**Model based evaluation of plant improvement at a large wastewater treatment
plants (WWTP)**

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Abstract

In this work, the effect of the improvement carried out at a large-scale wastewater treatment plants (WWTP) was evaluated, by means of modelling works, with the aim to determine the influence of the modernization over the process performance. After modernization, the energy consumption due to the aeration decreased about a 20% maintaining the effluent quality. In order to double-check the good effluent quality, modelling works were carried out at the full-scale plant. After calibration, the model was applied to the upgraded full-scale plant obtaining deviations lower than 10%. Then, the performance of the main biochemical processes was evaluated in terms of oxygen uptake rate (OUR), ammonia uptake rate (AUR) and Chemical Oxygen Demand (COD) consumption. The rate of the main processes depending on the aeration, that is OUR and AUR, were about 22 gO₂/(kg VSS·h) and 2.9 gN/(kg VSS·h) respectively.

Keywords: Activated sludge; Aeration; Modelling; Wastewater Treatment plant.

Introduction

The Polish National Program for Municipal Wastewater Treatment Plants (WWTP) aims to identify and to solve wastewater treatment and management problems. During the last years, this project has performed modernization or expansion of about 600 wastewater treatment plants and construction of nearly 200 new facilities, with a total population equivalent (PE) representing almost 97% of the total PE of the Polish National Program for Municipal WWTP. In these facilities, in order to achieve the quality standards defined by the European Union (EU) regulations, an intense process development has been required.

Currently, a large number of the Polish WWTPs use activated sludge systems with integrated carbon, nitrogen and phosphorus removal.^[1] In these circumstances, effective use of biodegradable substrates as an internal carbon sources for denitrification and enhanced biological phosphorus removal as well as optimizing the performance of aeration systems in bioreactors, may be useful for saving energy at WWTPs.^[2-4] In this situation, the aeration control in the bioreactors is very important, because it is one of the most energy-consuming processes in the wastewater treatment.^[5] The energy consumption in the aeration systems usually ranged 50% to 90% of the total electricity consumed by the WWTP (depending on size and technological solutions of plant), which corresponds to 15-40% of the total costs in the wastewater treatment budget.^[6, 7]

Challenges with optimization of aeration systems and ongoing process in the bioreactors of the WWTP's mainly depends on the complexity of the process and on the impact of various factors such as the process stability, treatment efficiency, etc.^[8]

In the literature, modelling of activated sludge WWTP has been used for different purposes such as evaluation of emissions, process design and control, ^[9-12] optimization ^[13; 14] and evaluation of process upgrades. ^[15-17]

In this context, the aim of this work was to evaluate the performance of a large WWTP after a modernization, paying special attention to both, the effluent quality and the energy consumption by the aeration systems. To do that, a modelling strategy has been used. With this aim, batch tests data, as well as additional data from the full-scale plant (such as inflow, quality of influent/effluent, actual parameter variations in bioreactor etc.), were used as experimental database for model predictions. The model used was ASM2d, ^[18] because this model deals with the biological carbon, nitrogen and phosphorus removal. Once modelled, the performance of the WWTP was ratified in terms of COD, ammonia and phosphorus removal and in terms of energy consumption for aeration.

Material and methods

Process Configuration and Control System

The Debogorze WWTP is one of the largest facilities in Poland. This WWTP treats wastewater originated from the city of Gdynia and adjacent communities, the average influent flow rate to the plant is about 65,000 m³/d and the maximum value about 90,000 m³/d corresponding the pollutant load to about 600,000 population equivalent. Until the beginning of the 90's, the plant only provided mechanical treatment. The first biological step, consisting on a two-stage activated sludge process, was implemented in 1994, but even after this modification the effluent quality did not meet the former Polish standards. On 2004, after the adhesion to UE, biological nutrient removal was

implemented in the WWTP. From 2009, after several expansions and modernizations, the treatment line consisted of four parallel bioreactors running in the Johannesburg (JHB) process. The new biological reactors were designed with simultaneous nitrification-denitrification and biological phosphorus removal in a carrousel system. The total volume of a single bioreactor line is 12,000 m³, being the volume corresponding to the aerobic zone about 4,625 m³. A schematic layout of the bioreactor, including information about the compartment volumes and on-line instruments locations, is presented in Figure 1.

