Wood Group GTS

HOW WE ASSESS THE EFFICIENCY OF A COMPRESSION PROCESS: A STATISTICAL METHOD WITH APPLICATION TO STAGING DESIGN AND SELECTION FOR A CENTRIFUGAL COMPRESSOR

Dorin Scheianu PE, PhD and Tarun Dhall
Wood Group GTS

Summary

-Introduction and definitions

-Assumptions and calculations

-Discussion on compression process

-Statistical distributions functions

-Description of the method and its three steps

-Example 1 – existing unit, analysis

-Examples 2.1-2.5 – existing units, analysis

-Discussion

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-Discussion and conclusions

-Questions?

Introduction

A compression process is defined by the main operating parameters:

- process gas suction pressure
- process gas suction temperature
- process gas discharge pressure
- process gas flow
- process gas composition
- site elevation (barometric pressure)
- ambient temperature
- equipment type (reciprocating, centrifugal etc.)

Efficiency is defined in different ways:

- operating expenses
- profit
- fuel and other energy consumption (or costs associated with)
- other consumables and parts (or costs associated with)
- manpower (or costs associated with)

Present paper will consider for analysis the fuel efficiency only

Introduction

Assumptions:

- The main driver is a type of combustion engine (gas turbine or reciprocating) and the fuel is natural gas or other distillate; if the driver is electric then the energy consumption may be expressed in kWh/hr and the analysis would be similar

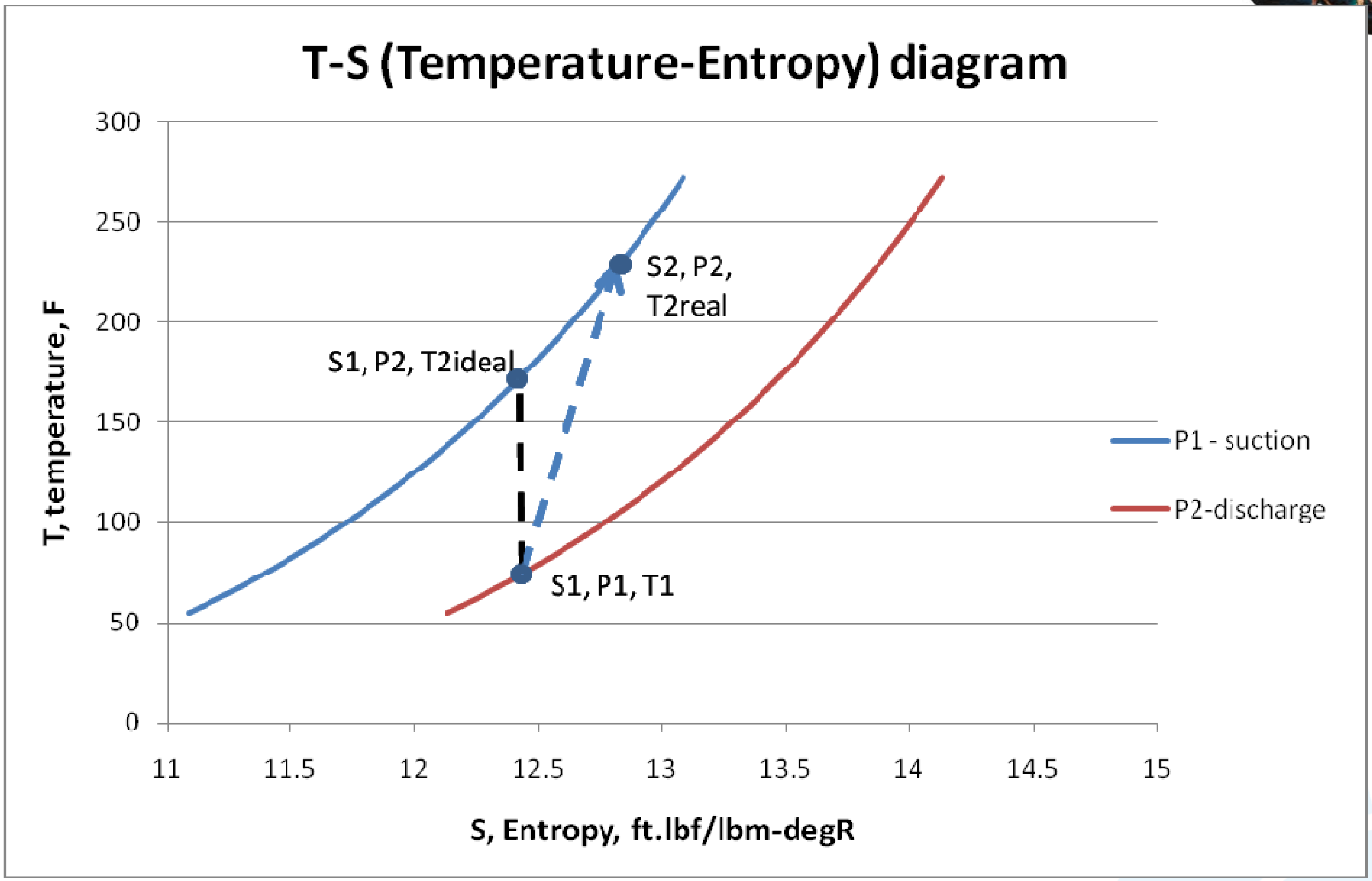
- The fuel consumption is converted in MMBtu/hr, using the associated heat value of the fuel and actual heat rate of the main driver

