FULL SCALE TUBULAR BIOREACTOR FOR HYDROGEN SULPHIDE REMOVAL

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ABSTRACT

The Wairakei geothermal power station situated in Taupo in the North Island of New Zealand was commissioned in 1958. Condensing water and geothermal steam condensate containing hydrogen sulphide is discharged to the Waikato River. Environmental concerns over sulphide aquatic toxicity in the river were considered when discharge permit conditions were reviewed in 2007. New discharge limits for the power station came into effect in August 2012, requiring the mass emission of hydrogen sulphide in the condensing water to be reduced from current levels of approximately 10,300kg/week to 2,800kg/week, with a further reduction to 630kg/week from 2016. This required a hydrogen sulphide concentration reduction from 1000mg/m^3 to less than 60mg/m^3 in a cooling water flow of 17m^3/s. An innovative tubular biofilm reactor was developed, leading to construction of a full scale plant in 2012. The full scale bioreactor consists of 1890 parallel 100mm diameter x 200m length pipes with a total length of 378km, believed to be the largest tubular biofilm reactor in the world at the time of construction.

KEYWORDS

tubular bioreactor, hydrogen sulphide, sulphur oxidising bacteria, geothermal power station.

1 INTRODUCTION

The Contact Energy Ltd Wairakei geothermal power station situated in Taupo in the North Island of New Zealand is one of the first of its kind in the world, and was commissioned in 1958. Due to the technology of the time the power station was designed with direct contact water condensers after the steam turbines using water drawn from the adjacent Waikato River. The water and steam condensate is discharged directly back to the river through an outfall structure. The condensing water flow is up to 17.2m^3/s (about 1,500,000m^3/d) when the station is operating at peak generating capacity of 157MW. Hydrogen sulphide (H_2S) is naturally present in the hot geothermal fluid extracted from the ground and this is carried into the geothermal steam feed to the power station where a portion is dissolved into the condensing water flow, resulting in sulphide concentrations of 800 - 1000mg/m^3 H_2S discharged to the river.

As early as 2000, Contact Energy Ltd recognised that environmental concerns over sulphide toxicity in the river would be a significant issue to address when the discharge permits for the power station were due for renewal in 2007. Studies were commissioned in 2000 to find a viable solution to mitigate the amount of H_2S entering the river. The Resource Consent hearing by the Waikato Regional Council in 2007 set new discharge consent standards for the power station discharge to come into effect in August 2012. By that date the mass emission of H_2S in the condensing water was to be reduced from approximately 10,300kg/week to 2,800kg/week, with a further reduction to 630kg/week from August 2016. This latter limit represents a target sulphide concentration reduction of approximately 95% from 1000mg/m^3 H_2S to 60mg/m^3 H_2S in a condensing water flow of 17m^3/s to the river.

2 INITIAL STUDIES

Naturally occurring sulphur oxidising bacteria (SOB) are endemic to the geothermal region and biofilms were observed on the submerged portions of the existing condensing water discharge structures. Studies carried out over the 2000 – 2005 period by Contact Energy Ltd and Beca investigated biological oxidation of H_2S as a potential process for treating the condensing water. The condensing water quality is typically pH 5.8 – 6.2 due to dissolved CO_2, with a temperature range of 25 – 35°C, with other parameters as shown in Table 1. Dissolved organic carbon and other nutrients are low in the river water. This water quality is conducive to the establishment of autotrophic SOB in the presence of H_2S.