[FIGURE 1 NEAR HERE]

Additionally, the WWTP Debogorze is equipped with a brand new automation system and computer control. In this system, information from field controllers and probes are on-line sent to the central control room. The computer network includes all the instrumentation system, which consist of 21 field controllers and operator stations SCADA 4. Each controller supports one separate area of technology and are located at different points of the plant.

Full-scale and laboratory experimental data

Full-scale data

In order to evaluate the performance of the WWTP, operational data were collected during about 3 months within fall and 2 months within spring seasons. Average daily time-

proportional samples of the influent wastewater, after mechanical treatment, were collected and analysed. Operating parameters were measured in the bioreactors including the mixed liquor volatile suspended solids (MLVSS) and the mixed liquor suspended solids (MLSS) concentrations, process temperature and dissolved oxygen (DO) concentrations in all the aerobic compartment. From these measurements calculable parameters such as solids retention time (SRT) were determined. The DO was measured by means of DO probes. The temperature was measured by means of Pt 1000 ohm RTD temperature element located at the DO and ORP probes. These measurements were recorded based on one-hour intervals similar to the flow rates (influent flow rate, internal recycles and return activated sludge flow rate Total suspended solids (TSS) and volatile suspended solids (VSS) parameters as well as MLSS and MLVSS in the full-scale JHB bioreactor were analysed in accordance with Standards Methods. ^[19]

Additional data sets (e.g. NH₄-N, NH₃-N, pH, ORP) were collected in order to reduce the uncertainty around the main processes. These data were taken on-line from each of the 10 processes lines of WWTP "Debogorze" by the new computer system: these analyses were carried out by using an automatic analyzer provided by Hach Lange GmbH:

1. NH₄-N/NH₃-N probe, AMTAX/NITRATAX (reagent analyzers) together with the probe filter, type: LXG421/LXG417,
2. DO concentration in each of the three oxygen sections at each bioreactor was measured on-line by using a luminescent dissolved oxygen probe.
3. pH and ORP were on-line measured by using pH and ORP probes supplied by Hach-Lange.

More details about the wastewater characteristics and operating conditions of the WWTP during the period of study, including Return Activated Sludge (RAS) and Volatile Fatty Acids (VFA) concentrations, are presented in Table 1.

[TABLE 1 NEAR HERE]

Laboratory tests

Laboratory test were performed in order to calibrate the main processes (COD, phosphorus and nitrogen removal) taking place in the Debogorze WWTP. To do that, aerobic, anoxic and anaerobic laboratory batch tests were performed with settled wastewater (SWW) and activated sludge from the Debogorze WWTP. These tests were carried out in experimental set-up consisting of batch reactors, volume of 4.0 dm³, equipped with control systems. The control system maintained the DO concentration around the set-point. The DO set-point was about 2 g O₂/m³, except in the last aerobic compartment which operate at 4 g/m³ in order to avoid denitrification in the secondary settler and therefore to avoid the undesirable flotation of the sludge due to the nitrogen gas generated. The temperature ranged between 15.4-17.8 °C depending on the season of the year.

In order to accurately study the aeration requirements, the heterotrophic and the autotrophic bacterial respiratory activity were isolated and determined, by adding alil thiourea (ATU) as nitrification inhibitor. The nitrifying experiments were performed under anaerobic-aerobic conditions (two stage batch test) which better reflected the actual conditions occurring in the activated sludge bioreactors of the full-scale WWTP. Each experimental series, fall and spring seasons, comprised both types of batch tests

including measurements (e.g. OUR, AUR and COD). Moreover, several parameters (pH, Temperature and ORP) were determined and recorded by using probes installed in the batch reactor and connected to the computer. Additionally, the total/soluble COD, NO₃-N, NH₄-N and PO₄-P were analysed by Hach “test-in-tube” using Xion 500 spectrophotometer (Hach Lange GmbH, Germany). The Total Nitrogen (TN) concentrations were measured using TOC/TN analyser (SHIMADZU Corporation, Japan). All the chemical analyses, which were adapted by Hach Lange GmbH (Germany), and the gravimetrical procedures were performed in accordance with Standard Methods. ^[19]