- The fuel consumption can be recorded and measured as an instantaneous value, as well as all process parameters

Purpose of present paper:

It was found that fuel efficiency varies in a wide range as the process parameters or ambient conditions change, from 30% to 140% on standard installations. The method proposed is intended to help understand how the process and the equipment can be matched to improve overall fuel efficiency.

Discussion on Compression Process



Use of isentropic head rather than pressure ratio or pressure differential expresses the process parameters in energy units

Calculated parameters

Typical calculated parameters:

- Isentropic head for the process

$$H_{is} = \frac{k}{k-1} R T_1 Z_1 \left(\left(\frac{p_2}{p_1} \right)^{\frac{k-1}{k}} - 1 \right)$$

- Inlet volume flow

$$Q_1 = WF_{gas} R \frac{T_1 Z_1}{p_1}$$

- Compressor power

$$P_c = \frac{WF_{gas} H_{is}}{\eta_{is} \eta_m} = \frac{1}{\eta_{is} \eta_m} * WF_{gas} \frac{k}{k-1} R T_1 Z_1 \left(\left(\frac{p_2}{p_1} \right)^{\frac{k-1}{k}} - 1 \right)$$

Statistical Distribution Functions

- Distribution functions: frequency of apparition for a certain event, which can be a specific value for a measured or calculated parameter

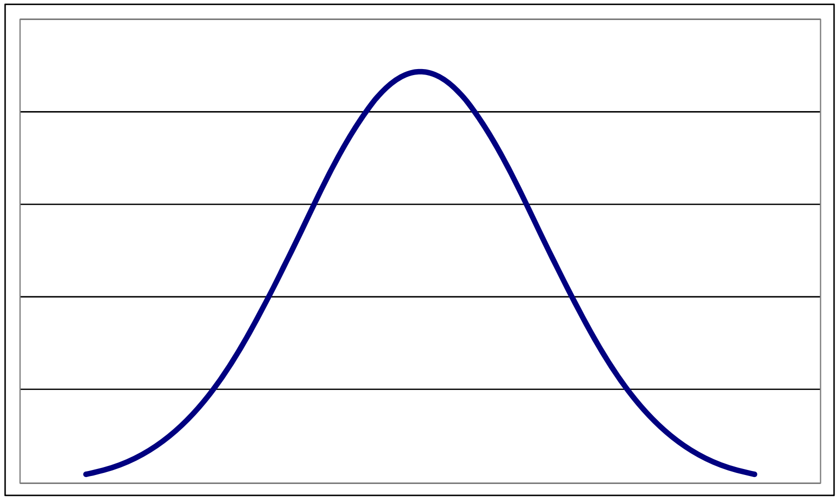
- Most known distributions: Normal distribution (Gaussian) and Exponential distribution

- Normal distribution: associated with events which tend to be on a specific target, and the outcome can be above or below the target. They are characterized by mean (zeroed on target for an accurate and calibrated process) and standard deviation, characterizing the spread of the process (it is smaller for a precise and repetitive process). It is symmetric.

