U.S. BUREAU OF RECLAMATION

Enhancement of Hydroturbine Operational Flexibility for Powerplant Cost Optimization – PropC 8301

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This research project explores the question what modifications can be made to powerplant and power system controls to optimize operations and improve overall plant efficiency. To answer this question the report provides an evaluation of the Hydroturbine Operational Flexibility software developed to answer the question. This software running at the Western Area Power Administration's Loveland, Colorado office provides hydropower generation unit setpoint control and automated unit commitment to Yellowtail Powerplant. The software optimizes the hydro-electric turbine unit load and control mode while avoiding running units in a pre-defined operating exclusion zone.

Figure 1 - The Yellowtail Power Plant/Dam

Contents

1. Conclusion

The Hydroturbine Operational Flexibility control was compared to the standard Reclamation practice of equal unit loading. The Flexibility control resulted in an average efficiency improvement of greater than 2% over the period of May 1 – December 31, 2013.

The Flexibility control was verified to be avoiding having units operating in rough zones, defined for this research as “exclusion zones”. The exclusion zone is an undesirable operating region that is uniquely characteristic of each hydroelectric unit. The control algorithm avoids running units in the exclusion zone using the lower and upper zone limits provided initially by the plant operators and refined over operation time.

When the Flexibility control algorithm requires a unit operating setpoint to move from one side of the exclusion zone to the other, the algorithm sends the new setpoint to the unit governor. The governor manages the zone crossing. Based on the data collected and calculating the zone width for each unit, a zone crossing takes between 32 – 38 seconds to occur. An estimate for the number of zone crossings that occurred during the time period studied is provided.

The hydro-electric turbine unit operational efficiency is calculated using Unit Load (MW), Unit Flow (cfs), and Unit Head (ft). Efficiency values of approximately 93% for a unit are the maximum that has been achieved with newer designs. In the course of this study it should be noted that values greater than 93% were seen, which could point toward calibration problems.

In late December 2013, a second phase of the Hydroturbine Operational Flexibility software was implemented. The new piece of software is the unit commitment portion of the optimization process. Unit Commitment works to keep the correct number of units online that are needed to meet generation and spinning reserve requirements. Modifications were made to the unit commitment software based on operator recommendations in January and February, 2014. Data for this phase of the research has yet to be collected. The additional software is expected to result in further improvements in the plant efficiency and reduction in plant maintenance costs.

2. Background

The Hydroturbine Operational Flexibility software was designed by the Bureau of Reclamation’s Technical Service Center (TSC) for the Yellowtail Power Plant/Dam (Figure 1) and implemented by Western Area Power Administration (Western) using the C programming language. Yellowtail power generation consists of four 12-foot diameter penstocks embedded in the dam supply water to four 87,500 horsepower, vertical-shaft, Francis-type hydraulic turbines each driving a 62,500-kilowatt generator. The Supervisory Control and Data Acquisition (SCADA) software for the plant is running on a Western’s Rocky Mountain Region XA/21 Energy Management System (EMS) Application Server located in Loveland, CO. Hydroturbine Operational Flexibility software consists of two major modules, the

Generation Control Module and the Unit Commitment Module. The Generation Control Module optimizes the operation of individual units and avoids undesirable operating zones, while the Unit Commitment Module is designed to find the optimal configuration for operating the entire hydroelectric plant.

The Generation Control Module determines the optimal hydroelectric unit loading (or unloading) depending on the current operational status of the plant and where the generation is with respect to the unit's “exclusion zone” (extended rough zone as described below). The Generation Control Module provides maximum exclusion zone avoidance by allocating the generation required to any other units that have available generation capacity before a unit crosses the “exclusion” region. At the same time, the design has been simplified to be more accessible so that a maintenance cost function can be integrated when the system is operational and data have been analyzed.

The Generation Control software monitors Yellowtail SCADA operating points and distributes the plant power setpoint among units that are on supervisory, on Automatic Generation Control (AGC), and in generating modes. For units that are generating and not on AGC or units that are condensing, the software considers the unit base loaded (unchangeable load) and subtracts the unit load from the plant setpoint. The software then distributes the remaining plant setpoint among the units that are generating and on AGC for the best efficiency (best power setting using the least amount of water). The generation control software’s first priority is meeting the plant generation setpoint. As long as the plant setpoint can be met without loading a unit in an exclusion zone, the software will avoid exclusion zones.

The Unit Commitment Module determines limits, modes, and will perform unit control functions. A Pre-processor places units in selection buffers (Available, Generating, and Motoring), taking into account actual modes, desired operator modes and unit constraints. The Unit Commitment Module selects units from the buffers based on the plant requirements for reserves and generation. When a unit is selected for a commitment change, it will be placed in a transition buffer, verify that the change of state is acceptable to the operator and then make the transition for the unit. The unit commitment software was not implemented until December 12, 2013, and therefore, was not in operation during the majority of the period of data collected for this study (May 1 – December 31, 2013).

Rough zones have been defined for hydroelectric units for many years. These normally occurring operational regions are a result of draft tube surging in Francis turbines under low load conditions, and are avoided for long-term generation. During peaking operations that occur at powerplants almost daily, the units are forced to load and unload quickly across these rough zones to meet changing plant generation requirements. The rough zones traditionally have been defined by measuring low-frequency shaft runout at the turbine guide bearings. In recent years, technology improvements have provided the potential to determine loading ranges where cavitation damage is most likely to occur. As a result, two zones that should be avoided during normal operations are defined for these units: a "cavitation zone" and a "rough zone." The "cavitation zone" appears to occur at lower loads, while the "rough zone" occurs at contiguous, but slightly higher loads. These two overlapping zones have been combined to define an "exclusion zone." Avoiding this area of operation is expected to reduce the number of repairs and extend the life of hydroelectric units.

One of the objectives of this research project is to redefine hydroturbine exclusion zones that in many cases have an unknown relationship from a machine condition/damage perspective. As such, the "cost of operating" in certain regions of the so-called exclusion zone is poorly understood. Having improved knowledge of the operation-damage relationship is expected to provide the necessary information for redefining hydroturbine exclusion zones and developing a cost model that can be used to optimize operations.

The Hydroturbine Operational Flexibility software monitors and determines the characteristic of rough zone vibration limits as a function of gross water pressure and energy generated. This characteristic is organized into three-dimensional tables where the rough zone monitor (vibration) amplitude will be recorded with respect to head and generation. One function of the software is to maintain rough zone limits for the system as depicted in Figure 2. Direct input from the rough zone (vibration amplitude) monitor at Yellowtail is used to provide a dynamic exclusion zone avoidance scheme. Rough zone limits determined by the monitor are updated as needed. Data are recorded to assist in developing maintenance cost data for future operations.

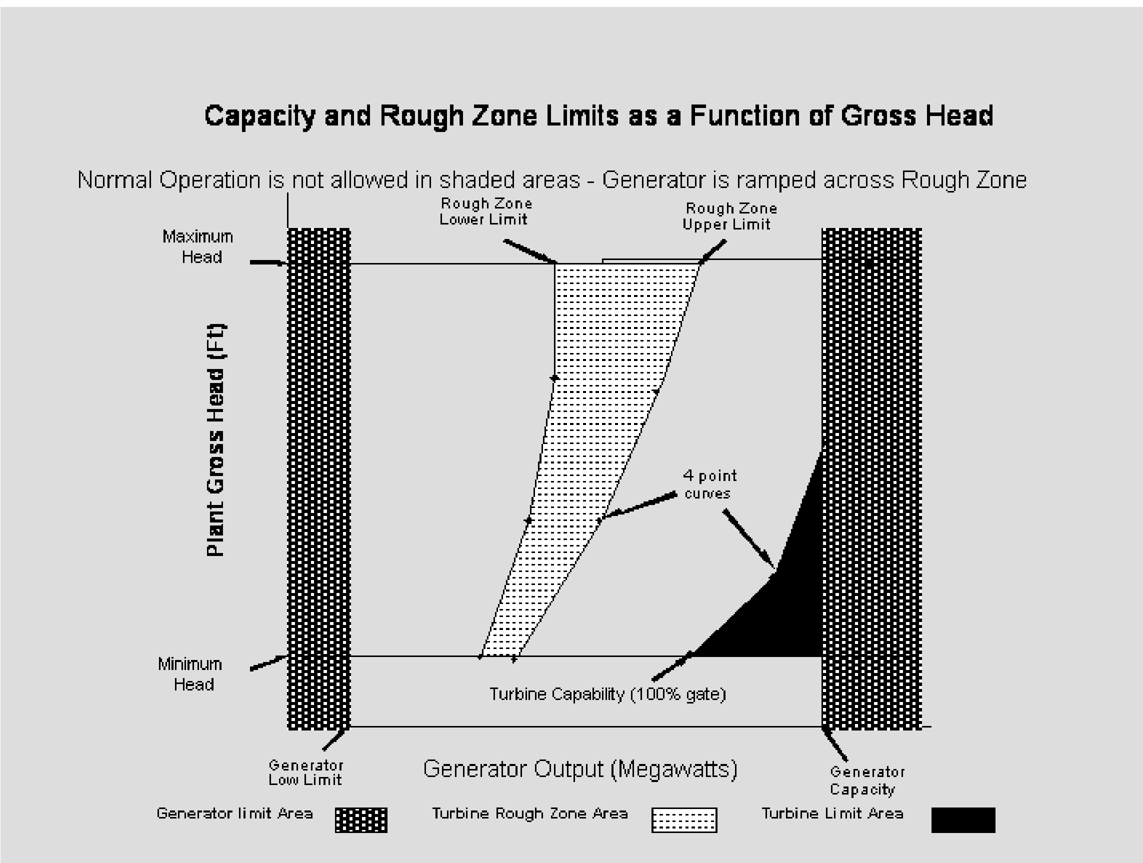


Figure 2 – Unit Capacity and Rough Zone Limits

During the generation operation, unit exclusion zone limits are calculated by lookup from updated tables to obtain the following values: normal capacity, exclusion zone high, exclusion zone low, and low limit—all of which are head dependent.

3. Software Design

Hydroturbine Operational Flexibility software is designed into two major modules, the Generation Control Module and the Unit Commitment Module. The Generation Control Module is designed primarily for unit operations and the Unit Commitment Module is for operation of the entire hydroelectric plant. These modules each comprise a number of specific functions. The Generation Control Module includes Unit Control & Calculations, Flow & Rough Zone Update, Flow Calculation, and Rough Zone Calculation functions. The Unit Commitment Module contains Plant Control & Calculations, Unit Commitment, and Plant Generation Allocation functions.

The Generation Control Module– the Generation Control Module defines behavior for each of the four hydroelectric units, each comprised of a generator and turbine. The Generation Control Module consists of functions and properties that represent the behavior of the hydroelectric units, triggered by events that occur in the context of the power plant.

The Generation Control Module comprises function sets that represent a hydroelectric unit for purposes of performing optimization and generation controls. There are four function sets that include the following: Unit Control & Calculations, Flow Calculations, Rough Zone Calculations & Flow and Rough Zone Update. These functions work together to perform unit operations. Unit Control then performs all the functions necessary to determine the unit control modes and perform unit control operation as required to represent the behavior of the generation system.

Unit Control &Calculations – Unit Control & Calculations are the heart of the unit operations as they administer all of the unit controls. The most important aspect of Unit Control & Calculations is the determination of the unit control mode.

Unit Control & Calculations also includes all the flow characteristic calculations, limit calculations, a unit mode function, unit control function and ramping limit function. The unit mode function determines the current unit mode status and makes changes to the mode as requested by the operator or as the unit conditions change. The unit controls function performs setpoint control for AGC units. A transition buffer indicates units selected for start, stop, condense, and generate controls. The unit controls function notifies the operator of the desired transition and executes the transition once the operator has approved it. Most of the basic functions have been completed and are implemented in the

Generation Control module. The remaining part of the Unit Control & Calculations involve integration of the Unit Commitment and the Generation Control functions.

Flow Calculations – The Flow Calculations functions are responsible for calculation of all head-dependent data that is required for the Automatic Generation Control and Optimization systems. These functions include head calculations, flow characteristic determination and unit limits calculation. The functions in the SCADA execute at program initialization and when the water pressure (head) changes more than a half foot. The head calculations function determines the gross water pressure differential for a number of parameters. Gross head is determined by the difference between the forebay and afterbay water elevations.

Rough Zone Calculations – The Rough Zone Calculations functions maintain rough zone limits for the optimization system as depicted previously in Figure 2 above. Direct input from the rough zone (vibration amplitude) monitoring functions at Yellowtail is used to provide an on-line, dynamic rough zone avoidance scheme. Rough zone limits determined by the monitor are updated as needed. Rough zone monitor amplitude data are recorded and stored for later analysis.

Flow &Rough Zone Update – The purpose of these functions is to support the development of characteristics for unit flow and unit rough zone operation as a function of gross water pressure (head) and energy generated (Mega Watts). The flow characteristic is organized into a three-dimensional table where flow data is recorded with respect to head and generation. For the rough zone characteristic development, the rough zone (vibration) monitor amplitude is recorded with respect to head and generation. The Flow & Rough Zone Update software is run as a stand-alone operation on a separate computer workstation. The software receives data regularly, but only performs updates to the flow curves and rough zones twice a month. Therefore, it lends itself to being separated easily from the EMS system.

The Unit Commitment Module– the Unit Commitment Module represents the behavior of the Yellowtail plant that controls and monitors the individual units. The plant software functions execute commands that determine the operating modes of the plant, in particular either manual or automatic. In automatic mode, the plant can operate according to operator setpoint, generation schedule or by AGC.