Model Description

Data sets obtained in the full-scale WWTP were used for steady-state simulations in the software GPS-X ver. 5.0.2. The mathematical modelling was based on the ASM2d Model. ^[18] In order to carry out an accurate calibration data sets from the full-scale WWTP and from the laboratory batch tests were used. The stoichiometric and kinetic parameters were determined by numerical optimization using the Nelder-Mead simplex method. ^[20] Regarding to the oxygen consumption, the combination of one stage batch (OUR and corresponding COD consumption) and two stages batch tests (AUR/OUR and corresponding COD consumption) were carried out and the consumption of oxygen, biodegradable substrates, ammonia and phosphorus as well as the conditions of activated sludge were determined. Once calibrated and validated the model, the GPS-X platform was further used in order to evaluate the performance of the Debogorze WWTP.

Results and discussion

Energy Consumption at Debogorze WWTP

As stated previously, the energy consumption by aerators is one of the largest share of total energy consumption at WWTPs. Because of that, in the modifications and expansions carried out at the full-scale WWTP, the aeration system was modified including more flexible devices, elimination over-aeration periods and a more robust operation of the whole system. Figure 2a presents the oxygen and ammonia concentration as well as the flow thru the aeration blowers, section 2b presents the specific energy consumption of the blowers. Sample results presented in this paper correspond to 2 working days of operation with the air blowers supplying the required level of oxygen, this level was determined by the control system. As can be seen in Figure 2a the oxygen concentration in the bioreactor ranged from 1.5 to 2.5 mg/dm³. In Figure 2b, the energy consumption in the aeration process is presented. As can be seen in this figure, despite of the increase in capacity of the biological reactors due to the expansion of the plant, 2.5 times bigger, the energy consumption used for aeration in the modernized plant decreased from 0.53 kWh/m³ to 0.42 kWh/m³, which represents about a 20% of energy savings.

[FIGURE 2 NEAR HERE]

From the obtained results, it must be highlighted that the novel aeration system contributed to significant savings, ensuring at the same time an effluent quality fulfilling

the legal requirements as indicated by the daily analyses performed at the WWTP. Additionally, it must be remarked that, after the expansion of the WWTP, the EU requirements for the effluent were much lower because the Debogorze plant became a large WWTP. From the data obtained in the full-scale WWTP, the very good performance was ratified. Anyway, it was necessary to verify the good condition of the activated sludge. To do that, the main biochemical processes carried out by the activated sludge were studied by means of modelling and simulation works.

Debogorze WWTP Modelling

Because of the complexity of the ASM models, extensive calibration and validation procedures were applied. The main kinetic and stoichiometric parameters were determined from the full and the lab-scale tests. The initial approximations of the stoichiometric and kinetic values obtained in the tests were adjusted so that the predictions of the model accurately agree with the actual data. To do that, the value of the parameters were modified with aim to minimize the errors with actual results. [21] The values of the less sensitive parameters were taken from data reported in the literature. [18]

OUR and AUR determination

The OUR and AUR were determined to evaluate the performance of the WWTP and to serve as initial approximations in the calibration stage. Sample results of the one and two-stage batch tests and model predictions of processes AUR/OUR and COD

utilization as well as additional on-line data (Temperature, pH, ORP, DO) are presented in Figures 3 and 4. Additionally, for the sake of clarity, OURs and AURs specific rates obtained in the tests performed in this study, as well as reference values from the literature, are presented in Table 2 and 3. The obtained results in both studies, the one and the two stage batch tests, are discussed above.

i) One stage aerobic “OUR” batch test

The OUR measurements were performed during one stage aerobic batch test every 3 minutes, until a stable profile at the lowest level (related to the hydrolysis and endogenous respiration) was achieved (Figure 3a). The area under the OUR profile is an accurate measurement of the level of biodegradable substrate utilized during the course of the test but also of the oxygen requirements. ^[22] According to activated sludge model definition, the first plateau of OUR measurement (during the first 10 min.) corresponded to the degradation of readily biodegradable COD (RBCOD). The second OUR level (from 35 to 45 min.) corresponded to the degradation of rapidly hydrolysable COD and, finally, the last plateau (from 1 to 6 h) corresponded to the degradation of slowly biodegradable organic compounds (SBCOD). In these tests, the pH and ORP values (Figure 3b) were stabilized around 7.5 and 60 mV respectively.