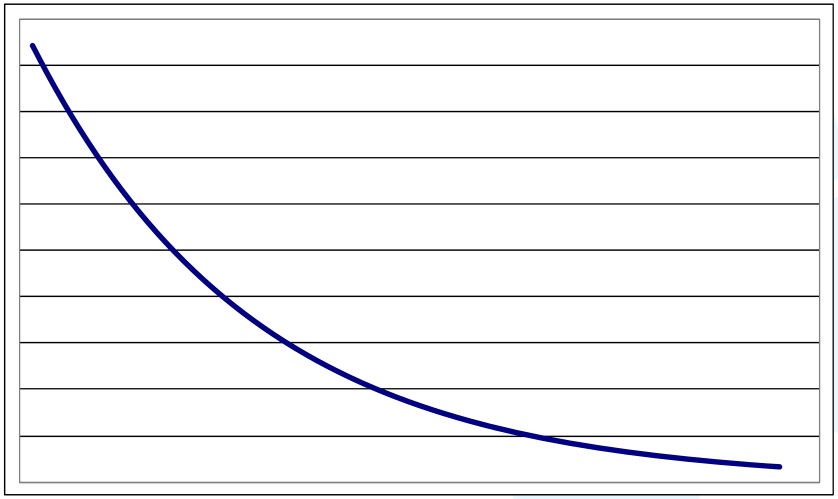
- Exponential distribution: associated with events where the outcome shall be only on one side of the target (ex. keeping the efficiency of a process at the highest level, or at the minimum fuel rate)

Statistical Distribution Functions

- Normal distribution graph



- Exponential distribution graph



Method of Analysis Proposed

The three points of this method of analysis:

1. Analyze any compression process by the head rise rather than pressure ratio or pressure differential; it is a direct measure of the specific energy required by the process. The ideal process will be isentropic and head rise will be

$$H_{is} = \frac{k}{k-1} R T_1 Z_1 \left(\left(\frac{p_2}{p_1} \right)^{\frac{k-1}{k}} - 1 \right)$$

2. Calculate the fuel efficiency in terms of the specific process heat rate calculated with

$$Process\ Specific\ Heat\ Rate = \frac{Btu_{gas\_turbine\_fuel}}{MMSCF * H_{is}}$$

3. Plot and interpret results as histograms of instantaneous values rather than functions or average values

Method of Analysis Proposed

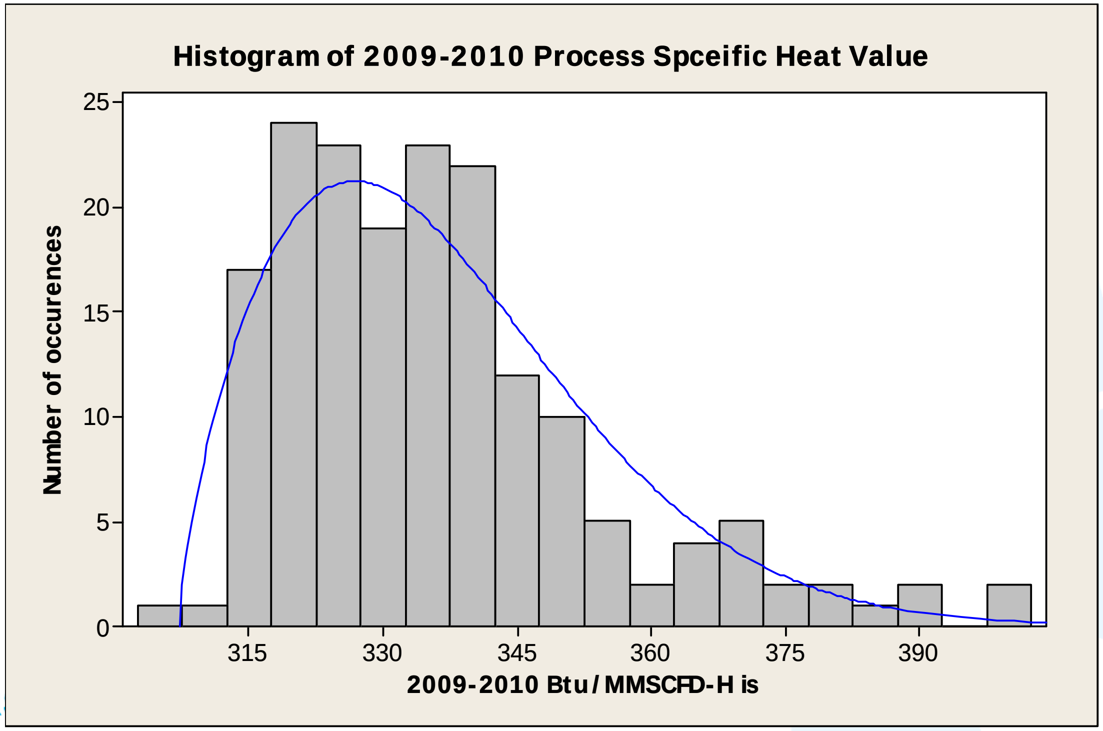
-Plot specific heat value as distribution for period considered

