COMBINED HEAT AND POWER (CHP) SYSTEM OPTIMIZATION USING ENERGY, EXERGY AND THERMODYNAMIC ANALYSIS

Alumina Refinery Power Plant Optimization – Two Case Studies

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Abstract: The conventional energy analysis evaluates the performance of a thermodynamic system generally on its quantity only. It gives no information about the effect of irreversibilities on performance that occurs inherently during any thermodynamic process. On the other hand, exergy analysis, based on the second law of thermodynamics recognizes magnitudes and locations of the losses due to these irreversibilities. This paper deals with the improved energy performance of two-alumina refineries in Jamaica. One refinery produces alumina from Jamaican bauxite ore, using the Bayer process. The first process includes the digestion of bauxite with sodium hydroxide at 135 deg.C, (low temperature digestion). The second process includes the digestion of bauxite with sodium hydroxide at 245 deg.C. Hence, the requirement for both steam and power. Steam is generated using heavy fuel oil. There is auxiliary power from Internal Combustion Engines, Gas Turbine Engine and the Power Grid. The engine (the machine) produces mechanical work and then electrical power. According to the Second Law of Thermodynamics, the machine gives back heat (a part of the useful energy delivered by CHP) to a cold sink (low temperature sink), before rejecting the remaining heat to the environment at the reference temperature. Losses to the low temperature sink is minimized. This resulted in daily fuel savings of 400 barrels of Heavy Fuel Oil (HFO) and an annual savings of 146,000 barrels of Heavy Fuel Oil.

Keywords: *combined heat and power, energy, exergy analysis.*

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1. Introduction

A cogeneration plant, also called a CHP system (Combined Heat and Power), can operate at efficiencies greater than those achieved when heat and power are produced in separate or distinct processes. For example, efficiency values go from 35%–40% for electrical or mechanical production, to 80%–85% for the cogeneration system efficiency.

1.1 Types of Cogeneration System

A number of cogeneration systems are used, namely the following:

- Steam Turbine cogeneration system.
- Internal Combustion Engine cogeneration system.
- Gas Turbine cogeneration systems.

This paper will present, case studies on two steam combined heat and power plants used to provide energy for two Bayer process alumina refineries in Jamaica.

1.1.1 Steam Cogeneration System

A conventional power plant makes electricity by an inefficient process. A fossil fuel such as oil, coal, or natural gas is combusted in a giant furnace to release heat energy. The heat is used to boil water and make steam, the steam drives a turbine, the turbine drives a generator, and the generator makes electricity.

The trouble with this is that energy is wasted in every step of the process—sometimes quite spectacularly. For example, the water that is boiled into steam to drive the steam turbines must be cooled back down using giant cooling towers (low temperature sink) in the open air (low temperature sink), wasting huge amounts of energy—much of which literally disappears into thin air! Now a fuel-driven power plant must work by heating and cooling—that is what the laws of thermodynamics say.

Instead of letting heat escape uselessly up cooling towers, why not attempt to use it. That is essentially the idea behind CHP: to capture the heat that would normally be wasted in electricity generation and supply it to an industrial facility. Where a conventional power plant makes electricity and wastes the heat it makes as a by-product, a CHP power plant makes both electricity and steam and supplies both to an industrial facility. Cogeneration (the alternative name for CHP) simply means that the electricity and heat are made at the same time.

1.1.2 Types of Steam Turbines

The two types of steam turbines most widely use are the back pressure and the extraction-condensing types (Fig. 1). The choice between backpressure turbine and extraction-condensing turbine depends mainly on the quantities of power and heat, quality of heat, and economic factors. The extraction points of steam from the turbine could be more than one, depending, on the temperature levels of heat required by the processes.

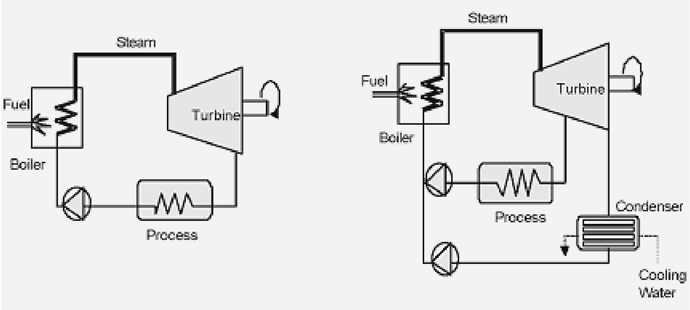

Figure 1: (a) Back-Pressure Turbine (b) Extraction-Condensing Turbine

1.2 Energy, Exergy and the Low Temperature Sink

- Energy: For this analysis, energy is the ability to cause work, and work is defined as any useful energy transformation. In most kinds of work, one type of energy is transformed into another with some going into a “used form” that no longer has potential for further work.