[FIGURE 3 NEAR HERE]

The diagrams of OUR values provided an accurate indication of the biological activity of microorganisms during consumption of biodegradable organic substrates in all tested samples during one-stage aerobic batch test. The average values of OUR ranged between 18.4-22.4 and 18.3-25.3 g O₂/(kg VSS·h) during fall and spring season respectively, see Table 2. These results indicate that the activated sludge was in very

good conditions. For comparison, values reported in the literature ^[23] for the OUR experiments with real wastewater and activated sludge from a pilot and full-scale plants ranged from 20 to 22-53 g O₂/kgVSS·h, respectively. In another study, ^[24] demonstrated that hydrolysis of primary sludge can produce a broad range of RBCOD as internal carbon source (ICS). The authors concluded on the observation that OURs with hydrolysate (a liquid phase of the anaerobically hydrolysed primary sludge) as a carbon source were typically 10-20% higher compared to the OURs with acetate. Moreover, it has been reported in the literature ^[25] that particulate COD contributed to the increase of total OUR (including nitrification) by approximately 5.5% when the particulate COD constituted 65% of total COD (50% of the particulate fraction was estimated to be biodegradable). As can be seen, the OUR obtained with sludge from the Debogorze WWTP was in the upper values, indicating the very good conditions of its activated sludge.

[TABLE 2 NEAR HERE]

ii) Two-stage anaerobic-aerobic “AUR/OUR” batch test

In the two-stage anaerobic-aerobic batch experiments, the AUR/OUR single processes as well as the COD removal associated with the consumption of the biodegradable substrates and phosphorous removal were studied. The results obtained are presented in Figure 4 and in Table 3. As a reference for comparison, Table 3 presents AURs values reported in the literature at lab-scale anaerobic-aerobic Sequencing Batch Reactors (SBRs) fed with different substrates and at full-scale WWTP. These experiments reflect, better than the one-stage OUR batch test, the actual conditions occurring in full-scale

Debogorze WWTP. This is because in the full-scale WWTP the aerobic phase follow after the anaerobic one.

[FIGURE 4 NEAR HERE]

The AUR values obtained from the fitting of the experimental results obtained to the model varied within the range 2.7-3.1 and 2.7-2.9 mg N/(g VSS·h) during the fall and spring season, respectively. These AUR values were lower than those reported in literature ^[29; 32; 33]. However, it must be noted that in these works, more readily biodegradable substrates, such as acetate, was fed. The AUR values obtained in this work were similar to results reported in the literature when feeding comparable influents, ^[34; 35] whereas smaller AUR values were reported in other publications. ^[33; 36] Moreover, the AURs measured by batch tests with the settled wastewater and biomass from Debogorze WWTP are comparable with the rates from two parallel lines of a full-scale WWTP in Italy ^[37] and the laboratory scale SBRs fed with mixtures of real wastewater without and/or with potato by-products addition. ^[29; 30]

[TABLE 3 NEAR HERE]

Regarding to these lab-scale experiments, it must be noted that very similar results, in case of the process kinetics of AUR and OUR, were obtained at the studied plant during both, the fall and spring seasons. This suggests that changes taking place during fall and spring seasons had minor effects on wastewater treatment processes in the studied plant. About the ORP and pH values, it must be remarked that the pH remained stabilized at about 7.2. However, the ORP values decreased from 120 mV until -240 mV due to the anaerobic conditions reached during the first stage of the process. Once the aerobic

conditions were reestablished, the ORP increased, reaching a steady-state value of about 50 mV, a value similar to that maintained when operating in the one-stage tests. With regard to the phosphorus removal, it can be seen in Figure 4a the typical behavior with initial COD storage and subsequent phosphorous removal. [8]

Remarks

Once finished the calibration stage, the model offered accurate predictions, being able to simulate the variations of the effluent concentrations. After calibration, the model was validated by comparing the actual results from unused data set with the model predictions obtained by the calibrated model. The average deviations between measured and calculated COD, ammonia and total phosphorus concentrations were always lower than 10%, which indicates that the calibrated parameters represents the Debogorze WWTP behavior without significant deviations. The main kinetic and stoichiometric parameters obtained are presented in Table 4.