Table 1: Cooling Water Discharge Quality

7/9/2007 to 18/2/2010	DO (mg/L)	pH	Temp °C	H_2S (Total) (mg/m^3)	CO_2 mg/L	NH_4^+ mg/L-N
Mean	3.2	6.2*	29.0	804.0	101.0	0.07
Max	4.7	6.7	35.6	1163.0		
Min	1.8	5.6	20.9	421.0		

* pH value is median

Initial experimentation with various types of media configurations found that naturally seeded SOB could be established as a biofilm on a number of substrates. Trials with Ringlace® and vertical flat sheets in flowing channels suffered problems of excessive filamentous algal growth seeded from the incoming river water and stimulated by light (Photograph 1). It was found that algal growth could be limited if the water velocity was increased and light excluded. This observation led to experimentation with water flowing in pipes where it was shown that naturally seeded SOB could be established as a thin biofilm on the inside wall of pipes and significant bio-oxidation of sulphide could be achieved with water velocities in the range 0.8 – 1.0m/s. Pipes up to 100mm diameter were tested over a range of flowrates and predictive sulphide removal curves developed from the data (Photograph 2).

Photograph 1: Ringlace® showing excessive growth

Photograph 2: Test pipes

This trial work formed the basis of a conceptual tubular bioreactor configuration to treat the large condensing water flow of 17m^3/s. It was reasoned that if a single 180m length of 100mm diameter pipe at a flow of 6.3L/s (0.8m/s) could achieve the required sulphide removal, a full scale bioreactor would require some 2700 pipes in parallel to treat a flow of 17m^3/s.

3 DETAILED DESIGN STUDIES

In 2010, after a peer review of the tubular bioreactor concept, Contact Energy Ltd proceeded with the detailed design of the full scale bioreactor. Further pilot investigations were carried out with two HDPE test pipes of 100mm diameter x 200m length and 150mm diameter x 400m length respectively to revalidate the earlier work and to provide design parameters. Sampling points were installed at 20% intervals along the length of the pipes. Samples were collected for total hydrogen sulphide ($H_2S + HS^- + S^{2-}$), pH, , DO, sulphate. Temperature, flow and pressure head were monitored. 1m long removable sections of pipe were located at the beginning, mid-point and end of each pipe to provide assessment of the biofilm biomass and structure (Photograph 3).

Photograph 3: Trial pipes; 100mm dia. x 200m, 150mm dia. x 400m

3.1 TRIAL PIPE PERFORMANCE

The performance of the test pipes over a 3 week period of stable operation is shown in Figure 1 and Figure 2.

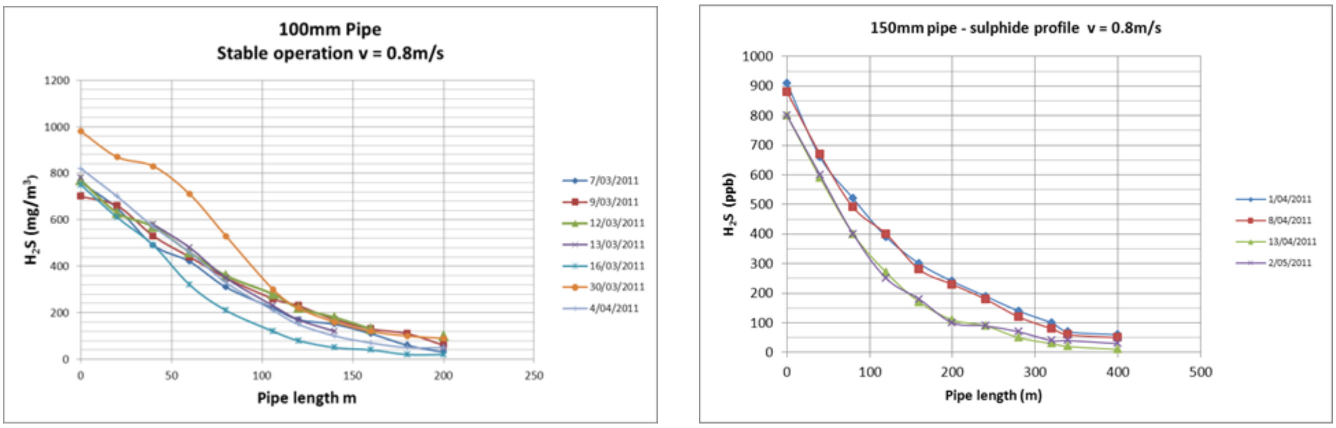


Figure 1, Figure 2: Sulphide removal for 100mm and 150mm dia. pipes

3.2 MODELLING BIOFILM PERFORMANCE

To better understand the biological performance of the biofilm, studies were carried out to develop a model of the sulphide removal to establish a design basis for the bioreactor.