The Unit Commitment Module consists of three function sets that represent the behavior of the Yellowtail plant. These three function sets include the following: Plant Control & Calculations, Plant Generation Allocation, and Unit Commitment. Plant Control & Calculations supports the other two function sets. It determines the Plant control mode and calculates a large set of quantities/limits that are used for the Allocator and Unit Commitment. The functional set also provides plant reference controls for modes other than AGC where the plant reference is driven by the operator or from an hourly schedule. The Plant Generation Allocation function performs the function of allocation of the plant generation reference to individual units. Normally, this function provides an optimization that allocates the plant reference to units in order to minimize water usage while avoiding exclusion zones and maintaining units within operating limits. Unit Commitment pre-processing involves calculating the plant generation capability (Figure 3). It then allocates a plant capacity requirement to the available plant units in a way that minimizes water usage by starting or stopping the best units to meet a particular capacity requirement.

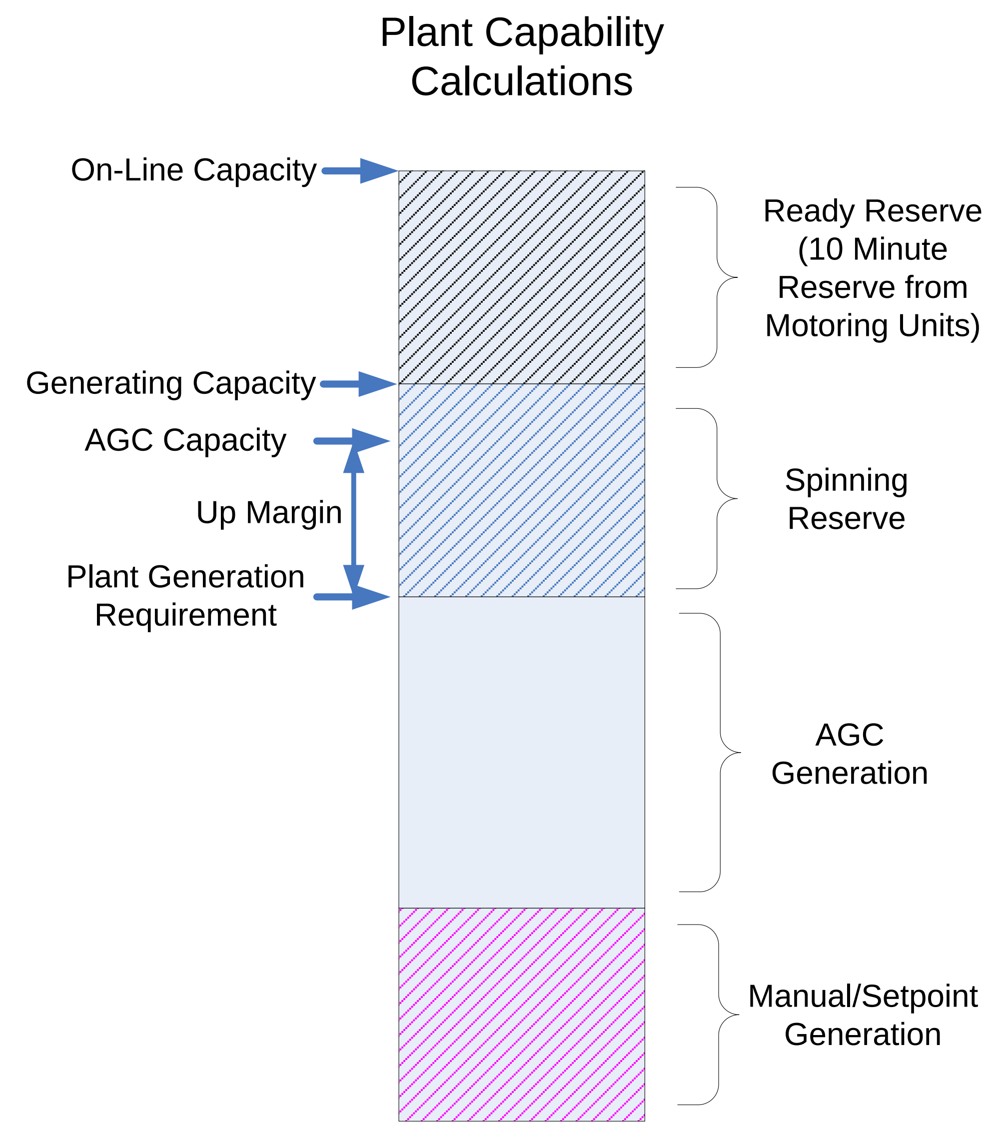


Figure 3 - Plant Capability Calculations

Unit Commitment – The Unit Commitment function involves several elements as shown in Figure 4. It uses six buffers for the selection and transition processes. Plant constraints, operator input, the current plant and unit conditions, and unit capabilities are all utilized in the selection process to determine the optimal system mode. Unit Control and Calculations directly supports the Unit Commitment as shown in the figure below. Unit Control and Calculations determine limits, modes, and performs unit controls functions. For Unit Commitment, a Pre-processing function determines unit priorities and places units in the selection buffer. The Pre-processing function considers actual modes, unit constraints and operator commitment modes for the units, and then places units in the various buffers (Available, Generating, and Condensing). The Unit Commitment function selects units from the buffers based on the plant requirements for reserves and generation. When a unit is selected for a commitment change, it, along with the commitment mode and time tag, is placed in a transition buffer used by Unit Commitment. The Unit Commitment function verifies that the change of state is acceptable to the operator and then makes the transition for the unit.

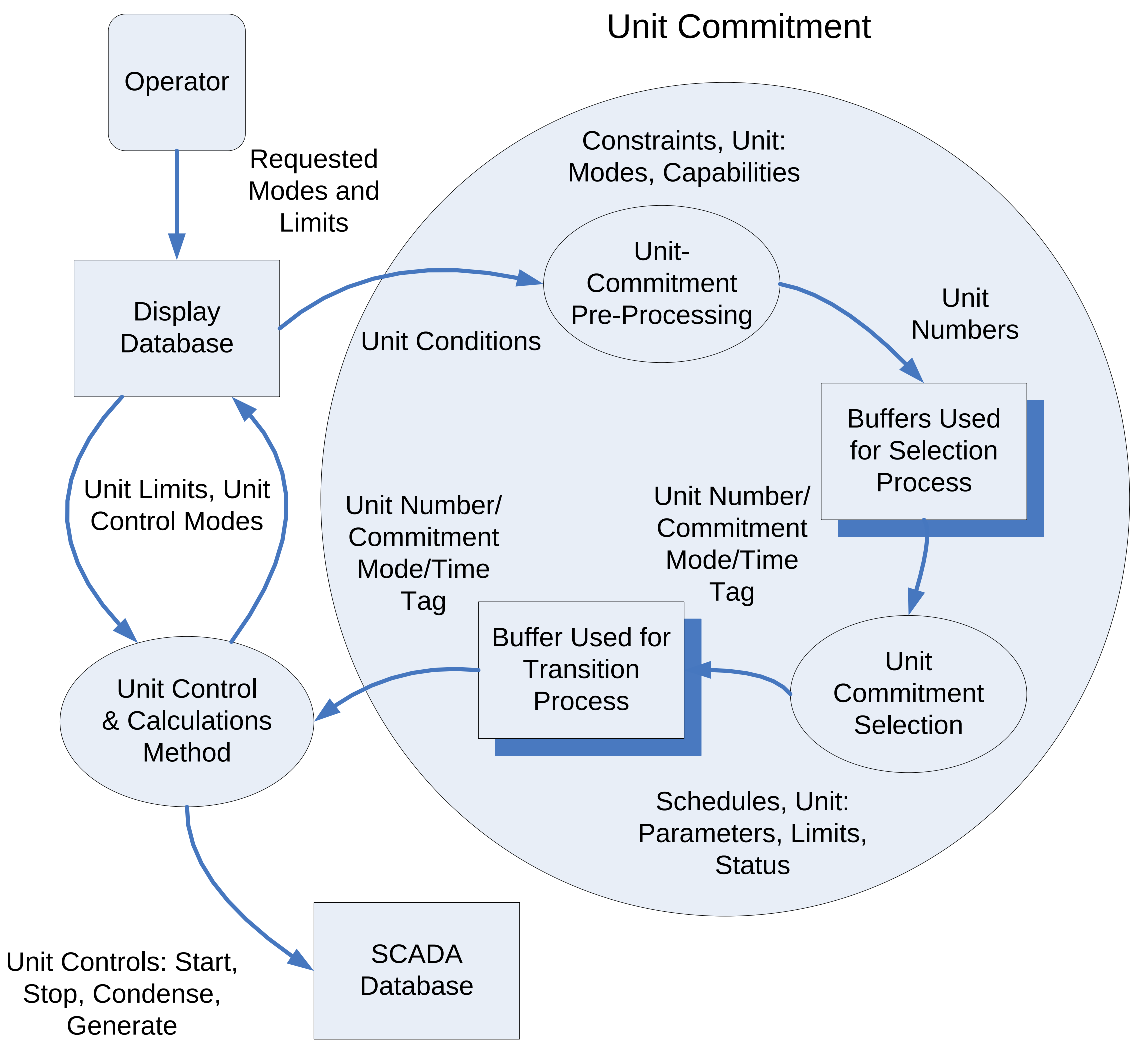


Figure 4 - Unit Commitment Overview

Water limits are calculated to assist the operator and dispatcher. The water limits show how much capacity is left in the up or down direction. An adjustable alarm is used to indicate when a minimum value for capacity either in the up or down direction is encountered. The water limits calculation may be used to determine the amount of reserves available from the power plant for ancillary services scheduling. The calculation determines an estimated volume of water left in the afterbay.

This calculation should determine the volume remaining in the afterbay for generation purposes (the volume to reach an afterbay limit). A content curve for the Afterbay that converts afterbay elevation to a particular volume is used. That volume is then converted to energy at an average efficiency of 80%. The calculated energy (MW-hrs) to reach a limit is output to the operator.

Vol = *f*(deltaF, Capacity – afterbay level)

where deltaF = difference between the flow into the afterbay and an assumed fixed flow out.

The flow characteristic is then used to compute an amount of generation (MW-hours) available from the volume of water remaining to fill the afterbay to capacity.

4. Data Collection

Data was collected at a 10 minute interval covering the period of May 1 – December 31, 2013 for evaluation of the Generation Control algorithm only. (The Unit Commitment algorithm has not been evaluated.) The following tables provide a summation of the data collection:

Table 1 provides monthly averages for each unit.

Load – The average load (MW) per month for the unit when the unit was running as a generator.
Eff – The average efficiency (%) per month for the unit when the unit was running as a generator.
Util – The utilization (%) per month for the unit. This is the percent of the month the unit was running as a generator and on AGC.

Table 1. Unit Monthly Averages

	U1 Average			U2 Average			U3 Average			U4 Average		
2013 Month	**Load [MW]**	**Eff [%]**	**Util [%]**	**Load [MW]**	**Eff [%]**	**Util [%]**	**Load [MW]**	**Eff [%]**	**Util [%]**	**Load [MW]**	**Eff [%]**	**Util [%]**
May	22.7	65.8	94.8	6.5	47.4	36.3	15.4	62.5	99.9	26.8	80.5	69.8
Jun	20.0	59.3	100.0	10.6	52.0	37.2	14.3	58.3	91.4	26.1	78.8	79.9
Jul	21.0	59.7	55.6	18.7	60.5	90.4	15.8	60.0	85.9	25.4	76.9	76.8
Aug	16.2	53.7	96.3	9.1	49.9	96.4	15.4	61.5	96.3	25.9	77.8	95.7
Sept	21.0	64.8	6.2	23.8	68.0	99.1	13.7	57.6	77.4	25.6	77.1	100.0
Oct	17.6	59.9	72.4	11.8	55.0	100.0	19.4	69.1	100.0	24.0	76.3	27.6
Nov	23.4	54.2	57.1	17.6	61.2	100.0	19.0	63.9	60.7	22.6	71.4	82.2
Dec	27.9	69.3	51.1	27.1	70.2	75.5	19.6	63.6	82.4	26.4	71.5	90.1

Table 2 provides monthly averages for the plant as follows:

Load - The average load (MW) per month for the plant.
Eff - The average efficiency (%) per month for the plant.
Util – The utilization (%) per month for the plant.

Table 2. Plant Monthly Averages

	Plant Average		
2013 Month	**Load [MW]**	**Eff [%]**	**Util [%]**
May	58.0	70.1	100.0
Jun	62.3	70.9	100.0
Jul	65.0	69.8	100.0
Aug	64.3	69.8	100.0
Sept	61.1	73.9	100.0
Oct	50.6	57.3	100.0
Nov	61.1	68.9	100.0
Dec	75.7	73.4	100.0

5. Evaluation

Evaluation of the generation control algorithm entails verifying that the algorithm is performing two functions as follows:

1. The algorithm is distributing the plant setpoint among the units and achieving a higher efficiency than standard loading practices.
2. The algorithm avoids loading units in an exclusion zone.

5.1 Efficiency Improvement

The generation control algorithm is providing higher plant efficiencies than the standard Reclamation practice of equal loading similar units. Table 3 shows the average efficiency benefit realized over the period of data collected was 2.3%. The monthly load and efficiency results for the plant are included in the Section 6 Appendix. The Section 7 Appendix includes the monthly plant efficiency gain (Hydroturbine Operational Flexibility vs. Equal Loading).

Table 3. Efficiency Comparison

	Yellowtail Average			
2013 Month	Load [MW]	GC Eff [%]	EL Eff [%]	Eff Gain (GC – EL) [%]
May	58.0	73.6	71.3	2.3
Jun	62.3	72.2	69.5	2.7
Jul	65.0	72.2	70.0	2.2
Aug	64.3	71.2	68.1	3.1
Sept	61.1	74.7	72.8	1.8
Oct	50.6	70.1	67.6	2.5
Nov	61.1	73.2	70.7	2.6
Dec	75.7	76.6	74.5	2.2

In order to evaluate the generation control algorithm efficiency improvements, a comparison between the generation control unit loading and the standard practice of equal loading units was performed. For simplicity, exclusion zones were ignored for the equal loading evaluation.