The modelization has been used to evaluate the performance of the WWTP in terms of pollutants removal and energy consumption. As it was previously indicated, the Debogorze WWTP reduced the energy consumption significantly. However, as can be seen from the data presented in this paper, the performance of the process was high when compared with results reported in the literature. Because of that, it can be stated that the lower energy consumption does not affect neither the activated sludge conditions, nor the performance of the main biochemical processes, maintaining a high quality treated wastewater, which were confirmed by the measurements at studied full-scale plant.

[TABLE 4 NEAR HERE]

This study showed that the implementation of innovative solutions and the continuous modernization of the process reduced costs, while maintained high efficiency of the most energy-intensive processes. Because of that, the modernization of the Debogorze WWTP was carried out correctly.

Conclusions

From the results obtained in this work it can be concluded that the modernization of the Debogorze full-scale WWTP leads to a decrease of about 20% in the energy consumption due to the aeration system. When comparing the results obtained in the modelling works with data reported in literature it has been confirmed that reduction in the energy consumption did not affect the performance of the process. Regarding to the process performance it must be highlighted that the measurement of AUR/OUR processes and corresponding COD utilization showed good conditions of the activated sludge from Debogorze WWTP.

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Table 1. Operational conditions and average wastewater characteristics during the study.

<i>Operational conditions</i>						
Location	PE (eq-Inh.)	Q (m ³ /d)	T (°C)	SRT (d)	MLSS (kg/m ³)	RAS (m ³ /d)
Bioreactor	420,000	54,690	15.4- 17.8 °C	29.2 ±7.8	4.75 ±0.9	55,600
<i>Wastewater characterization</i>						
Parameter	COD (gCOD/m ³)	VFA (g/m ³)	TP (gP/m ³)	TN (gN/m ³)	N-NH ₄ (gN/m ³)	N-NO ₃ (gN/m ³)
Influent	856±116	167±59	12.2 ±2.5	86.5±10.6	65.1±7.45	n.d
Effluent	25.4 ±4.7	n.d.	0.5 ±0.2	8.4±2.1	0.9 ±0.3	6.0±0.7

n.d: not determined

Table 2. Literature review of OUR values reported with different activated sludge systems and comparison with this study.

Reference	System	Object-scale	OUR gO ₂ /(kgVSS·h)	Temp. °C	Remarks
This study	One stage aerobic batch test fed with municipal wastewater	Full-scale	20.4 (±1.98)* 21.8 (±3.46)**	16.0-17.8	*Fall season **Spring season
	Two stage anaerobic - aerobic batch test fed with municipal wastewater		24.9 (±0.99)* 24.5 (±3.75)**		
[23]	Mixed liquor of wastewater and activated sludge from aeration tank	Pilot-scale	20	n.d.	
		Full-scale	22 – 53	n.d.	
[24]	Mixed liquor of tap water and RAS	Pilot-scale	3 – 5 *	20	* Carbon excess ** acetate *** Sludge hydrolysate
			20 – 30 **		
			22 – 36 ***		
		Full-scale	8 – 10 * 21 – 29 ** 22 – 35 ***		
[26]	Mixed liquor of wastewater and biomass	Lab-scale	50	n.d.	
[27]	Constantly aerated batch reactor with synthetic wastewater	Lab-scale	1.0 – 1.7	20	
[28]	Bed biofilm reactor operated as a SBR	Lab-scale	4.8	n.d.	
[29]	Anaerobic - aerobic SBR fed with real wastewater	Lab-scale	4.2 – 5.6	n.d.	Acetate addition
[30]	OUR batch tests fed with municipal wastewater	Lab-scale	10.1* 15.9**	14.7-18.5	Without* or with potato by-products** addition
[31]	OUR tests fed with raw wastewater	Lab-scale	7.77	13.3-18.1	Sugar industry waste addition

Table 3. Literature review of AUR values reported with different activated sludge systems and comparison with this study.