3.2.1 BIOMASS SLOUGHING

As the bioreactor is configured as an open ended pipe system discharging directly to the river, there is a continuous discharge of excess biomass from the pipe reactor due to the growth of SOB. There is no biomass capture.

For steady state flows there will be equilibrium between the growth and sloughing of biomass that will maintain a constant biofilm thickness. The biofilm thickness will be a function of the hydraulic shear conditions determined by the water velocity. An estimate of the biomass generation was made using literature values of the growth yield of the bacteria. Buisman et al. (1991) reported the growth yield of autotrophic sulphide oxidisers is rather low, around 5 – 13g dry cell mass material/mol sulphide oxidised, when sulphate is the end product.

For a single 200m pipe this would yield an estimated biomass growth of between 0.226 – 0.587g. The total volume of the pipe is 1.57m3, giving an estimate of excess biomass concentration of between 0.14mg/L and 0.37mg/L in the discharge from sulphide oxidation. Measurement of the TSS discharge from the 100mm trial pipe confirmed solids concentration around 1mg/L during constant flow.

3.2.2 BIOMASS MEASUREMENT

After several months of operation the removeable 1m pipe sections from the beginning, middle and end of the trial pipes were examined to provide quantification of the dry weight biomass per m^2 (Table 2).

Table 2: Test sections biomass dry weight

	Biomass dry weight g/m^2	
	100mm dia.	**150mm dia.**
Section 1	5.28 (0m)	9.56 (0m)
Section 2	3.95 (100m)	4.89 (200m)
Section 3	3.84 (200m)	3.58 (400m)

The decline in biomass weight per m^2 of pipe wall along the length is considered to be the reducing sulphide substrate available for growth. The higher unit weight in the first section of the 150mm dia. pipe compared with the 100mm dia. pipe is most likely due a period of low flow (<0.8m/s) just prior to removal of the section. The biofilm thickness is very sensitive to the flow shear and for lower velocities the biomass thickness increases significantly, especially in the initial section of the pipe where the sulphide concentration is higher.

Visual inspection of the pipe sections showed a relatively uniform coverage of whitish-grey biofilm (Photograph 4, Photograph 5). The colour is considered due to suphur granules in the SOB. Biofilm thickness was estimated around 0.4mm.

Photograph 4, Photograph 5: Biofilm growth on beginning and end section of 100mm dia. pipe

3.2.3 SULPHIDE REMOVAL MODEL

The Monod equation is often used to describe the growth kinetics of biological systems. For the bioreactor the equation was simplified assuming that the biomass concentration remains constant and is much greater than the sulphide concentration. This is a reasonable assumption as the biofilm has reached a quasi-steady state with constant thickness, viz. growth = detachment. The Monod equation form simplifies to:

$$\frac{dS}{dt} = -v_m \frac{S}{(K_s+S)} \qquad (1)$$

where:
dS/dt = rate of substrate (sulphide) change
v_m = maximum substrate utilisation rate
k_s = half saturation constant

The mean sulphide removal rate ($gH_2S/m^2/d$) for each 20m pipe interval was calculated from the sample data and a non-linear least squares Monod function (Equation 1) fitted to the data to provide a design basis. The curve was extrapolated to 1000 mg/m^3 to cover the expected range of sulphide concentration in the condensing water. The least squares Monod parameters gave the maximum removal rate v_m = 13.85 $gH_2S/m^2/d$ and the half saturation K_s = 235mg/m^3 sulphide. Data for the 100mm dia. pipe is shown in Figure 3. The Monod equation parameters were used to generate a design removal curve (Figure 4). Similar curves were developed for the 150mm dia. pipe (not shown).