1. For each time step in the data, the units being utilized by the generation control algorithm were determined and the load values for those units were summed to determine the plant setpoint (Eq 1). Units that were not being utilized by the generation control algorithm were given a setpoint of 0 (MW).
2. Unit flows were calculated for the generation control unit loading (Eq 3).
3. The plant generation control flow (Eq 4) was calculated by summing the unit flows from Eq3.
4. The plant generation control efficiency was calculated (Eq 7).
5. The plant setpoint was then divided by the number of units utilized by the generation control algorithm to determine the equal loading setpoint for each unit (Eq 2).
6. Unit flows were calculated for the equal load unit loading (Eq 5).
7. The plant equal load flow (Eq 6) was calculated by summing the unit flows from Eq 5.
8. The plant equal load efficiency was calculated (Eq 8).
9. Finally, the plant equal load efficiency was subtracted from the plant generation control efficiency (Eq 9). A positive value signifies an improvement in efficiency.

5.1.1 Setpoint Equations

(Eq 1): Plant Setpoint Equation

$$SP_{plant} = \sum_{i=1}^{4} SP_{i(GC)}$$

$$SP_{plant} = plant\ set\ point\ (MW).$$

$SP_{i(GC)} = \ unit\ generation\ control\ set\ point\ (MW).$

$i = \ unit\ number.$

(Eq 2): Equal Loading Unit Setpoint Equation

$$SP_{i(EL)} = \frac{SP_{plant}}{Count}$$

$SP_{i(EL)} = \ unit\ equal\ loading\ set\ point\ (MW).$

$Count = \ count\ of\ units\ utilized\ by\ generation\ control.$

5.1.2 Flow Equations

(Eq 3): Generation Control Unit Flow Equation

$$Fl_{i(GC)} = A_i + B_i * SP_{i(GC)} + \frac{C_i}{Hd} + D_i * SP_{i(GC)}^{\ 2} + \frac{E_i}{Hd^2} + F_i * \frac{SP_{i(GC)}}{Hd} + G_i * SP_{i(GC)}^{\ 3} + H_i * \frac{SP_{i(GC)}}{Hd^2} + I_i * \frac{SP_{i(GC)}^{\ 2}}{Hd}$$

$Fl_{i(GC)} = unit\ generation\ control\ flow\ \ (cfs).$

$Hd = Head\ on\ unit\ (ft).$

$A_i, B_i, C_i, D_i, E_i, F_i, G_i, H_i, I_i = coefficients\ for\ unit\ flow\ calculation\ (Table\ 3).$

(Eq 4): Generation Control Plant Flow Equation

$$Fl_{plant(GC)} = \sum_{i=1}^{4} Fl_{i(GC)}$$

$Fl_{plant(GC)} = plant\ generation\ control\ flow\ \ (cfs).$

(Eq 5): Equal Loading Unit Flow Equation

$$Fl_{i(EL)} = A_i + B_i * SP_{i(EL)} + \frac{C_i}{Hd} + D_i * SP_{i(EL)}^{\ 2} + \frac{E_i}{Hd^2} + F_i * \frac{SP_{i(EL)}}{Hd} + G_i * SP_{i(EL)}^{\ 3} + H_i * \frac{SP_{i(EL)}}{Hd^2} + I_i * \frac{SP_{i(EL)}^{\ 2}}{Hd}$$

$Fl_{i(EL)} = unit\ equal\ loading\ flow\ \ (cfs).$

$Hd = Head\ on\ unit\ (ft).$

$A_i, B_i, C_i, D_i, E_i, F_i, G_i, H_i, I_i = coefficients\ for\ unit\ flow\ calculation\ (Table\ 4).$

(Eq 6): Equal Loading Plant Flow Equation

$$Fl_{plant(EL)} = \sum_{i=1}^{4} Fl_{i(EL)}$$

$$Fl_{plant(EL)} = plant\ equal\ loading\ flow\ \ (cfs).$$

Table 4. Unit Flow Coefficients

	U1	U2	U3	U4
A	-2.18478E+03	-1.74930E+03	-1.74930E+03	-9.86292E+02
B	1.55430E+02	1.16315E+02	1.16315E+02	7.90871E+01
C	1.59564E+06	1.35526E+06	1.35526E+06	8.44754E+05
D	-1.50887E+00	-1.02445E+00	-1.02445E+00	-6.79247E-01
E	-2.68797E+08	-2.34466E+08	-2.34466E+08	-1.47766E+08
F	-8.19490E+04	-5.93361E+04	-5.93361E+04	-3.82789E+04
G	4.51732E-03	2.70461E-03	2.70461E-03	1.63906E-03
H	1.39847E+07	1.05602E+07	1.05602E+07	7.52012E+06
I	4.59493E+02	3.17610E+02	3.17610E+02	2.25801E+02

NOTE - The above flow coefficients are used by the generation control algorithm.

5.1.3 Plant Efficiency Equations

(Eq 7): Generation Control Plant Efficiency Equation

$$Eff_{plant(GC)} = \frac{SP_{plant}}{Fl_{plant(GC)} * Hd * (8.46 * 10^{-7})}$$

$$Eff_{plant(GC)} = plant\ generation\ control\ efficiency\ (\%).$$

(Eq 8): Equal Loading Plant Efficiency Equation

$$Eff_{plant(EL)} = \frac{SP_{plant}}{Fl_{plant(EL)} * Hd * (8.46 * 10^{-7})}$$

$$Eff_{plant(EL)} = plant\ equal\ loading\ efficiency\ (\%).$$

(Eq 9): Plant Efficiency Gain Equation

$$Eff_{gain} = Eff_{plant(GC)} - Eff_{plant(EL)}$$

$$Eff_{gain} = gain\ in\ efficiency\ by\ generation\ control\ (\%).$$

5.2 Exclusion Zone

The generation control algorithm is designed to avoid operating in the exclusion zone. The upper (MW) and lower (MW) exclusion zone values for each unit are entered on the operator screen by the operator. The algorithm uses the exclusion zone values to determine the most efficient solution that does not load a unit in an exclusion zone. If a solution is available, each unit is sent its setpoint. If a solution is not found that avoids the exclusion zones, the solution with the least number of units in an exclusion zone will be chosen. Remember, the main objective of the generation control algorithm is to meet the plant setpoint.

5.2.1 Exclusion Zone Avoidance

Analysis of the data collected shows that the generation control algorithm is avoiding exclusion zone operations. It is clear the generation control algorithm bumps the load up against the exclusion zone limits. Below is a graph for unit 3 during the month of June. The graph clearly shows how the generation control algorithm is using the exclusion zone limits to load the unit.

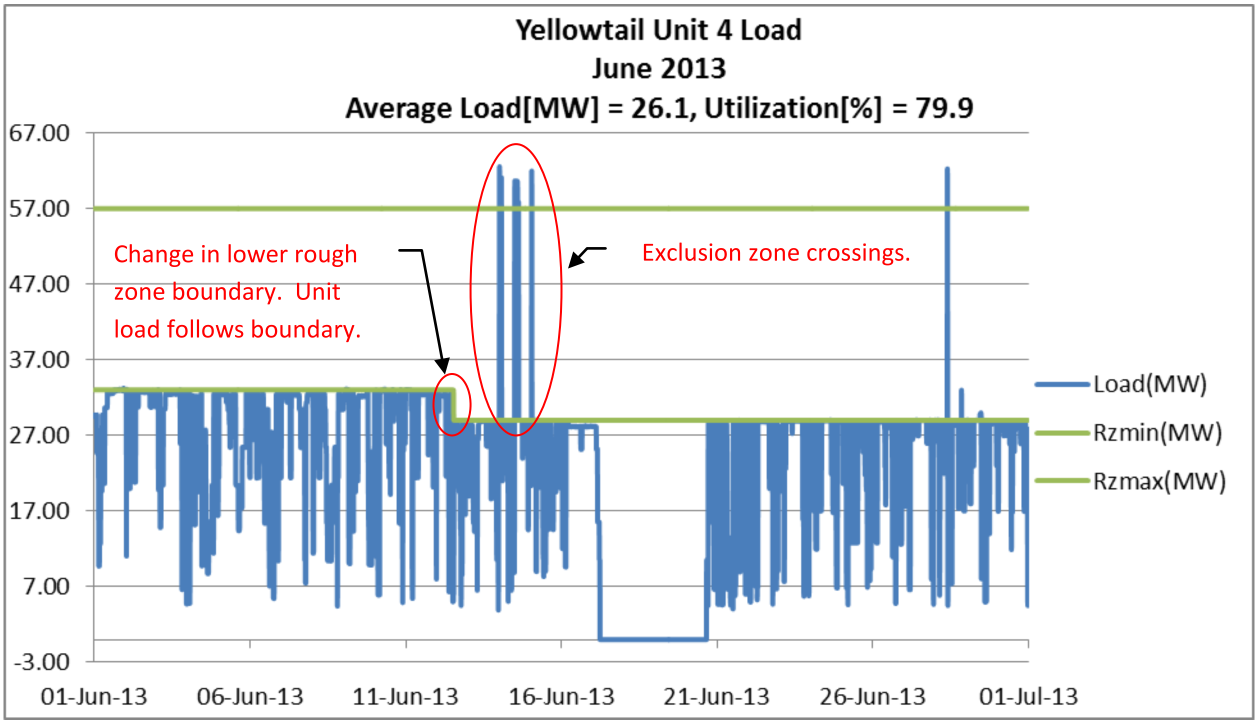


Figure 5 - Exclusion Zone Crossing

If more or less generation is needed from a unit at the exclusion zone limit, the generation control algorithm will redistribute the load among the units available and move a unit across the exclusion zone. Table 5 shows the number of exclusion zone crossings that each unit performed each month based on the 10 minute data collected for the study.

Table 5. Exclusion Zone Crossings

	U1	U2	U3	U4
2013 Month	**ExclusionZone Crossing**	**ExclusionZone Crossing**	**ExclusionZone Crossing**	**ExclusionZone Crossing**
May	204	10	11	2
Jun	153	19	13	11
Jul	130	131	34	26
Aug	114	28	9	10
Sept	10	141	12	20
Oct	165	79	18	0
Nov	167	151	28	14
Dec	173	190	92	68
Total	**1116**	**749**	**217**	**151**

It can be assumed the exclusion zone crossing time is limited by the governor ramp rate, due to the fact that the generation control algorithm is only providing a power setpoint to the governor.

Once the setpoint is received by the governor, the governor manages the power change to meet the new setpoint. The governor control is based on the error in the current load from the new setpoint value.

An estimate of the time it takes each unit to cross the exclusion zone was established. The governor changes load at an approximate rate of 0.8MW/second for a 30MW change in setpoint. The average exclusion zone limits and width were calculated from the data collected. Table 6 shows the averages calculated and the approximate time it takes for per exclusion zone crossing.

Table 5. Exclusion Zone Average

	RZ Min (MW)	RZ Max (MW)	RZ Width (MW)	RZ Cross (seconds)
U1	15.0	45.2	30.2	37.8
U2	17.4	42.9	25.5	31.9
U3	29.9	55.8	25.9	32.4
U4	29.2	56.7	27.5	34.4

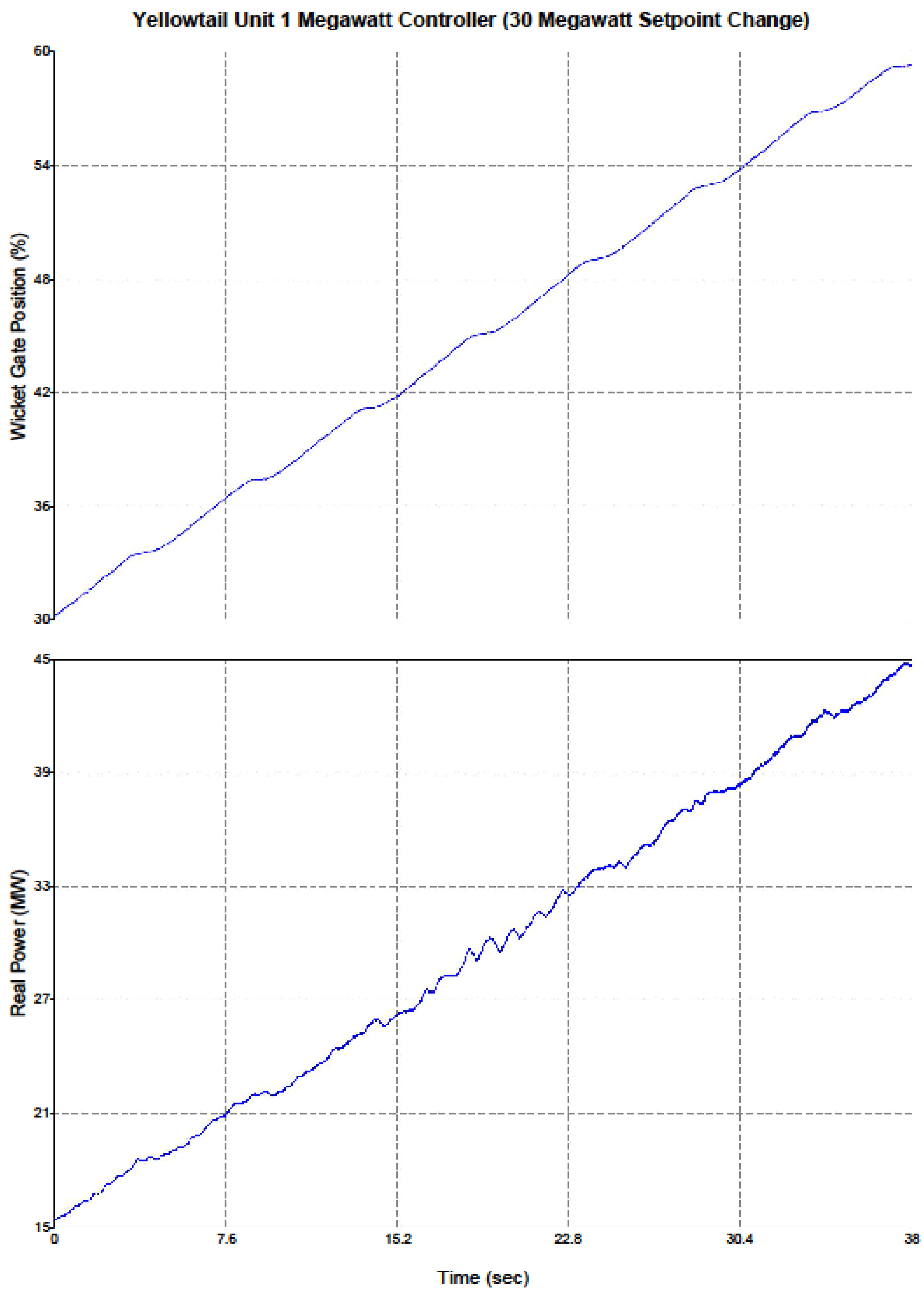
Based on Table 5 and Table 6 an estimate of the time each unit spent crossing exclusion zones can be calculated by multiplying the total number of exclusion zone crossings by the time it takes the unit to cross the exclusion zone. Table 7 shows the total time each unit spent in the exclusion zone while crossing through the exclusion zone over the period of this study.

