulation of inert sludge
- Oxygen Control
  ➔ Biofilm or Granular Sludge allow higher DO (1 mgO_2/l) and continuous aeration (cost of aeration equipment)
- Volume
  ➔ Granular sludge allows more compact reactor design
  Pure Anammox > 10 kgN/m3.day
  Nitritation/Anammox ~ 3 - 4 kgN/m2.day
- Start-up
  ➔ Granular Sludge/Carriers – longer startup from scratch but easier to transport/long life time

	FLOCCULENT	BIOFILM
Biomass Retention	-	+
Reactor Volume	-	+
Process Stability (COD, solids)	-	+
Startup	+	+ -

Recent Startup in China

Largest load: 11 ton N/d

Volume:
6700 m^3

Load:
1.7 $kgN/m^3.day$

Startup time:
1 month
(95% conversion)

16 ANAMMOX® references - spring 2012

STW Rotterdam	(NL)	700	kg N/d
Semiconductor Industry	(JP)	220	kg N/d
Tannery	(NL)	325	kg N/d
STW Switzerland	(CH)	60	kg N/d
STW Olburgen	(NL)	1200	kg N/d
Yeast Industry	(CN)	1000	kg N/d
Fermentation Industry	(CN)	11000	kg N/d
Fermentation Industry	(CN)	9000	kg N/d
Fermentation Industry	(CN)	10700	kg N/d
Yeast Industry	(CN)	7000	kg N/d
Distillery	(PL)	1200	kg N/d
STW Zwolle	(NL)	660	kg N/d */**
Food Industry	(CN)	2200	kg N/d **
Food Industry	(CN)	6100	kg N/d **
STW Minworth	(UK)	4000	kg N/d **
Winery	(CN)	900	kg N/d

* Conversion of existing Sharon into One Step Anammox

Side Stream Treatment - last note

Usually only 10-15 % of total N-load
➔More measures needed to really improve effluent concentration

- WWTP optimization:
  - Improve COD removal by precipitation/flocculation
  - Effluent recycle for extra denitrification
  - Better sludge thickening

➔ Increased N-load to side stream treatment

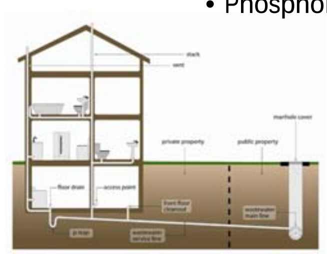
Is this all anammox can do ??

New frontier: anammox in the main-stream

Conventional Municipal WWTP

Main pollutants

- Organic matter
- Nitrogen
- Phosphorus



Conventional Municipal WWTP

WATER LINE

Organic matter:

$C + O_2 \rightarrow CO_2$ (Activated sludge)

Nitrogen:

$N + O_2 \rightarrow NO_3$ (Nitrification)

$NO_3 + COD \rightarrow N_2$ (Denitrification)

Phosphorus:

P-incorporated in biomass → Sludge disposal (P-removal)

SLUDGE LINE

Primary settler + Excess biomass (sludge) → $CH_4 + CO_2$ (Anaerobic Digestion)

Conventional Municipal WWTP

..different approach..

Organic carbon in wastewater = chemical energy

⇓

Maximize the yield of the COD removal process to maximize biogas production

(i.e. A-stage in A-B concept)

Benefits:

- higher methane production
- less oxygen consumption
- less CO_2 emissions

Conventional Municipal WWTP

Organic carbon in wastewater = energy (biogas)

⇓

Maximize the yield of the COD removal process to maximize biogas production

Drawbacks:

- no COD left for Denitrification → N-pollution problem or high N-removal costs

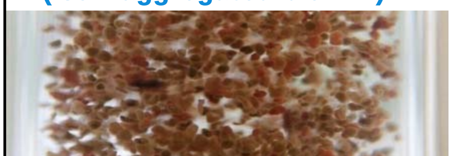
⇓

Autotrophic nitrogen removal !!!