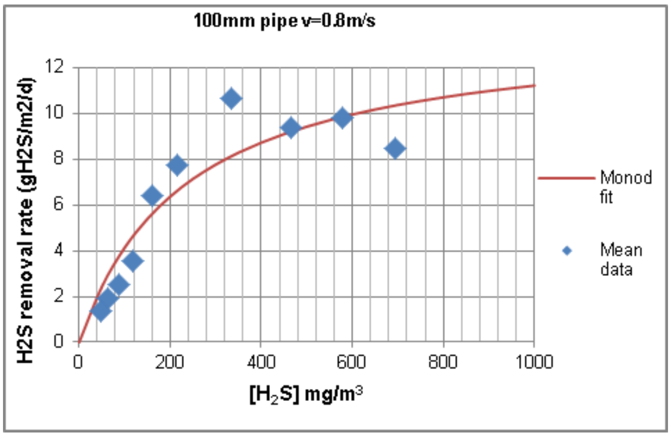


Figure 3: Sulphide removal rate model

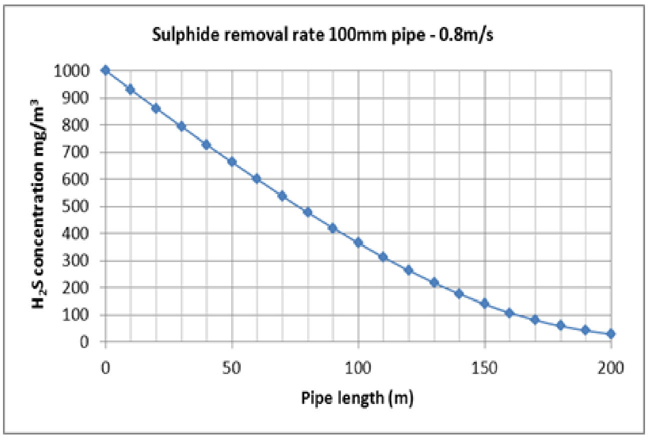


Figure 4: Design removal curve 100mm dia. pipe

3.2.4 FRICTION FACTOR AND PIPE ROUGHNESS

Headloss measurements along the pipes (Figure 5) were used to calculate the pipe friction caused by the biofilm in order to determine the pumping requirement. The friction factor and pipe roughness attributed to the biofilm is not a constant value but changes both with the biofilm thickness and with the fluid velocity. Lambert *et al*. (2009) investigated the impacts and found that biofilms grown under higher velocity conditions were less rough than those grown under lower velocities and proposed a modified Colebrook-White friction equation to account for the impact of the biofilm.

The Colebrook-White friction factors for the measured headloss of the 100mm dia. pipe using the Lambert et al. (2009) formulation were calculated. For the purposes of design the following roughness factors were proposed for the 100mm dia. pipe:

ε = 2mm for pipes with a velocity of 0.8m/s
ε = 1mm for pipes with a velocity of 1.0m/s.

In addition to the pipe headloss, additional headloss associated with static lift and bioreactor entry and exit losses were factored into the pump performance selection.