-The spread on the horizontal axis is a measure of process variability

-The peak of distribution will indicate, on the horizontal axis, at which value the process is mostly operated

-The minimum value will indicate when the process was operated at its best fuel efficiency

- All of the above and the shape of distribution can be used for process improvement



Method of Analysis Proposed

Note regarding data collection in the examples.

All records are from the standard instrumentation of existing packages, under standard calibration and maintenance plan. Data were typically collected daily, at a random time, and are considered covering operating and ambient conditions. The condition of each machine was the one existing at the date of data collection and no consideration for equipment age, normal wear and tear or other adverse condition (like fouling) was made. The results of the analysis are not intended to represent a performance test, but they are considered representative for the operating profile of the installation and for fair comparison between machines.

Example 1

Gas compressor package commissioned in 2008 in a gas processing plant

Type: centrifugal, 4 stages, impelled dia. 12"

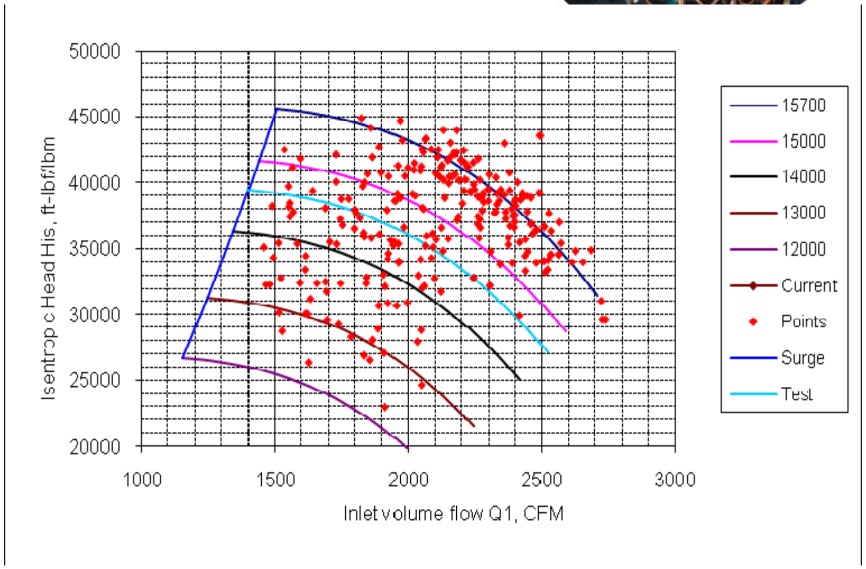
Driver: gas turbine, ISO power 3.5 MW

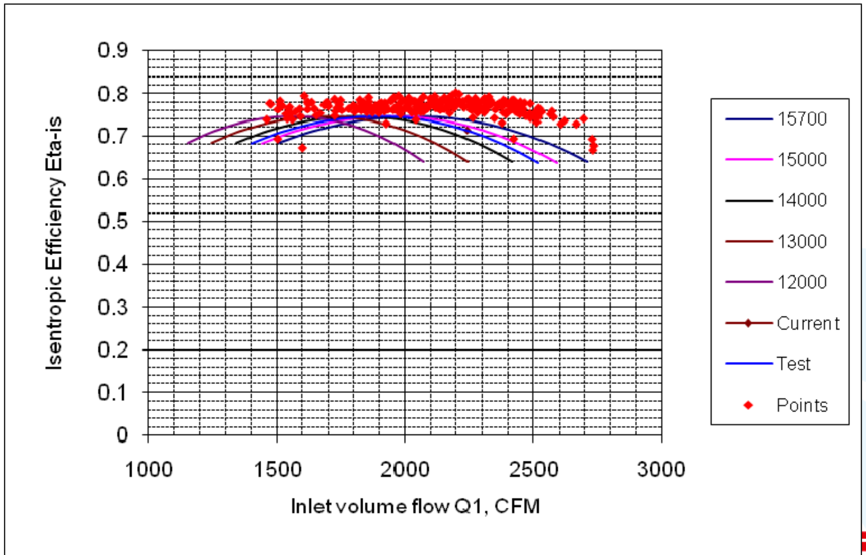
Operating points since commissioning plotted on compressor map shows the operation of the unit relatively all over the design parameters