Table 6 - Total Time In the Exclusion Zone

	RZ Crossing [Count]	RZ Crossing Time [hr]	Time in RZ while crossing (May 1 – December 31, 2013) [hr]
U1	1116	0.010500	11.72
U2	749	0.008861	6.64
U3	217	0.009000	1.95
U4	151	0.009556	1.44

Graph 1 below shows actual data taken for Yellowtail Unit 1 during governor testing and commissioning. All four units use the same governor settings for setpoint control and, therefore, should require the same amount of time to cross the exclusion zone.

Graph 1



Yellowtail Unit 1 Megawatt Controller (30 Megawatt Setpoint Change)
Wicket Gate Position (%)
60
54
48
42
36
30
Real Power (MW)
45
39
33
27
21
15
0
7.6
15.2
22.8
30.4
38
Time (sec)

6. Appendix of Plant Load and Efficiency Graphs

NOTE – The following graphs contain the raw data obtained from the SCADA system. Efficiency values greater than 93% should be ignored. These values are not frequent enough to invalidate the data set.

Figure 6

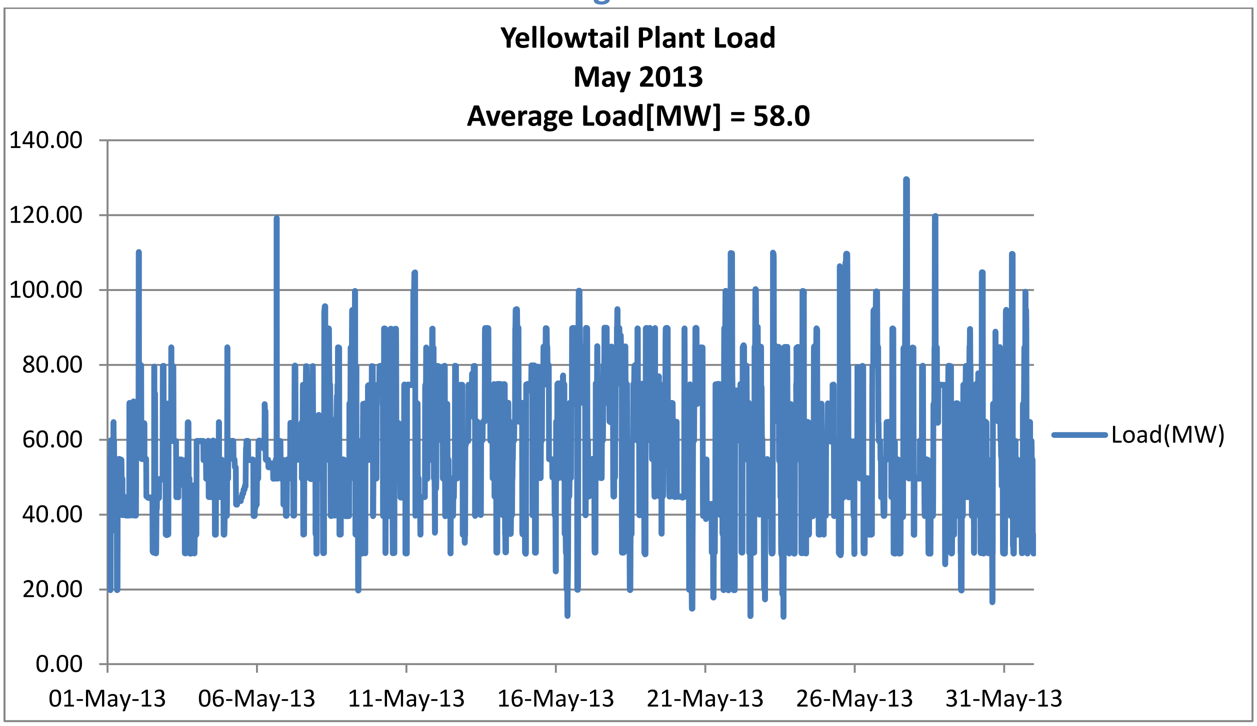


Figure 1

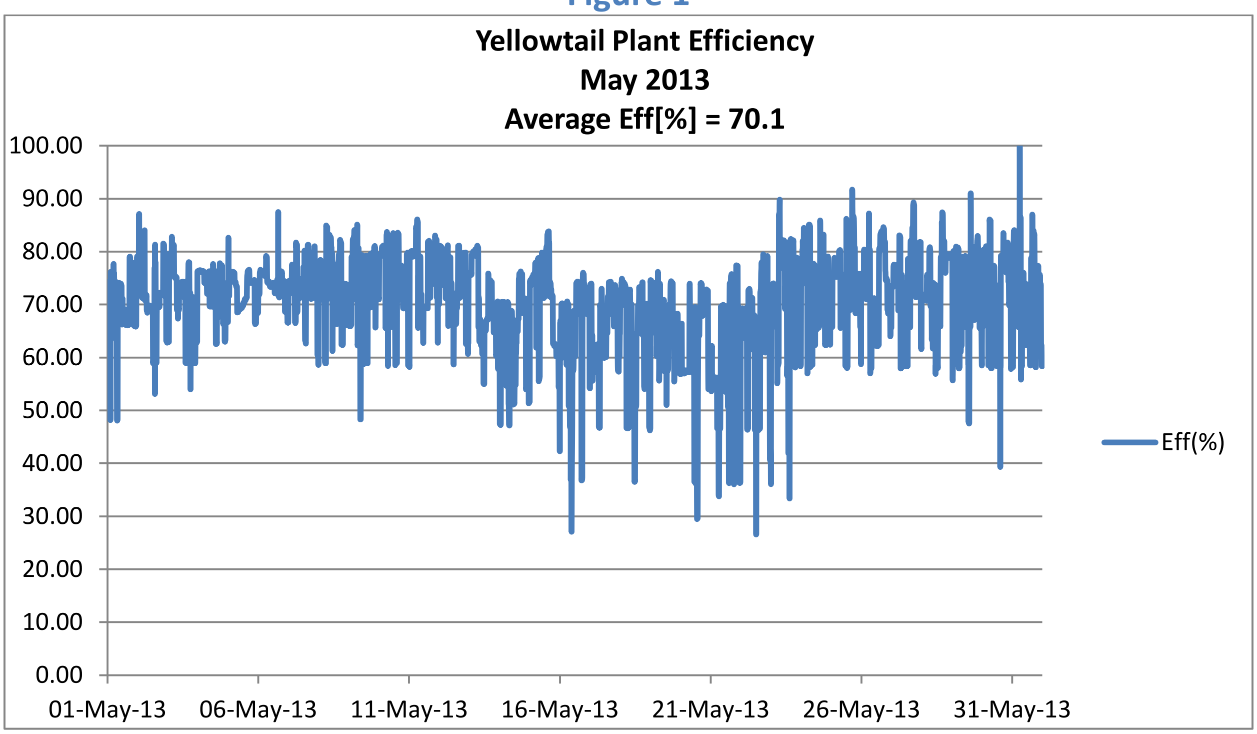
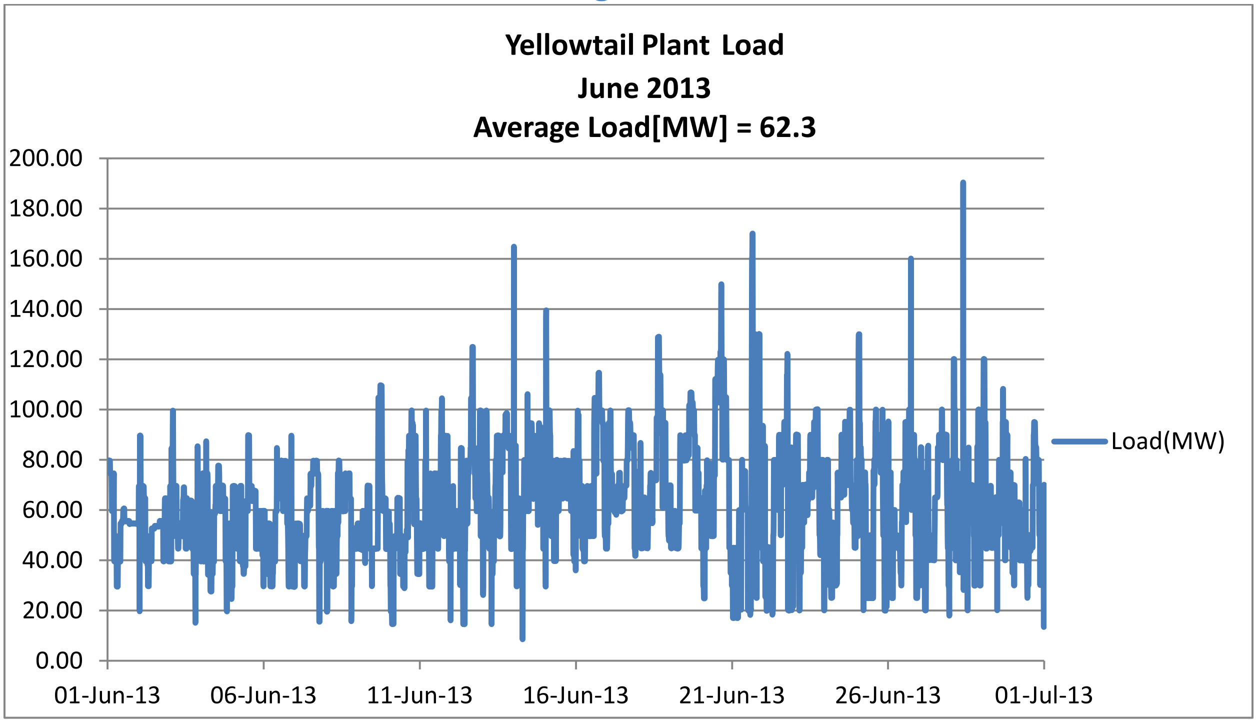


Figure 2



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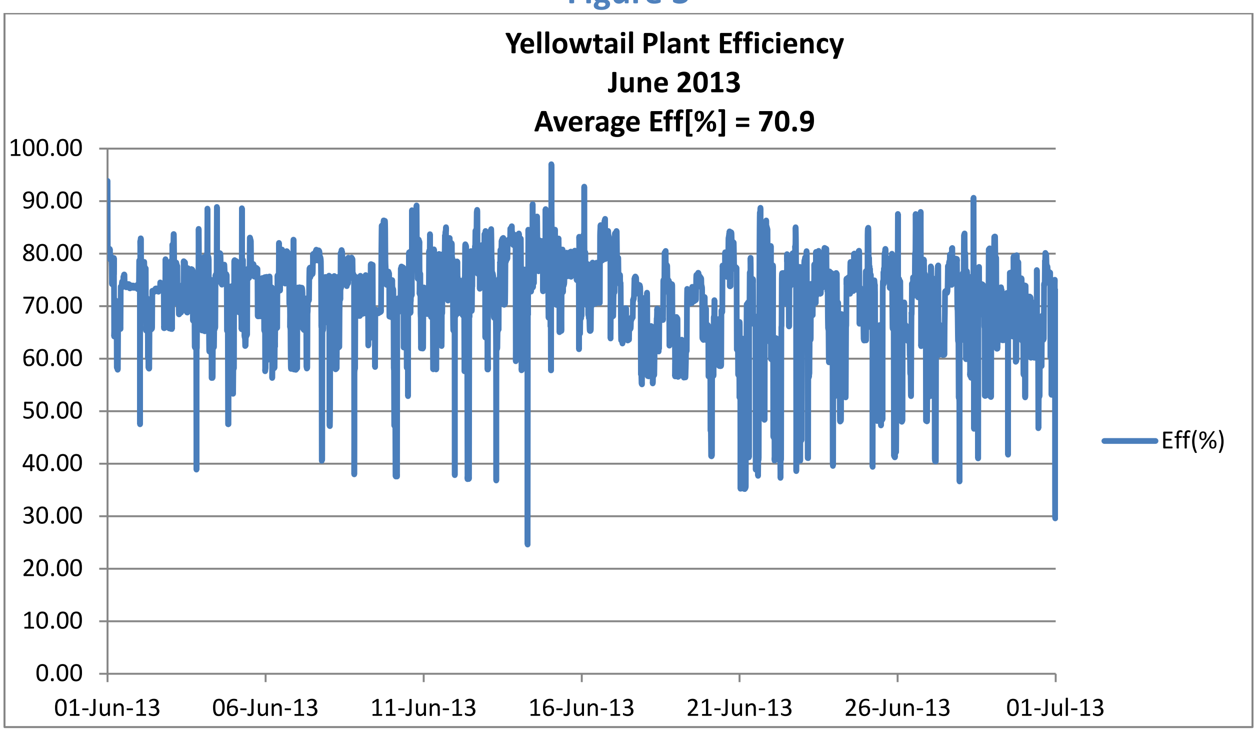
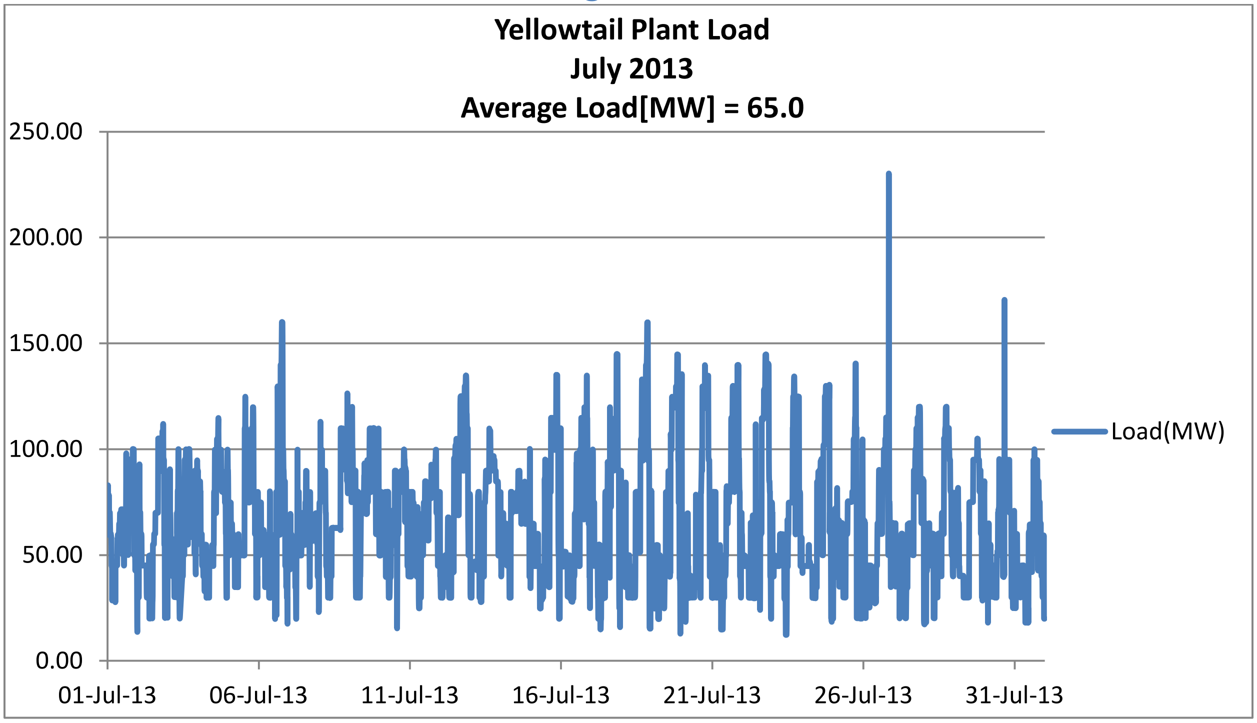