- Exergy: Exergy is available energy. When the surroundings are the reservoir, exergy is the potential of a system to cause a change as it achieves equilibrium with its environment. Exergy is then the energy that is available to be used. After the system and surroundings reach equilibrium, the exergy is zero. The term was coined by Zoran Rant [1] (a Yugoslavian chemical engineer) in 1956, but the concept was developed by J. Willard Gibbs [2] in 1873 (American physicist and chemist).
- Laws of Thermodynamics [3]:

  First Law of Thermodynamics: During energy transformations, energy cannot be created or destroyed.

  Second Law of Thermodynamics: the total entropy of an isolated system can never decrease over time. Entropy can increase or remain the same. Heat transfer occurs in one direction, high temperature to low temperature. The second law of thermodynamics also tells us that it is not possible to convert all the heat absorbed by a system into work.

  Entropy: The entropy of a substance is real physical quantity and is a definite function of the state of the body, like pressure, temperature, volume of internal energy. It is difficult to form a tangible conception of this quantity because it cannot be felt like temperature or pressure. We can, however, readily infer it from the following aspects:

  Entropy and unavailable energy: The second law of thermodynamics tells us that whole amount of internal energy of any substance is not convertible into useful work. The portion of this energy, which is used for doing useful work, is called available energy. The remaining part of the energy that cannot be converted into useful work is called unavailable energy. Entropy is a measure of this unavailable energy. In fact, the entropy may be regarded as the unavailable energy per unit temperature.

  The Second Law of Thermodynamics is about the quality of energy. It states that as energy is transferred or transformed, more and more of it is wasted. It is impossible to construct a heat engine of 100% thermal efficiency.

  The third Law of thermodynamics: the entropy of a system approaches a constant value as the temperature approaches absolute zero.

  Exergy is the energy that is available to be used. In contrast to energy, exergy is always destroyed when a process is irreversible, for example loss of heat to the environment. This destruction is proportional to the entropy increase of the system together with its surroundings.

  Energy is quantity, Exergy is quantity and quality. The basis of powerhouse optimization is to reduce exergy losses to the low temperature sink.

2. Low Grade Heat Minimization/Recovery

1. A large amount of low-grade heat in the temperature range of 30 deg. C and 180 deg. C are readily available in process industries, and wide range of technologies can be employed to recover and utilize low-grade heat [4].
2. The basis of this optimization is to minimize losses to the low temperature sink.

3. Case Study 1 – 1,650,000 t/y Alumina Refinery

The powerhouse consists of three 1500 psig 270 t/h boilers, a 365 t/h boiler, two 20 MW topping steam turbine generators operating at 1500 psig and exhausting at 635 psig, a two 10 MW extraction-condensing turbine generator, and a standby 15 MW gas turbine generator. The plant operates at 60 Hz. The schematic is shown in Fig. 2.