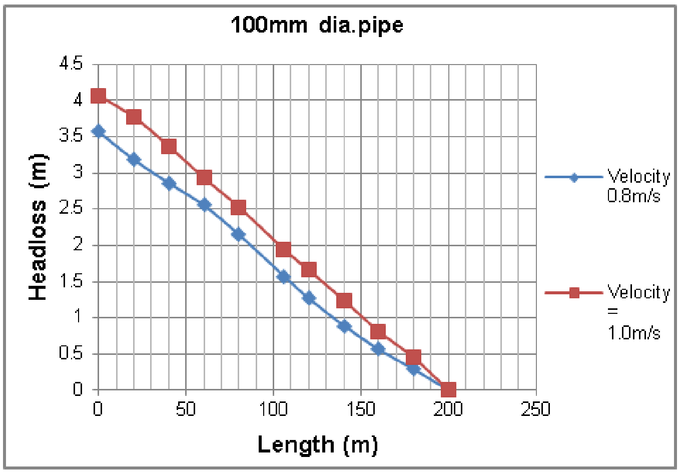


Figure 5: Headloss measurements

3.2.5 BIOREACTOR DESIGN SELECTION

Using these data the selection of an optimal pipe diameter and length was made considering a balance between water velocity (affecting headloss, residence time and pumping energy) against sulphide removal performance and practicality of construction. A 200m length of 100mm diameter HDPE pipe at a water velocity of 0.8m/s was shown to achieve the required sulphide removal (residual H_2S 60mg/m3) and was selected for the full scale reactor configuration.

4 FULL SCALE BIOREACTOR

As Contact Energy had also embarked on the construction of a new geothermal power station on the same Wairakei geothermal reservoir in 2011, there would eventually be a decrease in generation at the Wairakei station and a corresponding decrease in condensing water discharge. The required design flow for the bioreactor was therefore reduced from 17m3/s to 13m3/s, with up to 4m3/s untreated condensing water mixed with the bioreactor discharge flow able to meet the 2012 permit sulphide mass emission condition of 2,800kg/week in the interim. After 2016 when the sulphide limit drops to 630kg/week, the power station generating capacity will be reduced to limit the condensing water flow to 13m/s. All condensing water will then pass through the bioreactor for treatment.

The full scale bioreactor consists of 1890 parallel 100mm diameter x 200m length pipes with a total length of 378km, believed to be the largest tubular biofilm reactor in the world at the time of construction.

4.1 DESIGN CHALLENGES

Detailed engineering design and construction started in January 2011. As a bioreactor of this configuration and size had never been built before a number of innovations were required to meet design challenges and to bring the concept to reality.

4.1.1 HYDRAULIC DESIGN

The relative level of the power station and adjacent river provided a minimal hydraulic head of less than 2m to drive the bioreactor; requiring pumping of the 13m^3/s flow. One of the main design constraints of the bioreactor was the need to minimise power usage. An innovative hydraulic design was developed whereby the 200m pipe length was split into two 100m pipe fields in a novel ‘over and under’ configuration to create a hydraulic siphon which reduced pumping head (Figure 6). The water flow maintains the syphon prime, however a supplementary vacuum system is provided for priming if required.