Anammox process in the side-stream

TU-Delft proposal

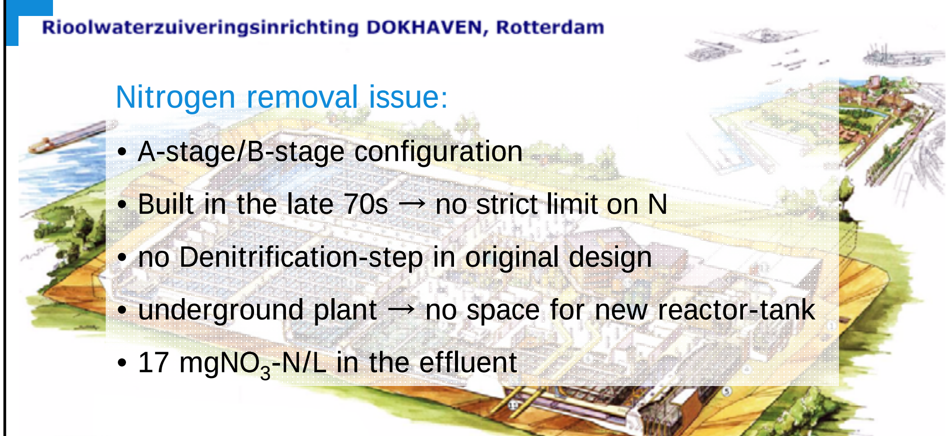
- CANON with Granular Sludge
  (self-aggregated biofilm)



- High volumetric rates
- Biomass retention at short HRT
- Low maintenance operation
- No complex process control
- No prone to nitrite inhibition
- No prone to solids/COD shock-loads
- Integrated settler

Anammox process in the main-stream

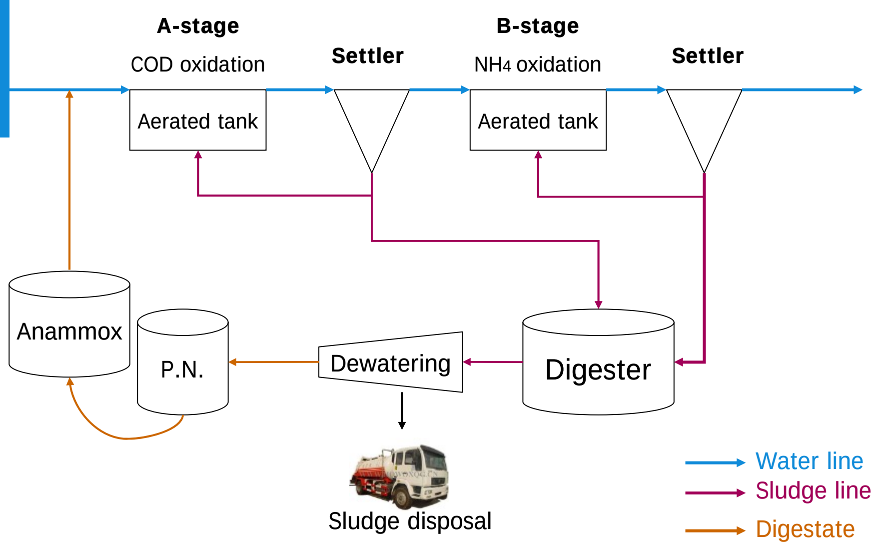
case study: Dokhaven WWTP, Rotterdam (620000 p.e.)