Reference	System	Object-scale	AUR g N/(kg VSS·h)	Temp. °C	Remarks
This study	Two stage anaerobic-aerobic batch test fed municipal wastewater	Full-scale	2.9 (±0.21)	16.0-17.8	Fall season
			2.8 (±0.07)	15.4-16.2	Spring season
[29]	Anaerobic-aerobic SBR fed with real wastewater	Lab-scale	4.2 – 5.6	n.d.	Acetate addition
[30]	AUR batch tests fed with municipal wastewater	Lab-scale	2.52 [*] – 2.58 ^{**}	14.7-18.5	Without [*] or with potato by-products ^{**} addition
[32]	Batch tests fed with settled wastewater	Full-scale	4.6	20	
[33]	Batch tests fed with pre-settled or raw influent by-passed directly to the anaerobic reactor)	Full-scale	5.0 – 5.3	20 ±0.5	Lower values with pre-settling
[34]	Batch test fed with municipal wastewater	Full-scale	3 – 4	25	Without primary clarification
[35]	Anaerobic - aerobic SBR fed with real wastewater	Lab-scale	2 – 3	20 ±2	Acetate added
[36]	Anaerobic-aerobic SBR fed with synthetic wastewater	Lab-scale	1.0 – 1.7	20-30	Acetate addition
[37]	Intermittent aeration	Full-scale	3.2 ±0.63	n.d.	
	Pre-denitrification	Full-scale	3.3 ±0.63	n.d.	

508 **Table 4.** ASM2d default values of kinetic and stoichiometric parameters and values
509 adjusted during model calibration.

Parameter	Symbol	Unit	Default value ^[18]	Calibrated value
<i>Hydrolysis:</i>				
Hydrolysis rate constant	K_h	d^{-1}	3.0	2.5
Anaerobic hydrolysis reduction factor	η_{fe}	-	0.4	0.1
Saturation coefficient for particulate COD	K_x	-	0.1	0.2
<i>Heterotrophic organisms (X_H):</i>				
Yield coefficient heterotrophic biomass	Y_H		0.63	0.68
Maximum growth rate on substrate of X_H	μ_H	d^{-1}	6.0	3.0
<i>Autotrophic (nitrifying) organisms (X_A):</i>				
Maximum growth rate of X_A	μ_A	d^{-1}	1.0	1.35
Saturation coefficient for ammonium of X_A	$K_{NH_4,A}$	$g\ N/m^3$	1.0	1.3
Saturation coefficient for phosphate of X_A	$K_{PO_4,A}$	$g\ P/m^3$	0.01	0.001
<i>Phosphate accumulating organisms (X_{PAO}):</i>				
Poly-phosphate requirement for PHA storage	Y_{PO_4}	$g\ P/g\ COD$	0.4	0.32
Rate for lysis of X_{PHA}	q_{PHA}	d^{-1}	3.0	6.0
Rate for lysis of X_{PP}	q_{PP}	d^{-1}	1.5	4.5
Reduction factor anoxic activity of X_{PAO}	$\eta_{NO_3,PAO}$	-	0.6	0.5
Saturation coefficient for X_{PP} of X_{PAO}	$K_{PP,PAO}$	$g\ COD/g\ COD$	0.01	0.02
Saturation coefficient for S_A of X_{PAO}	$K_{S_A,PAO}$	$g\ COD/m^3$	4.0	1.0
Saturation coefficient for X_{PP} storage of X_{PAO}	$K_{IPP,PAO}$	$g\ P/g\ COD$	0.02	0.1
Saturation coefficient for X_{PHA} of X_{PAO}	$K_{PHA,PAO}$	$g\ COD/g\ COD$	0.01	0.2
Saturation coefficient for ammonium of X_{PAO}	$K_{NH_4,PAO}$	$g\ N/m^3$	0.05	0.01
Saturation coefficient for phosphate of X_{PAO}	$K_{P,PAO}$	$g\ P/m^3$	0.01	0.001

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FIGURE CAPTIONS

Figure 1. Layout of the bioreactor after modernization at the Debogorze WWTP.

Figure 2. (a) Oxygen and ammonia concentration profiles and flow thru of the aeration blowers at Debogorze WWTP (b) Specific energy consumption by aeration systems during last years.

Figure 3. One-stage sample results of (a) measurements (points) and model predictions (line) of the COD and OUR behavior by the ASM2d (b) pH, ORP variations during one-stage OUR batch tests.

Figure 4. Two-stage sample results of (a) measurements (points) and model predictions (line) of the COD, ammonia, phosphorus concentrations and OUR behavior by the ASM2d (b) pH, ORP variations during two-stage AUR/OUR batch tests.

Figure 1

Figure 2

Figure 3

Figure 4