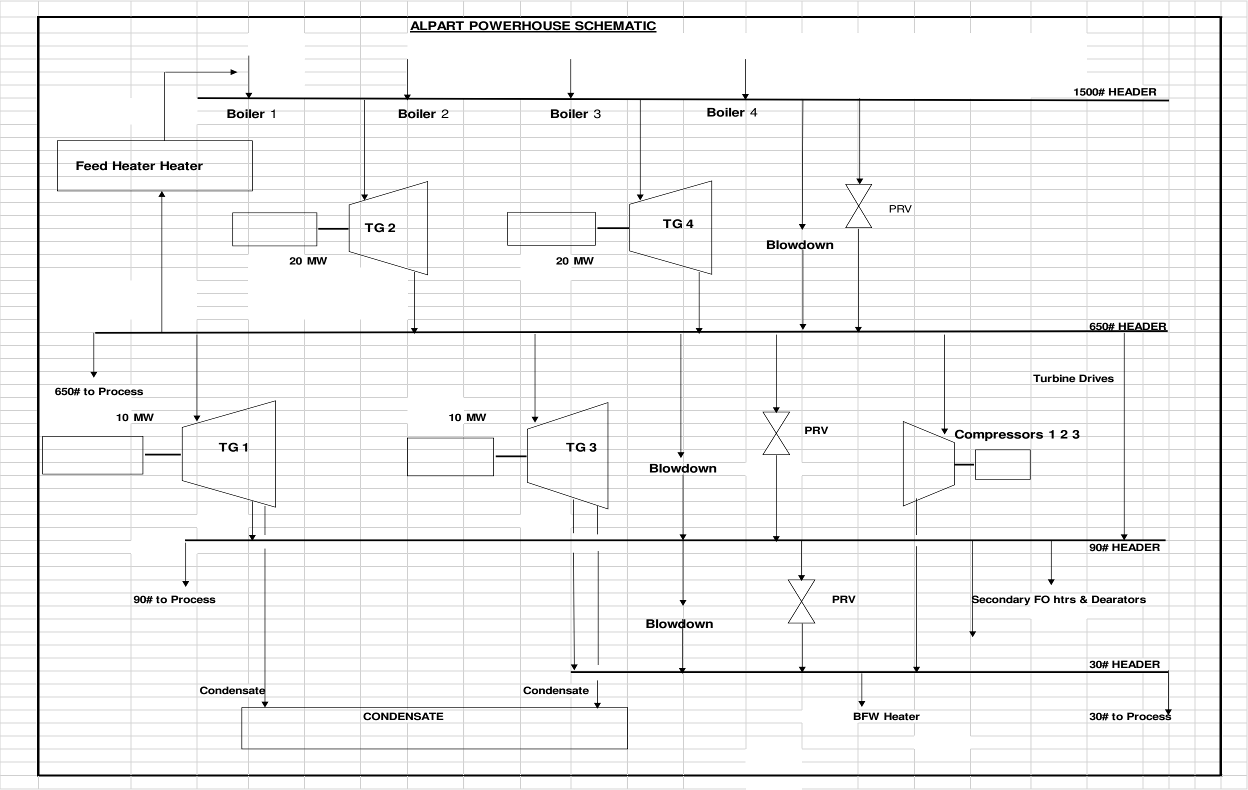

Figure 2: Powerhouse Schematic

3.1 Power Plant Design

Table 1: Powerhouse Major Equipment

Boilers 1-3	270 t/h
Boiler 4	365 t/h
2x Topping Steam Turbines	20 MW
2x Condensing Turbines	10 MW
635# Boiler Feed Water Heater	
GE Combustion Turbine	15 MW

Table 2: Process Variables and Energy Consumption

	As Found	Phase 1	Phase 2 (Proposed)
Production (tpd)	4,550	4,550	4,550
Plant Flow (gpm)	10,850	10,850	10,850
Boilers On-line	4	4	2
Total Steam (t/h)	995	840	635
Powerhouse Steam (t/h)	385	245	25
Process Steam (t/h)	610	595	610

635# Digestion Steam (t/h)	420	410	420
635# Calcination Steam (t/h)	50	50	20
90# Steam (t/h)	95	75	130
30# Steam(t/h	55	60	180
Total Power (MW)	54	48	40
Topping Power (MW)	34	32	20
Condensing Power (MW)	20	16	0
Supplementary Power (MW)	0	3	30
Evaporation Rate (t/h)	450	450	450
Condensate Return (t/h)	255	255	255
Precipitation Yield (%)	67.8	67.8	67.8
Boiler Fuel Oil Consumption (bbls/day)	**8,600**	**8,200**	**5,300**
Boiler Fuel Oil Energy (GJ/t)		**12.87**	**7.84**
Diesel Fuel Consumption (bbls/day)		280	35
Diesel Fuel Energy (GJ/t)		**0.40**	**0.05**
Energy From 30 MW (GJ/t)	**-**	**-**	**0.57**
Calcination Fuel Oil Consumption (bbls/day)	2,600	2,600	2,600
Calcination Fuel Oil Energy (GJ/t)		**3.92**	**3.92**
TOTAL ENERGY (GJ/t)		**17.19**	**12.38**

Three scenarios are presented in Table 2. Scenario 1 is the as found situation, with power at 54 MW and the 635# feedwater in service at 235 deg.C. Scenario 2 is the optimized case with the 635 psig heater out of service and 4 MW power reduction (by replacing the electrical boiler feedwater pumps with steam driven pumps). Scenario 3 is the proposal to remove the condensing turbines and replace them with 35 MW of auxiliary power.