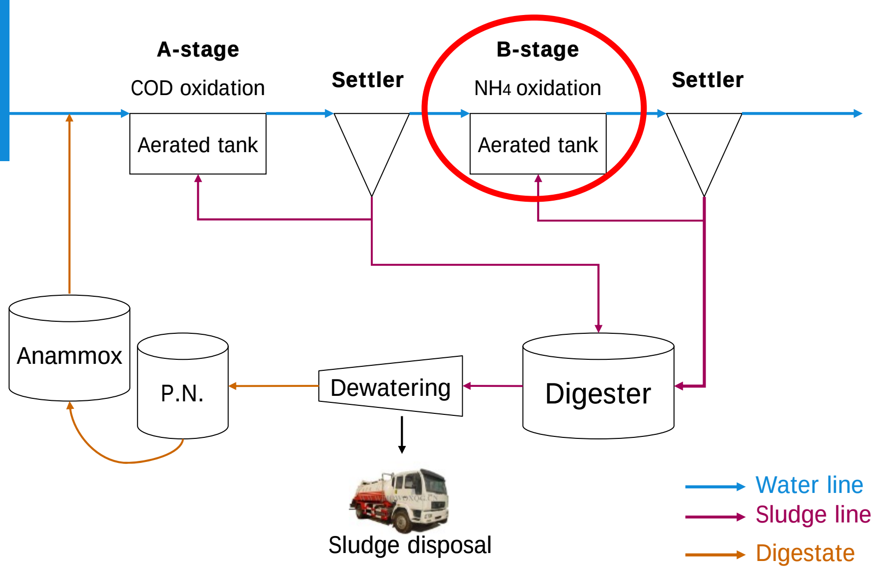
Nitrogen removal issue:

- A-stage/B-stage configuration
- Built in the late 70s → no strict limit on N
- no Denitrification-step in original design
- underground plant → no space for new reactor-tank
- 17 mgNO_3-N/L in the effluent

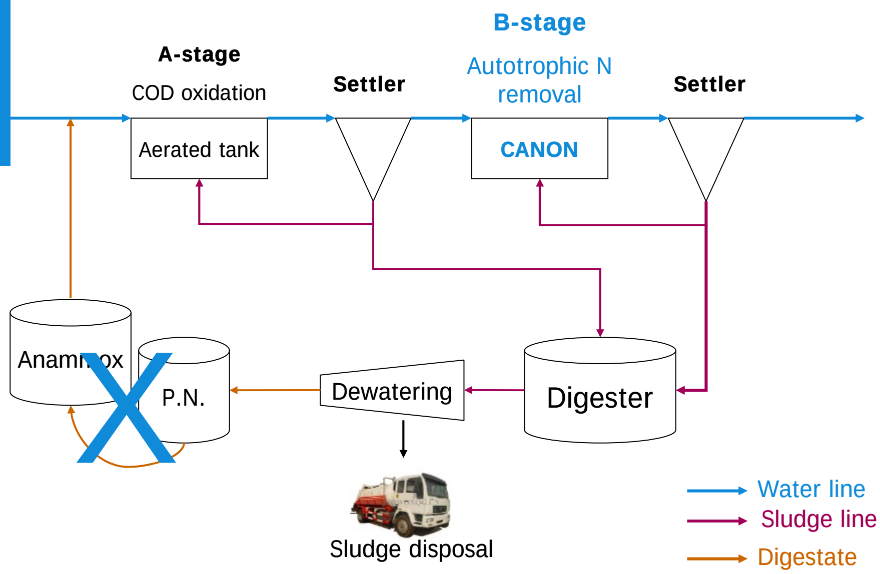
Anammox process in the main-stream



Anammox process in the main-stream



Anammox process in the main-stream



NET ENERGY (calculations)

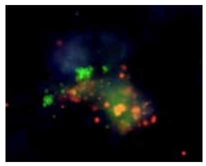
Conventional Treatment

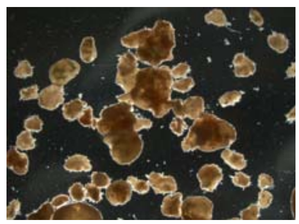
-44 Wh p-1 d-1

Optimized treatment with anammox in the main-stream

+24 Wh p-1 d-1

...on going research...





ANAMMOX, take-home message

- Fully developed technology
- Several Suppliers
- Applied on a wide scale of wastewaters
- Focus on Main Stream Applications

Once upon a time ...
... it was
nitification/denitrification

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