Figure 10



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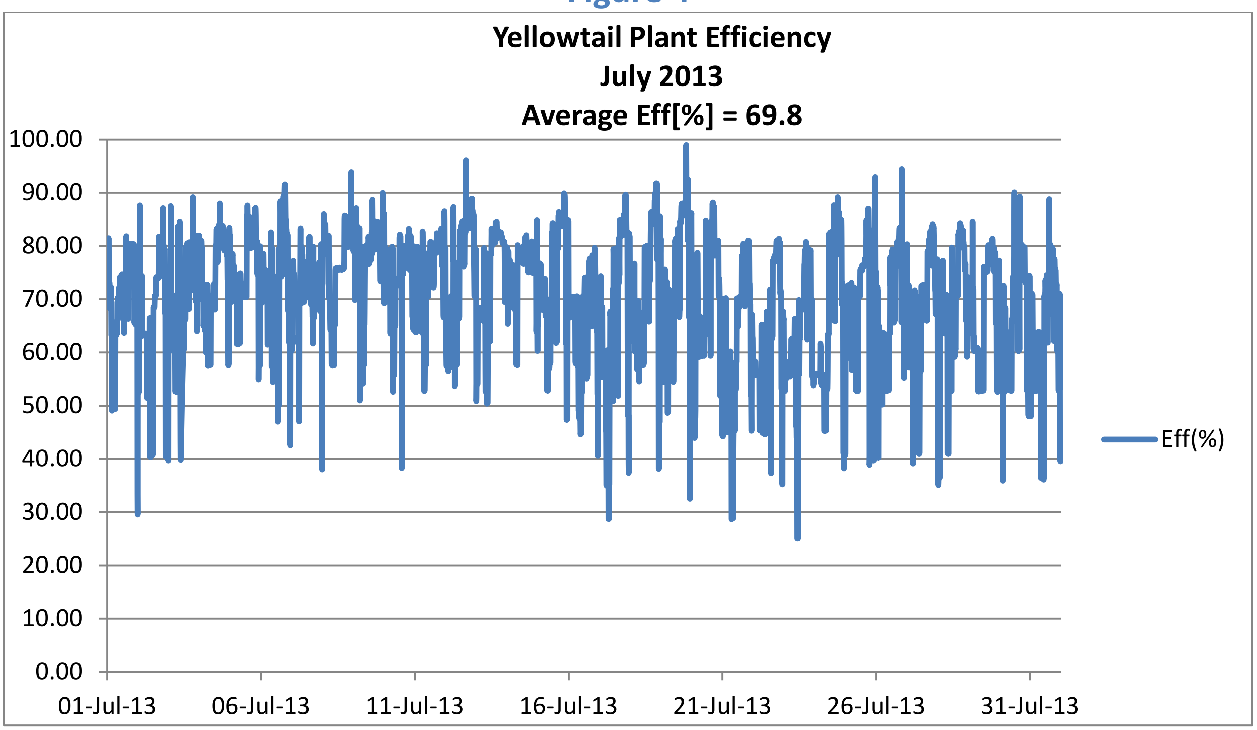

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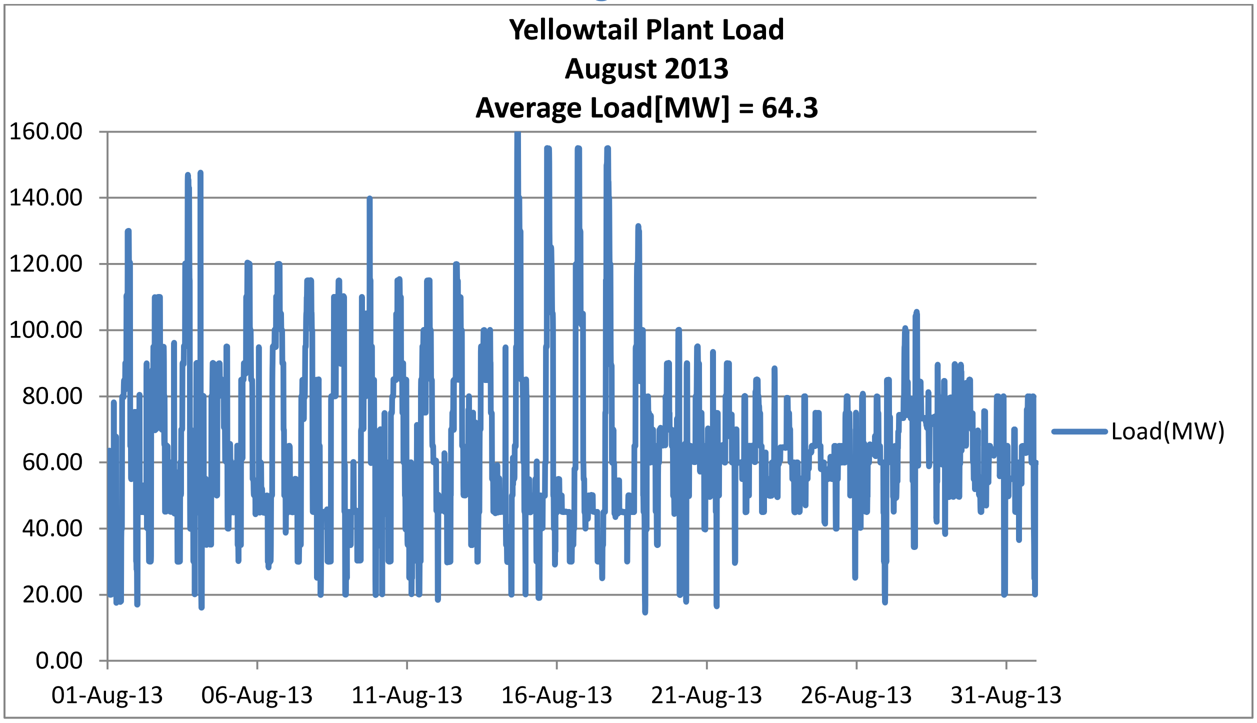

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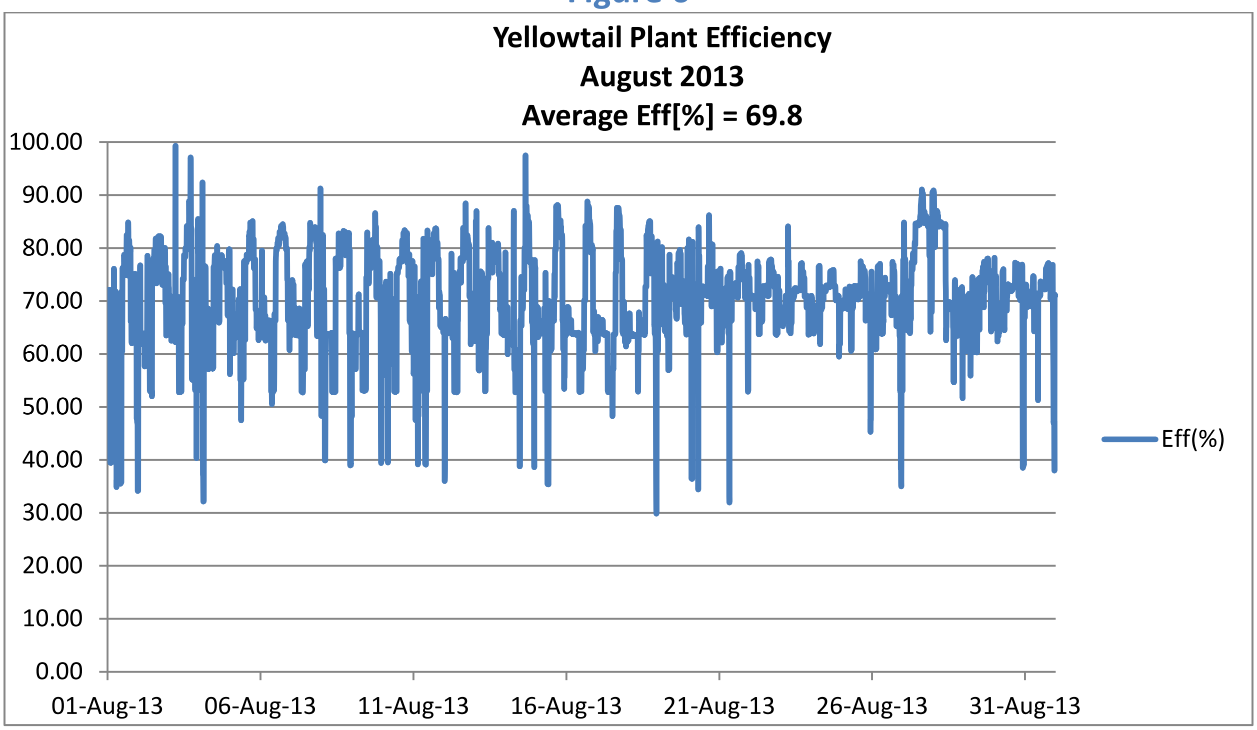