The oil savings was 400 bbl./day or 146,000 bbl. of Heavy Fuel Oil per year. The oil savings for the proposed addition of 35 MW of auxiliary power and taking the condensing service could result in an annual fuel savings of 3,300 bbl./day or 1,204,500 bbl. of Heavy Fuel Oil per year.

4. Case Study 2 – 650,000 t/y Alumina Refinery

The powerhouse consists of three 600 psig 100 t/h boilers, a 70 t/h boiler, two 10 MW extraction steam turbine generators operating at 50 Hz, a 6.9 MW extraction-condensing turbine generator, and standby grid power from the utility grid. The grid does not provide reactive power (Vars) support. The as found schematic is shown in Fig. 3.

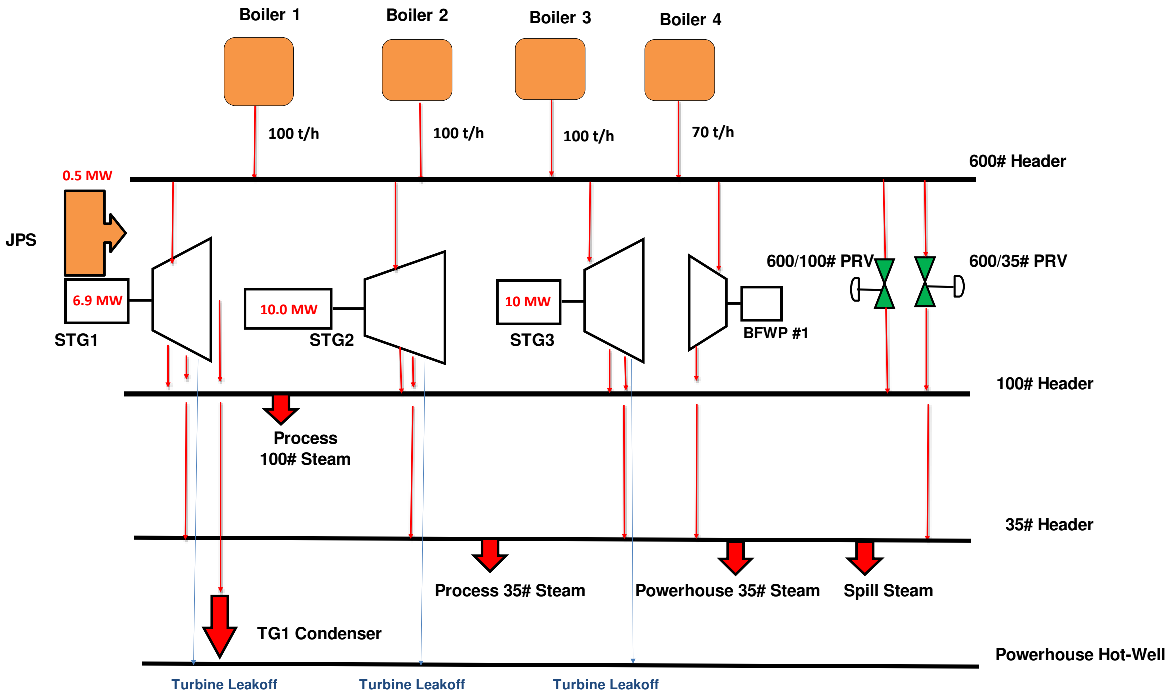

Figure 3: Powerhouse Schematic (as found before optimization)

An analysis of the powerhouse showed that both PRVs were leaking steam to the 100# and 35# headers, bypassing the steam turbines. The 6.9 MW steam turbine generator was maxed out. It meant that based on process steam use, additional power was generated by venting steam at the 35# header (additional steam flow through the turbine generators). The solution for this was to import incremental power from the grid.

3.0 - 4.0 MW of grid power was imported, and STG1 and the condensing steam turbine generator taken out of service. This was referred to as 3 Boilers and 2 Steam Turbine Generators (or 3+2). This was Powerhouse Optimization Phase 1. The schematic is shown in Fig. 4.