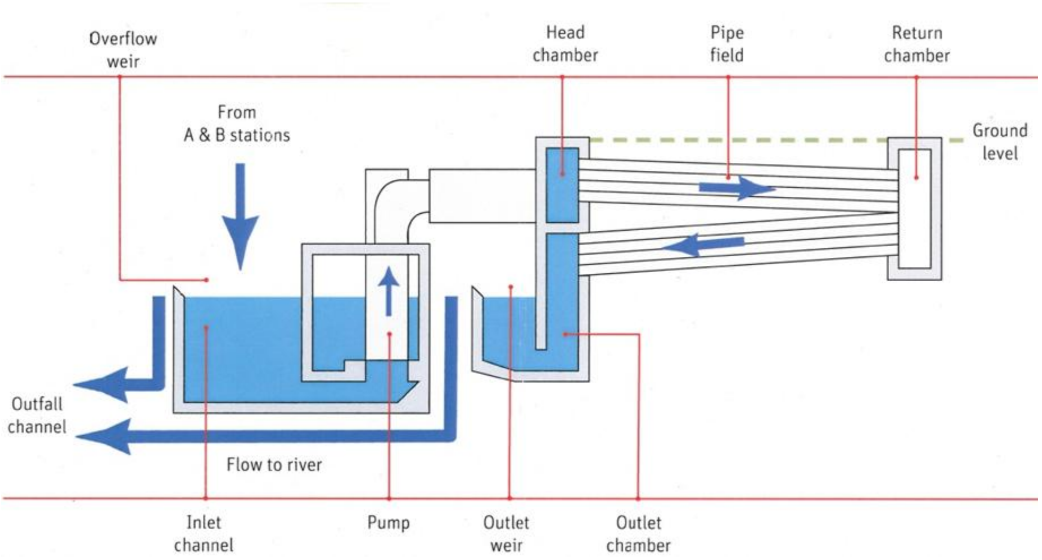


Figure 6: Schematic cross-section of the bioreactor (one of 5 banks)

The design has five variable speed submersible axial-flow pumps, each with a maximum duty of 3500l/s at 6.5m head. Each pump serves an independent bank of 378 pipes. Under normal operating flow of 2,600L/s (v=0.8m/s) each pump operating head is approximately 4.5m with a power demand of 150kW. Total power consumption is ~750kW.

4.1.2 BYPASS WEIR

The condensing water flow from the power station is continuous and cannot be stopped. A reliable method of immediately bypassing the total flow to the river in the event of a pumping faliure was required. After considering a number of options a 50m long side-weir was incorporated into the wall of the inlet channel, allowing a discharge directly into the outlet channel. This passive structure is fail-safe and can discharge the current total 17m^3/s flow with only a 300mm rise in the inlet channel water level. Photograph 6 shows the passive weir discharging approximately 4m^3/s cooling water.

Photograph 6: Bypass side-weir on inlet channel

4.2 CONSTRUCTION CHALLENGES

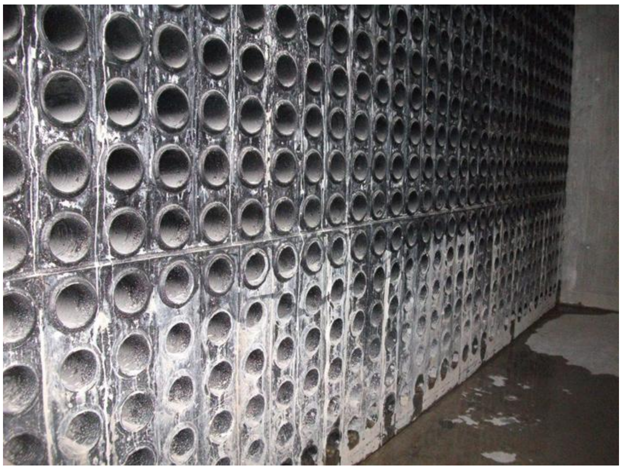
Construction challenges included the deep excavations for the pump station and inlet structures in an area with very shallow water table subject to geothermal activity.

The pipe field presented the biggest construction challenge in terms of physically laying the pipes while working in a safe manner around other crews within the pipefield. The 100m lengths of thin wall (2.5mm) 100mm diameter HDPE pipe were extruded on site to avoid issues with transportation and quality control. Single 100m lengths reduced the number of in-field welds required. A capstan winch was used to pull seven pipes into place at a time (Photograph 7).

Innovation overcame the design challenge of finding a material to hold the thin-walled HDPE pipes in place when laid in the pipe field. Due to the deep excavations required for the bioreactor structure, soil and pumice was abundant on site. A cement and soil/pumice mix was created, termed ‘soil-crete’, which had the strength to hold the pipes in place without the weight of normal concrete so that the pipes maintained their cylinderical integrity. Each layer of 40 pipes per bank was cemented one layer at a time and nine successive layers built up to form the complete bioreactor.

The pipes were manually slotted into fusion puddle flanges located at either end of the pipe field before being welded into place in the head chambers and tested (Photograph 8). Around 380km of HDPE pipe was extruded and laid over a five month period.