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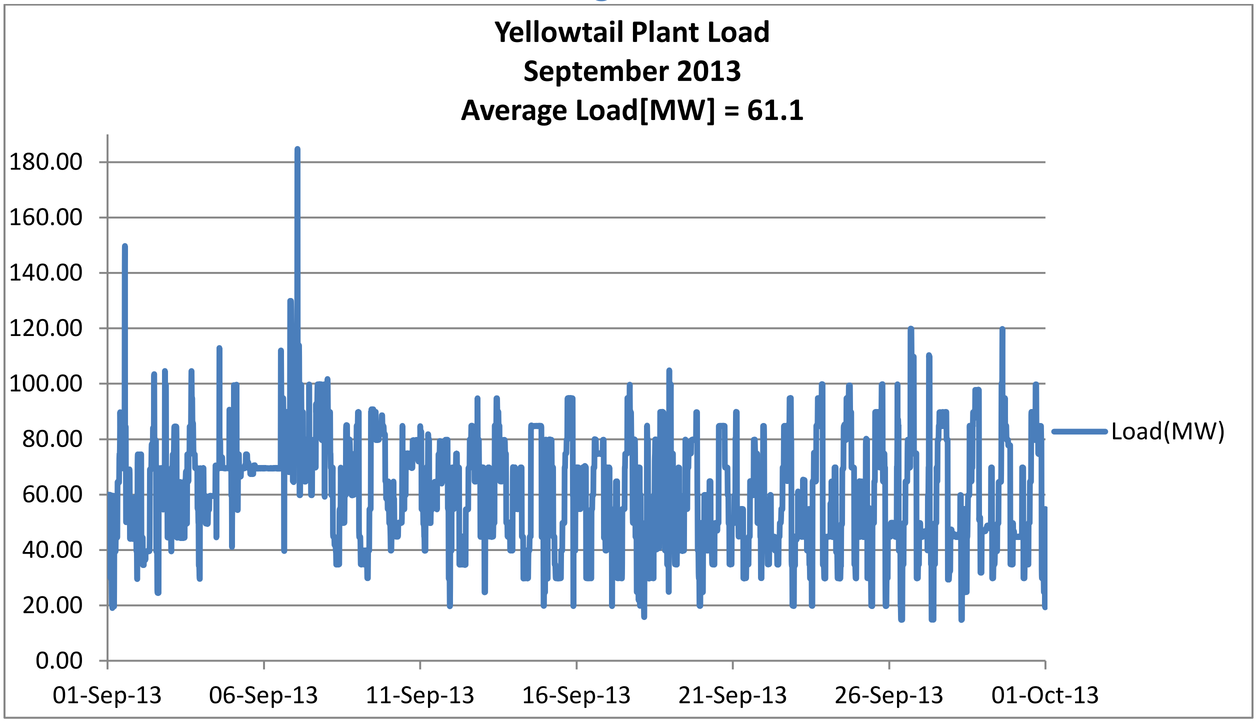
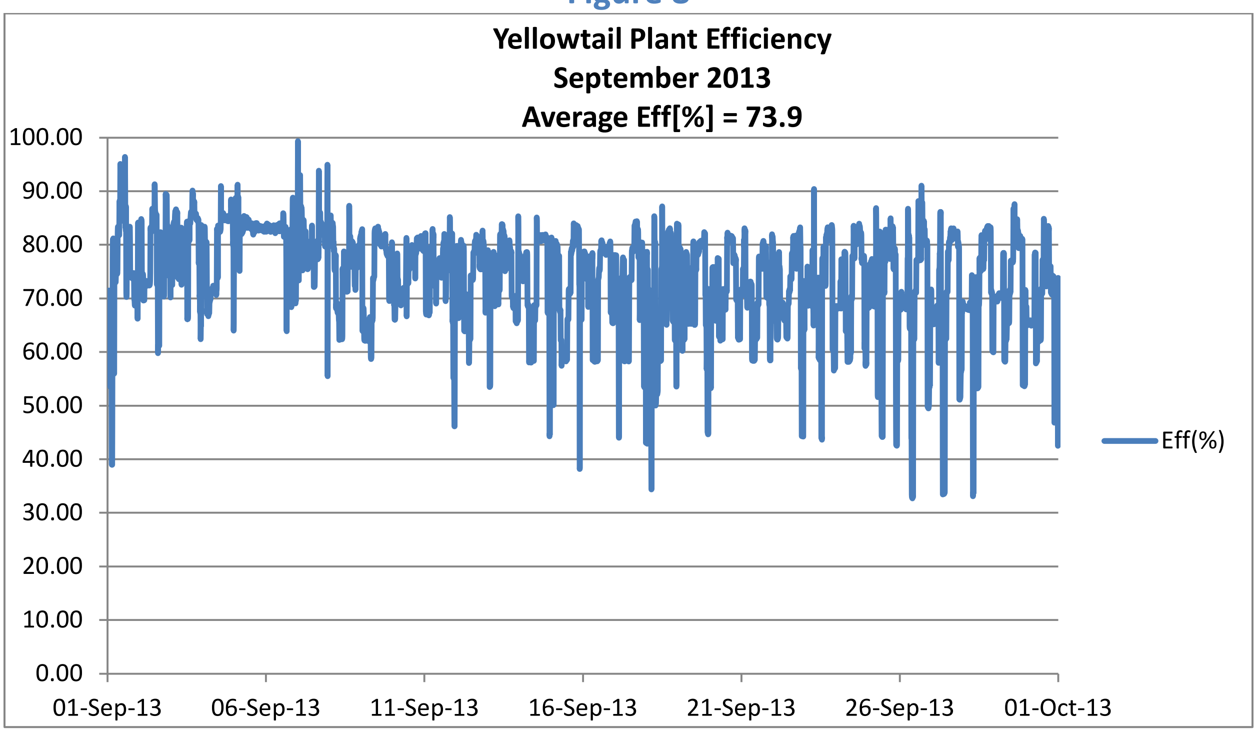


Figure 8



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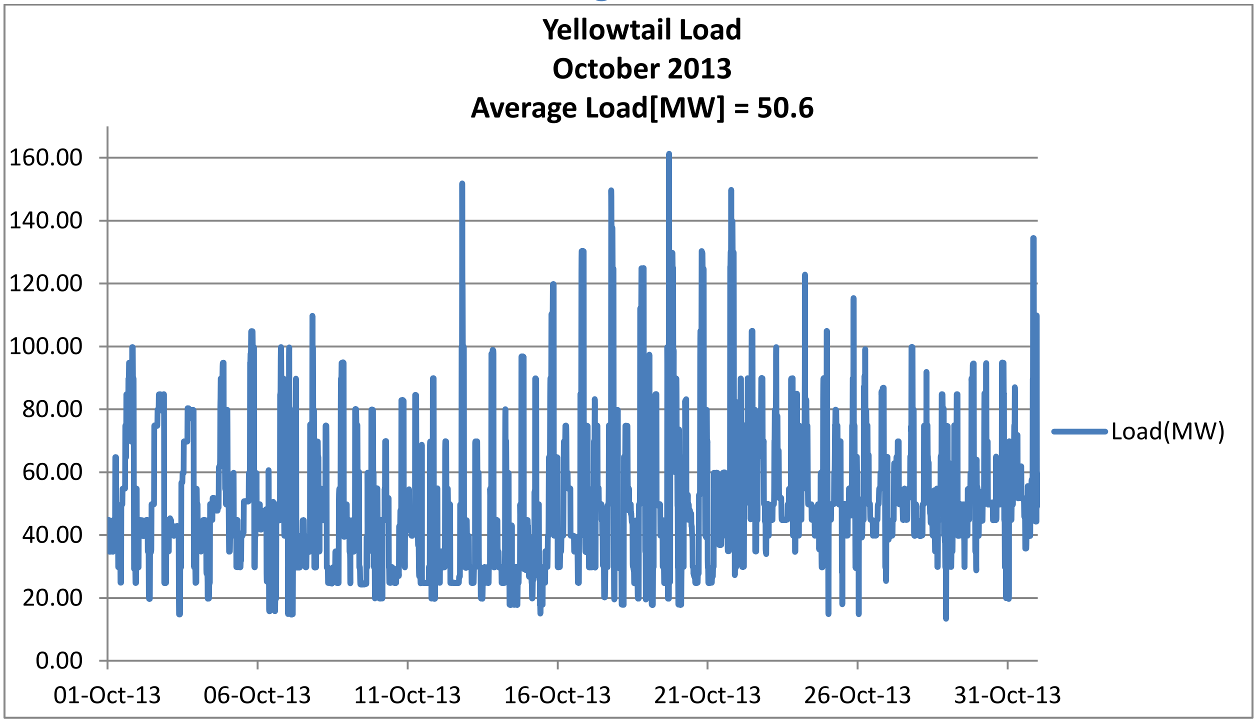