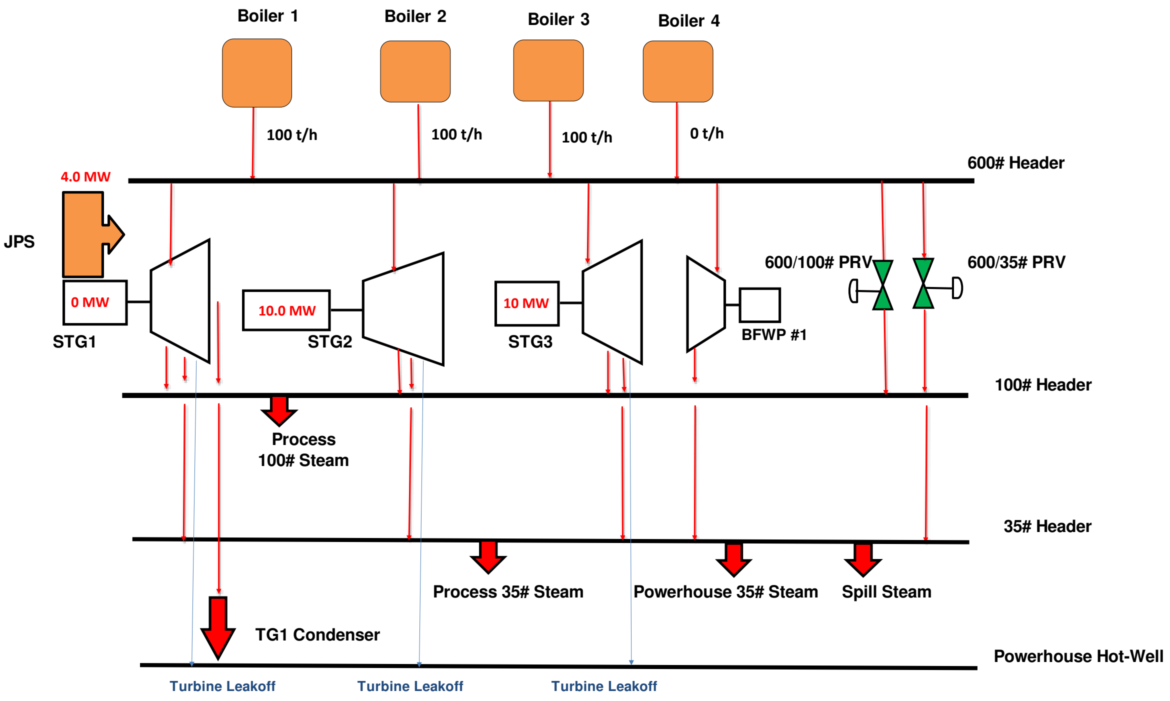

Figure 4: Powerhouse Schematic (after optimization Phase 1)

A project was set up to replace the malfunctioning PRVs (referred to as Powerhouse Phase 2), which would restore the Powerhouse to original design. The original design was three 100 ton/h boilers in service, 70 t/h boiler on stand-by, all three steam turbine generators in service.