Photograph 7: Pulling 100m lengths of pipe into position.



Photograph 8: Head chamber construction

5 COMMISSIONING

Commissioning of the bioreactor started in May 2012. Mechanical and electrical commissioning involved rigorous testing of the pumps and variable speed drives and auxiliary vacuum systems. Biofilm establishment took approximately two weeks with a constant bioreactor flow of 13m^3/s (velocity 0.8m/s) and was consistent with the time observed in the trial pipe investigations. Process commissioning commenced from this point and involved a number of trials to test the SOB biofilm performance and how it would behave under different flow conditions. Pump outages, flow changes and a station outage were simulated prior to the consent date of 20th August to confirm the system could respond to conditions influenced by the power station generating operation or other outside factors and would meet the consent conditions. The commissioned bioreactor project was opened in September 2012 (Photograph 9).

5.1 BIOREACTOR PERFORMANCE

Since commissioning the bioreactor has operated continuously and consistently achieved 90 – 95% H_2S removal. Figure 7 shows the bioreactor discharge H_2S removal for the period from commissioning in October 2012 to April 2013.

Figure 8 shows the weekly mass discharge of H_2S and the permit limit of 2800kg/week. The small number of values around the limit were due to maintenance requirements when bypass weir flows were increased when one bioreactor bank was shut down.

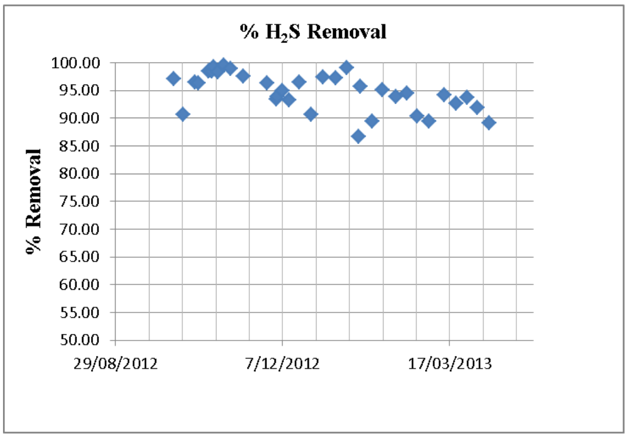


Figure 7: H_2S removal performance

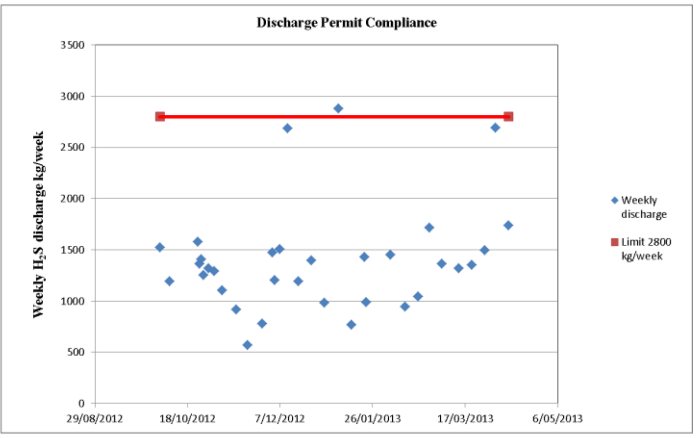


Figure 8: Weekly H_2S discharge October 2012 to April 2013

6 CONCLUSIONS

The Wairakei bioreactor project is an innovative solution to a unique problem. As with any new system there have been some steep learning curves in regards how to operate the bioreactor, particularly during station maintenance when cooling water flows are reduced. Monitoring will continue and the effect of varying flow regimes to optimise the biofilm condition to minimise biomass discharge and to minimise power usage will be further investigated, however the performance of the bioreactor to date gives confidence that the 2016 consent limit of 630kg/week H_2S will achieved.

Photograph 9: Completed bioreactor September 2012

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