Compressor efficiency is maintained at higher values

Overall process efficiency will be analyzed using distribution functions and the Process Specific Heat Rate,

$$\frac{Btu_{gas\_turbine\_fuel}}{MMSCF * H_{is}}$$





Example 1

The package analyzed after in factory tests and before shipment to customer

Example 1 - Conclusions

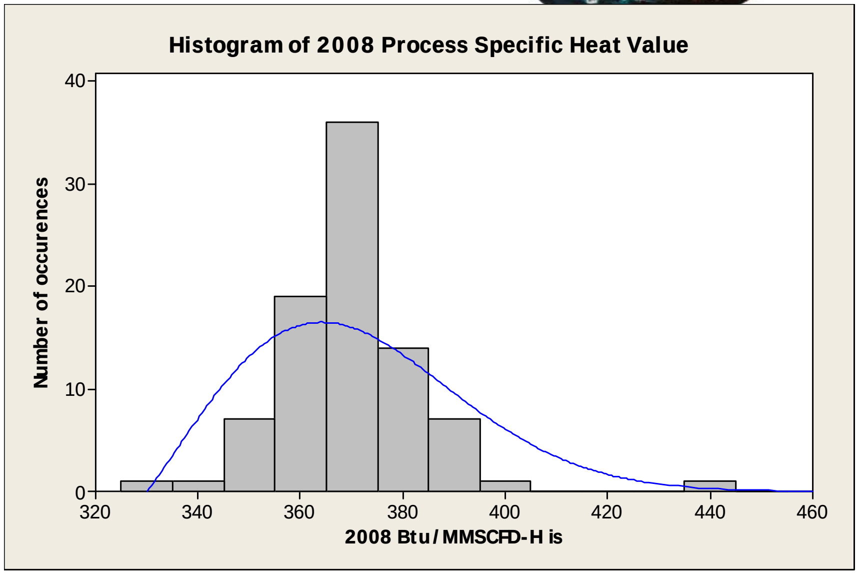
-In 2008 best efficiency obtained was 330 Btu/1MMSCF-1ft.lbf/lbm, with a peak of most common operation at 370

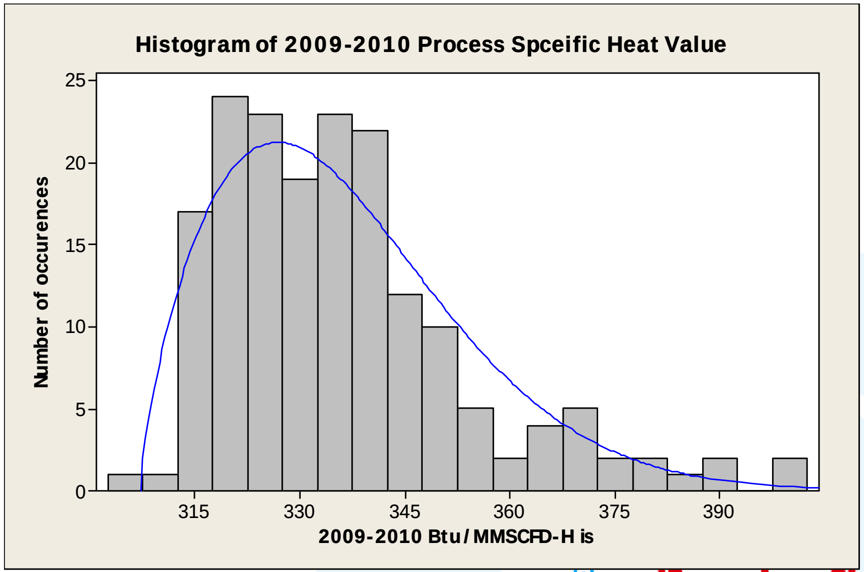
-In 2009-2010, the best efficiency was 310 Btu/1MMSCF-1ft.lbf/lbm, with a peak of most common operation at 330 and a spread up to 400, 30% above the best value