Figure 10

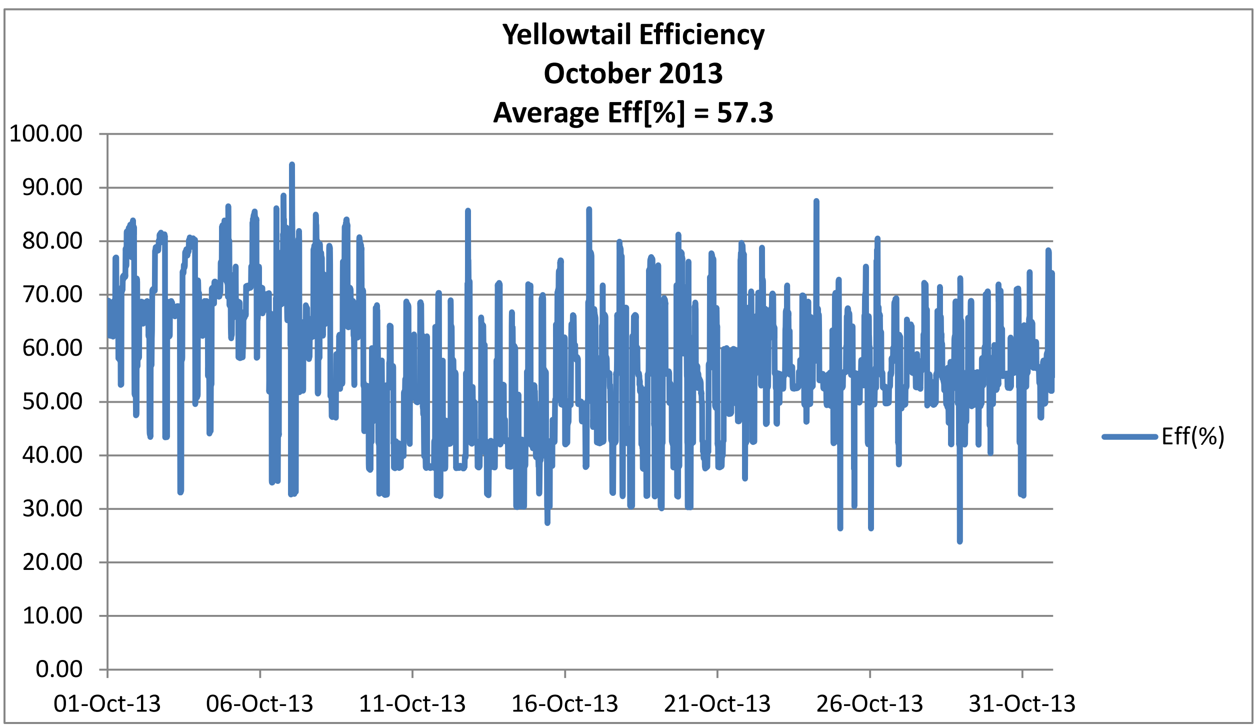


Figure 11

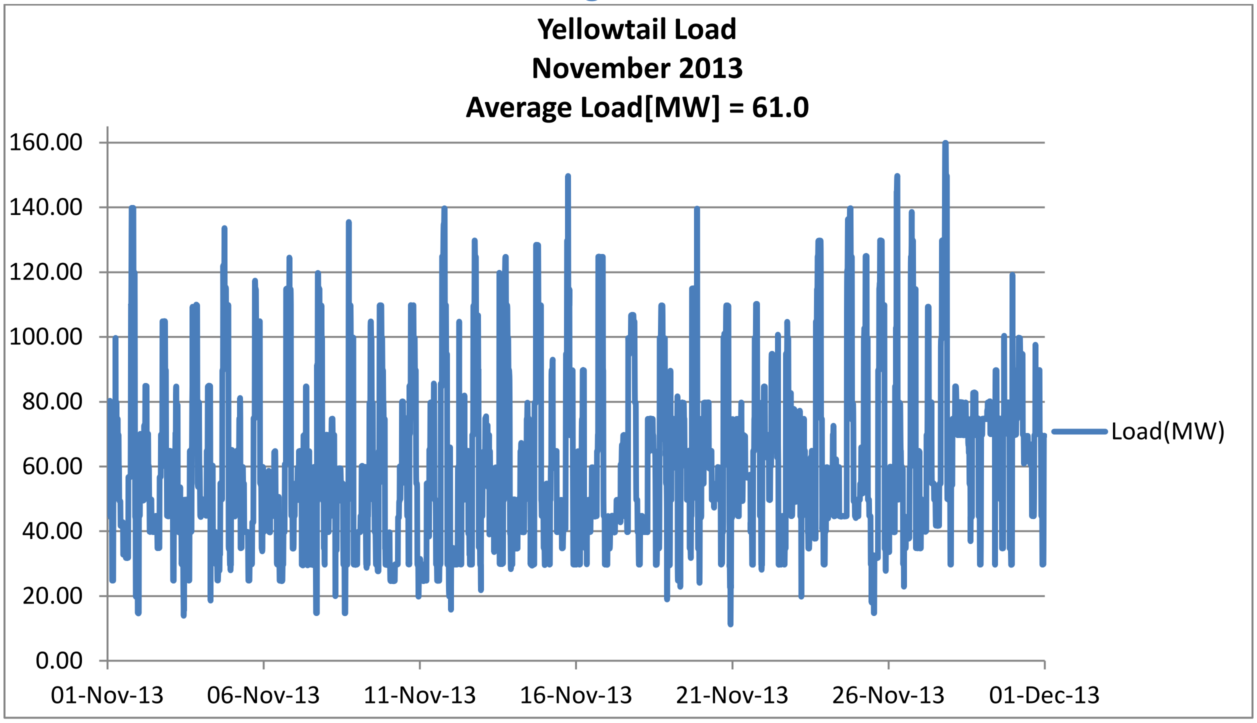


Figure 19

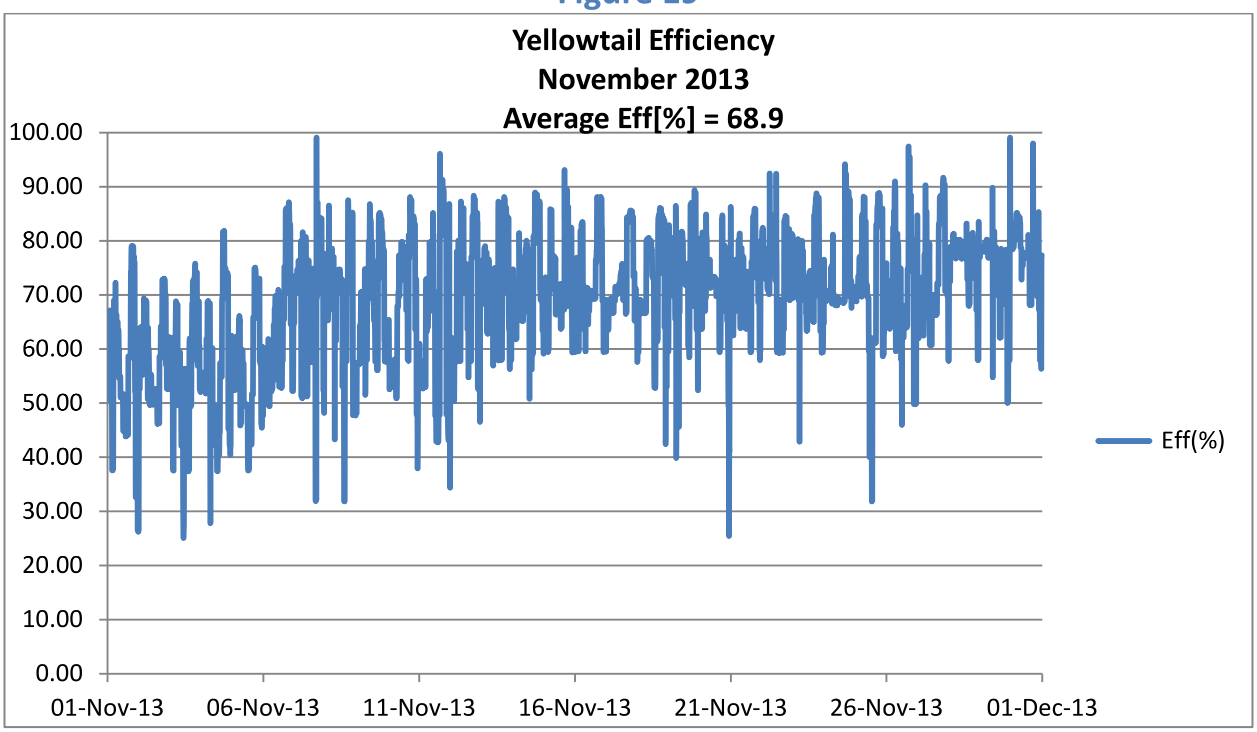


Figure 12

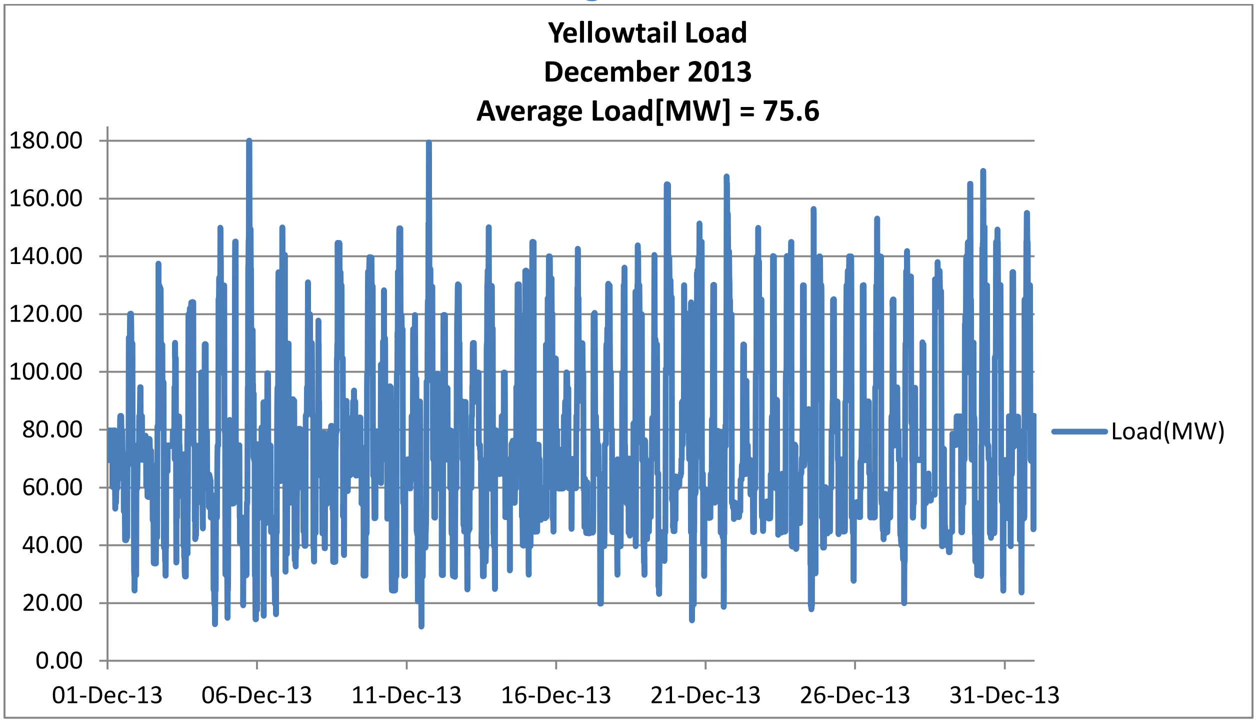
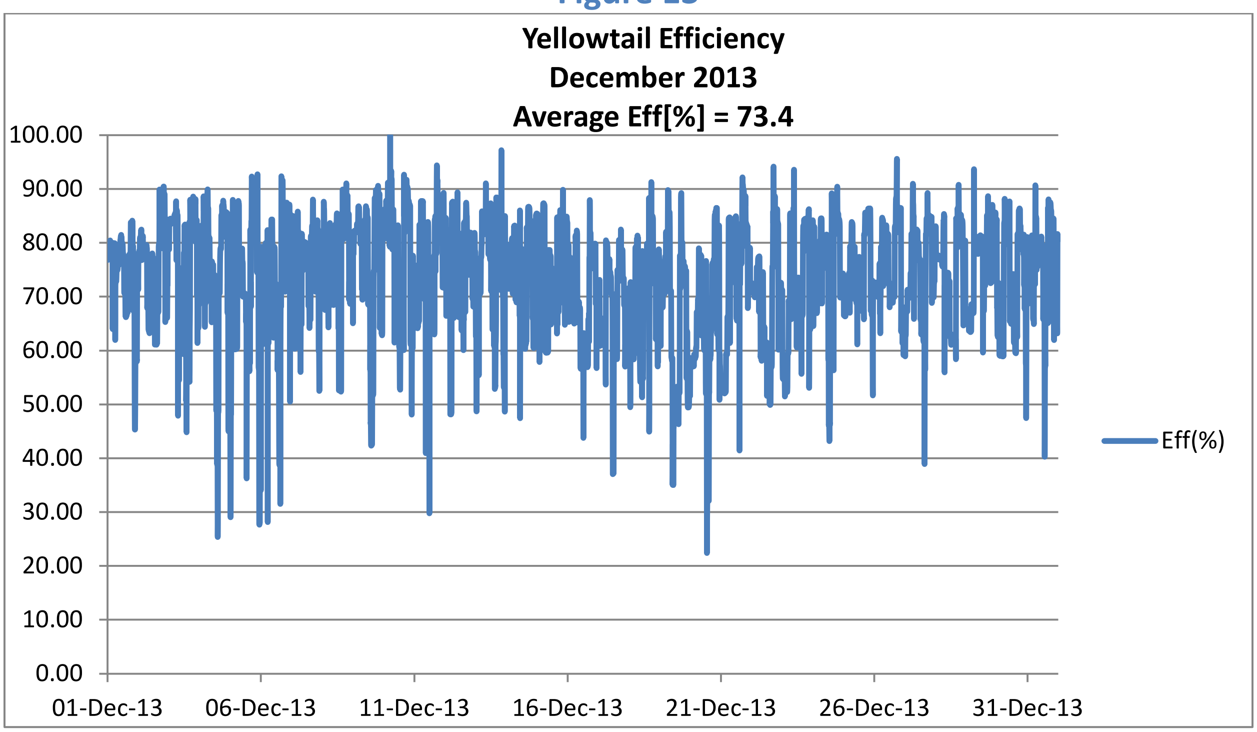