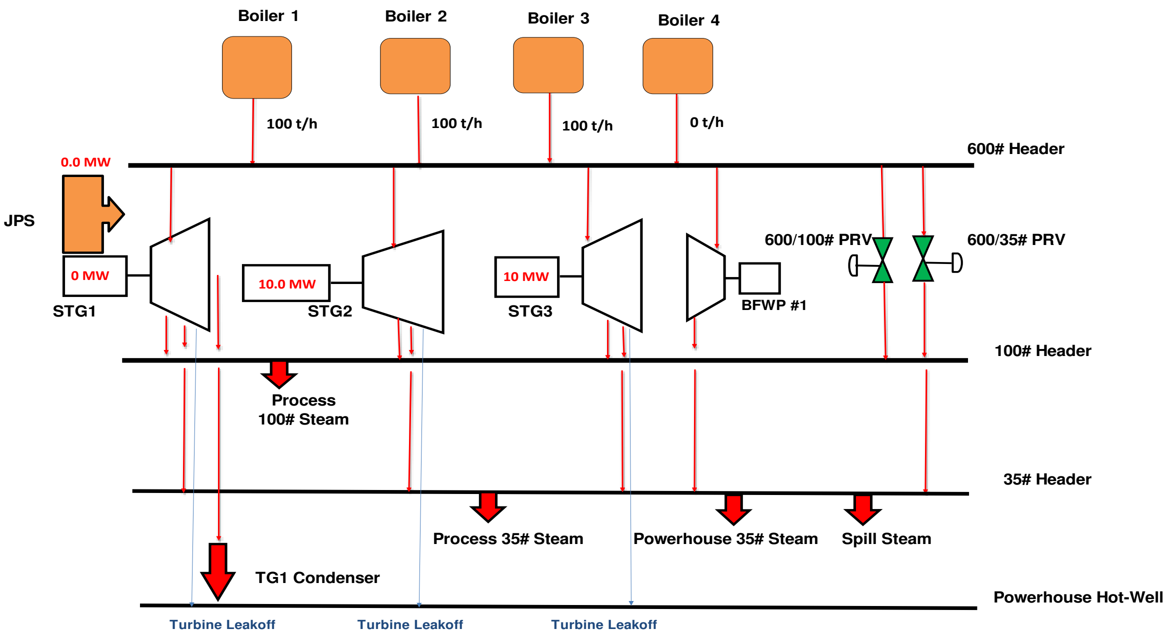

Figure 5: Powerhouse Schematic (After PRV replacement – Phase 3)

The operating regime for the condensing turbine was set to minimize losses to the low temperature sink as follows:

Figure 6: STG1 Steam Schematic

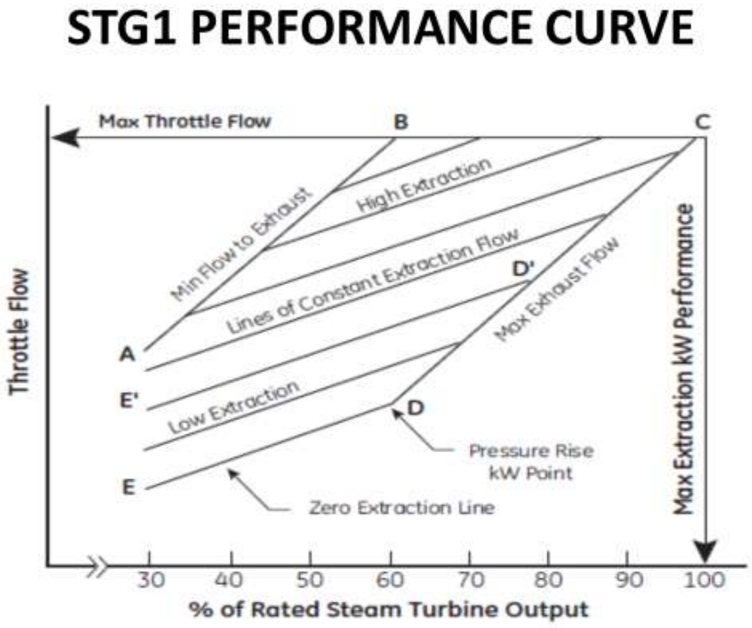

Figure 7: STG1 Performance Curve

- STG1 to operate at 3.0 – 3.5 MW.
- STG1 to operate on the minimum exhaust line of the performance curve (allows minimum condenser flow).
- Incremental 100# and 35# steam production from STG1 by reducing steam flow to the condenser.

The results are shown in Table 3.

Table 3: Operating Data

	AS FOUND (4+3)	PHASE 1 (3+2+JPS)	PHASE 2 (3+3)
Boiler Steam (t/h)	274	238	240
STG1 (MW)	2.6	0.0	3.5
STG2	8.7	7.7	8.7
STG3	8.8	9.8	8.8
JPS	0.5	3.1	0.0
TOTAL MW	20.5	20.6	21.0
Spill Steam (t/h)	20	1.5	0.0
Process Steam (t/h)	201	208	204
PRV Steam (t/h)	44	23	0
Production (t/d)	1,638	1,787	1,720
Plant Flow (m^3/h)	1,297	1,338	1,300
Boiler Fuel (t/d)	486	418	426

Fuel Savings 60 t/d or 400 bbl./day = 146,000 bbl. of Heavy Fuel Oil per year were realized.

5. Conclusions

1. Savings of 146,000 bbl. of HFO per year at Refinery 1.
2. Reconfigured Refinery 1 by retiring two 270 t/h boilers, retiring 20 MW of condensing power, and purchasing 35 MW of auxiliary power. Potential fuel savings of 1,204,500 bbl. HFO/year.
   This project was presented to the Board in Moscow. The Partners were instructed to pursue. Lost opportunity. Alpart was reopened 2017 after being shuttered in 2009. Refinery closed September 2019. This plant is slated for optimization, for reopening 2021.
3. Savings of 146,000 bbl. of HFO per year at Refinery 2. This project prevented the refinery from closing 1Q 2012 after reopening in 2010. Refinery still operating in 2019.

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