Figure 13



7. Appendix of Comparative Monthly Plant Efficiencies

Figure 14

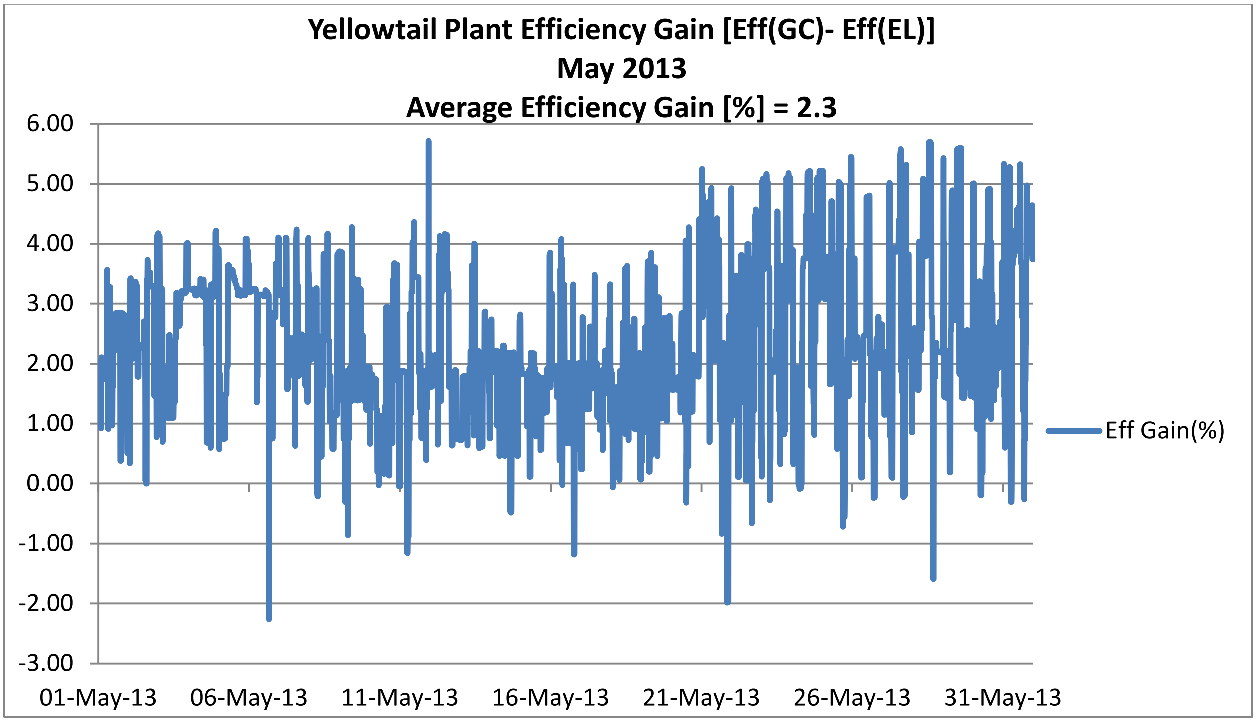


Figure 15

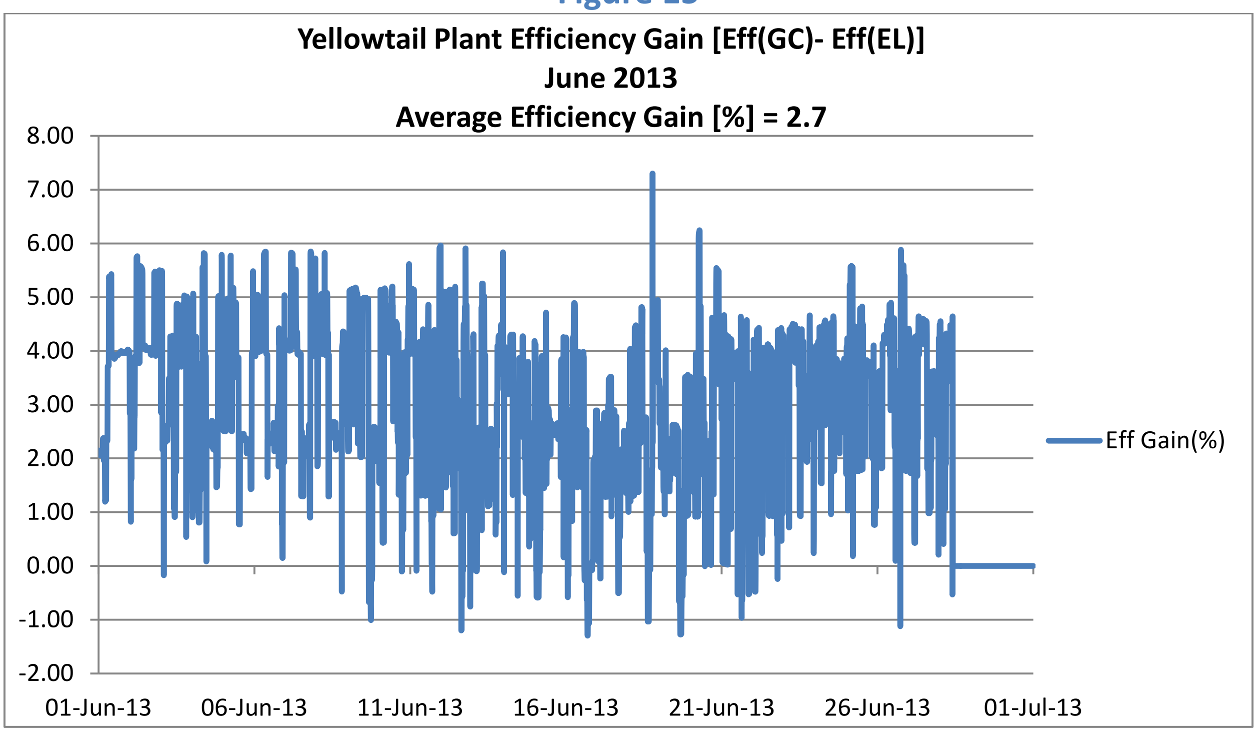


Figure 16

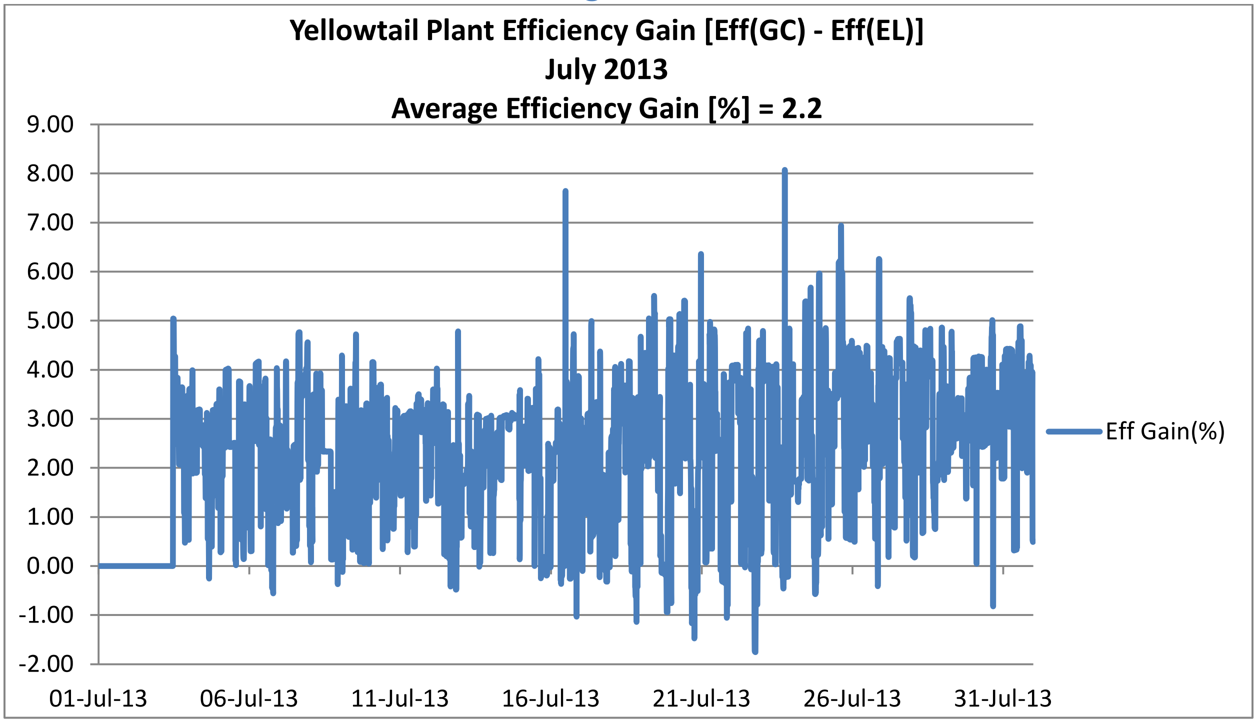


Figure 25

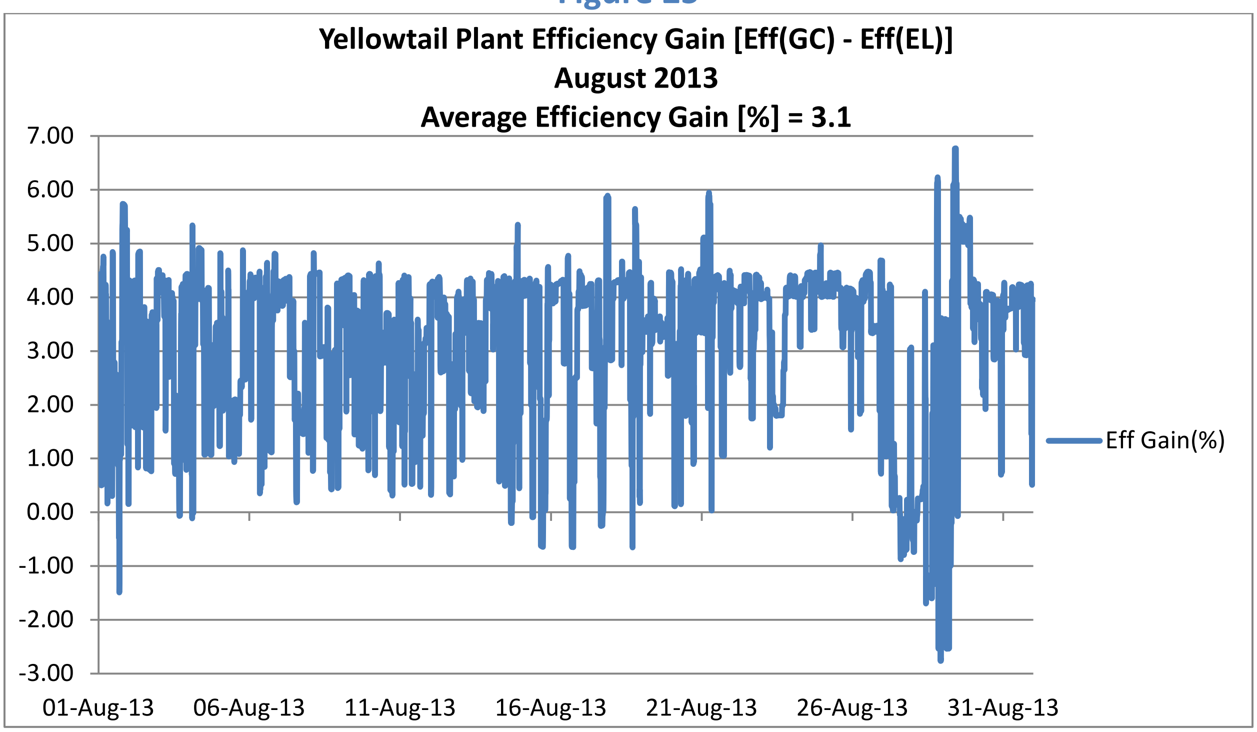


Figure 17

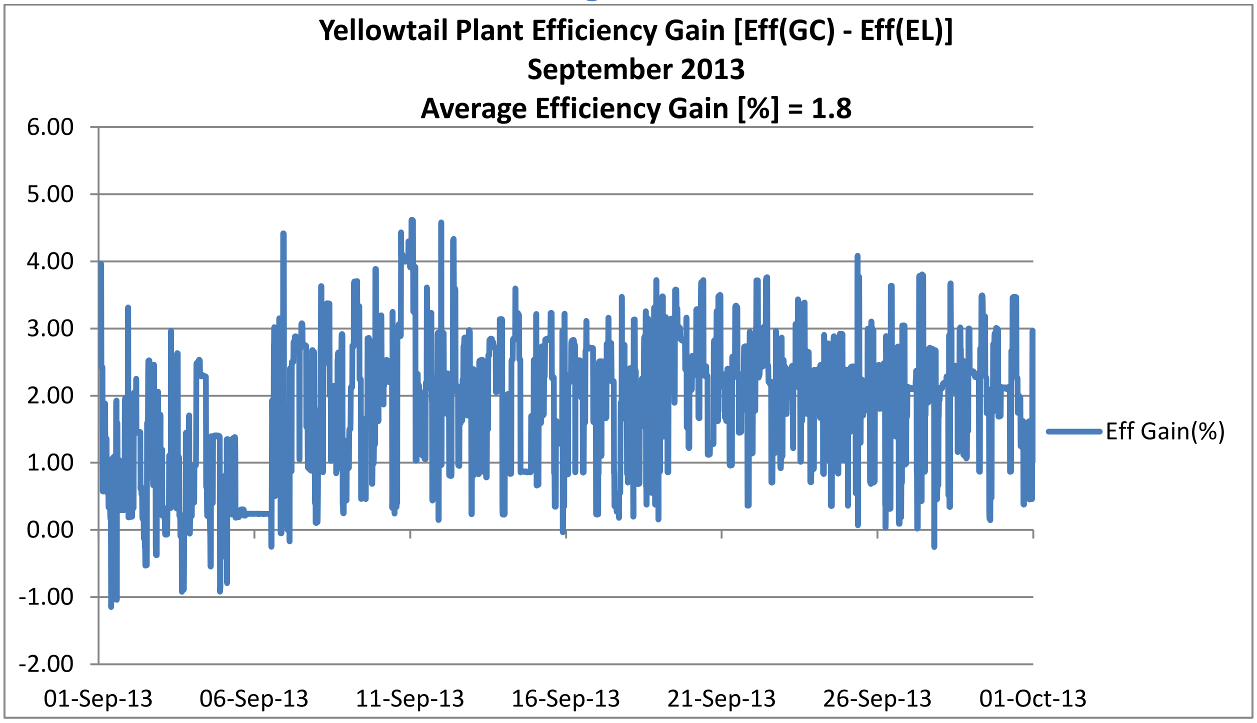


Figure 18

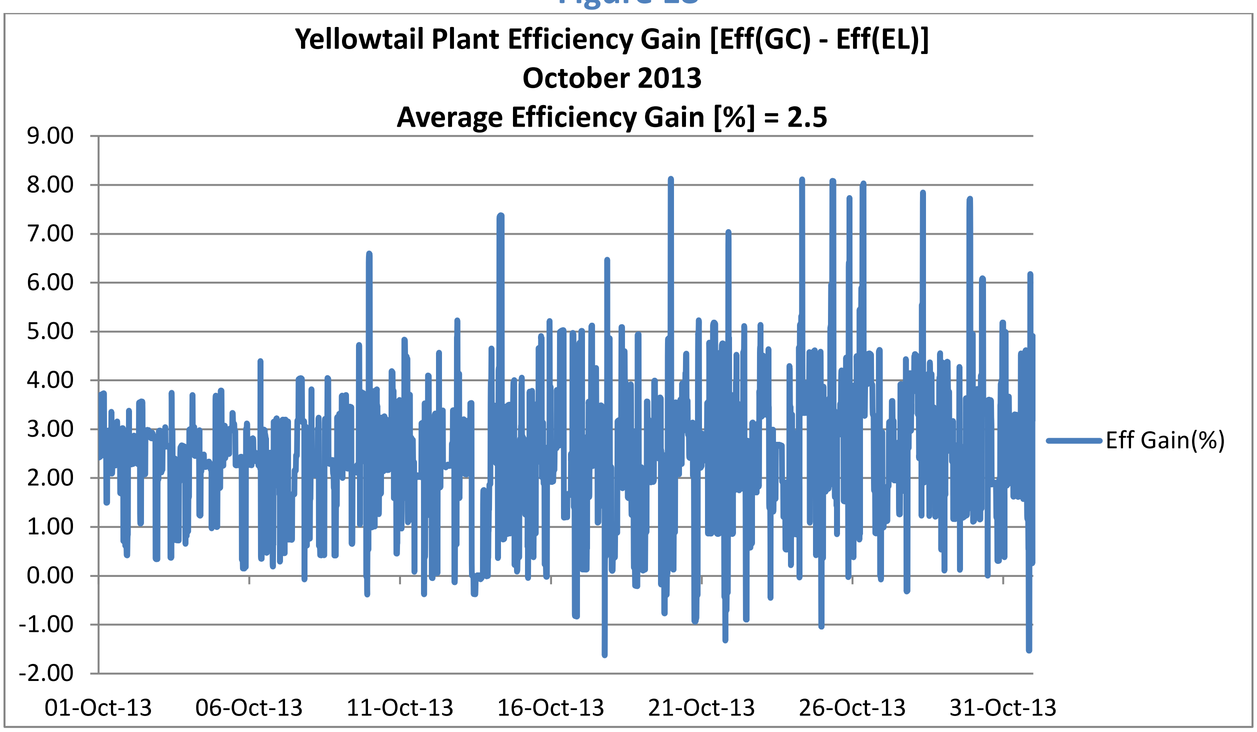


Figure 19

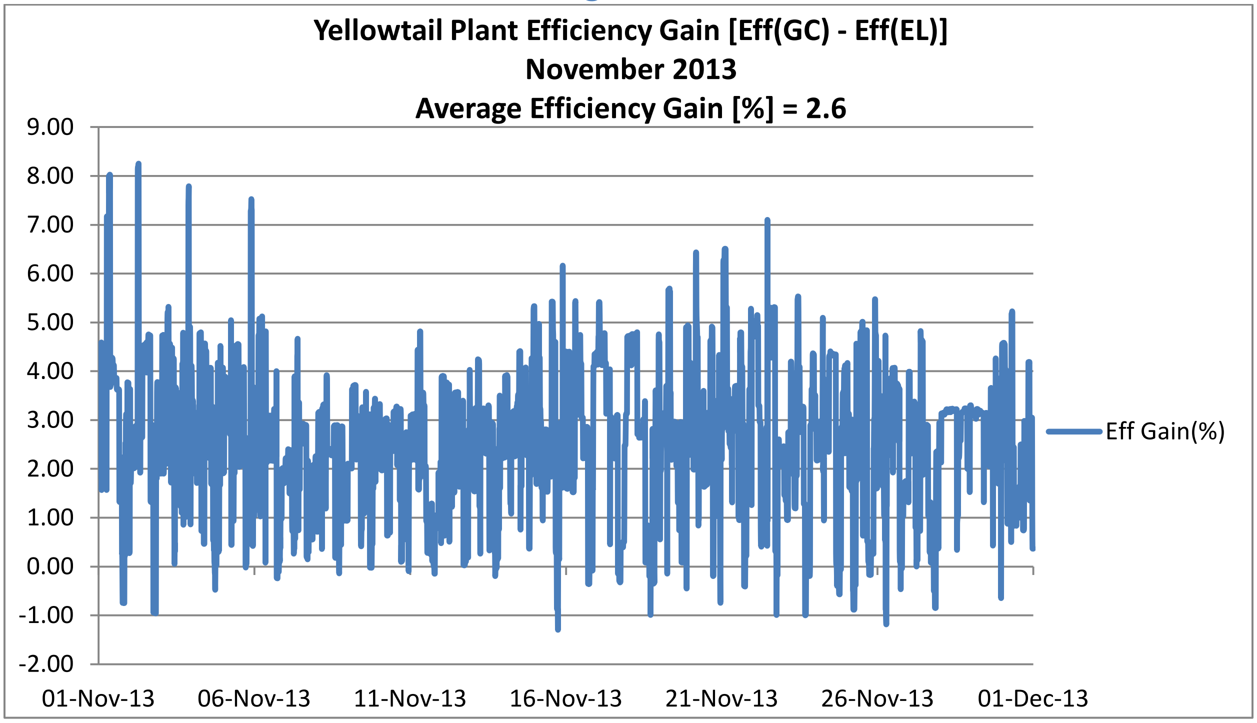


Figure 20