-The change suggests better tuning the process in order to get the most out of the equipment

-- No matter how the process was operated, the best efficiency obtained was 310 Btu/1MMSCF-1ft.lbf/lbm

-Tuning the process will change the mostly operated value and accordingly the average, but not the minimum value which represents what the equipment can do the best

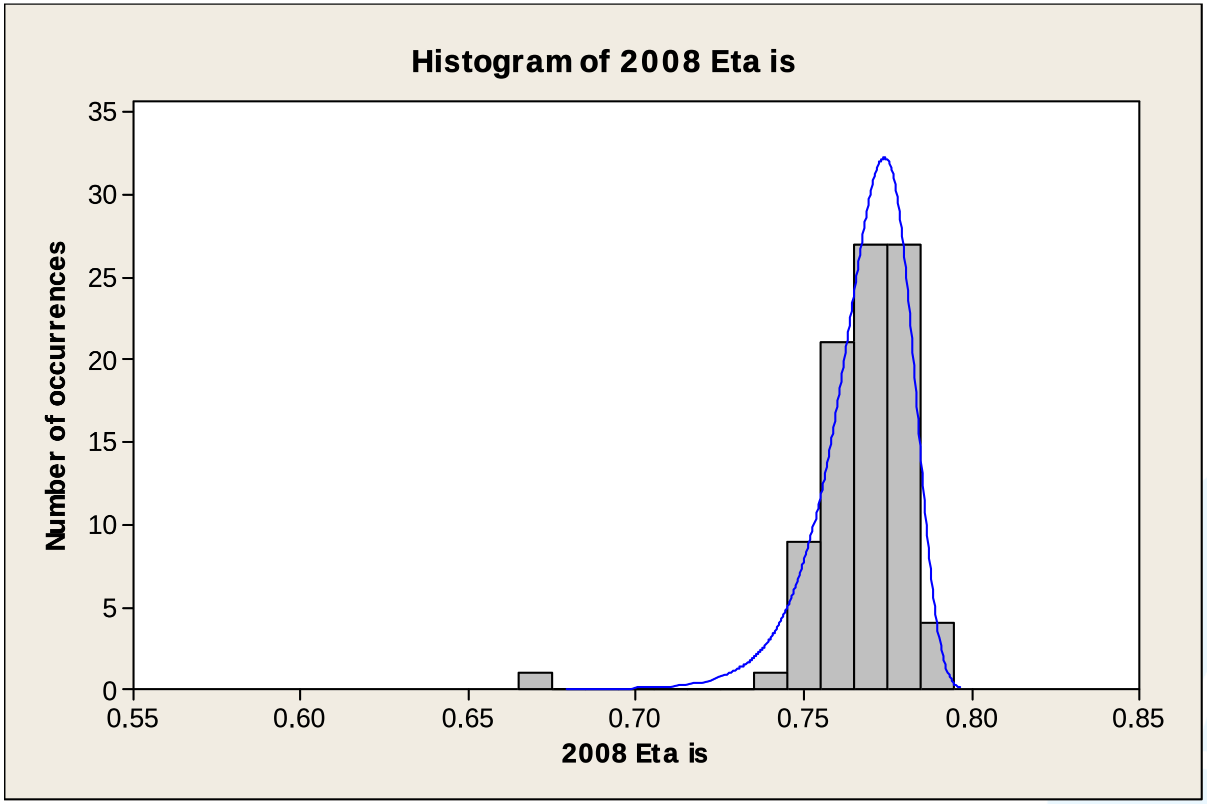




Example 1 - Conclusions

-Compressor isentropic efficiency was situated in the range common for this class of compressors (max value 0.79 with mostly operated value at 0.77)

-The method of analysis can be applied to any other equipment and will provide results that will allow comparison of processes



Example 2.1

ATMOS ENERGY Unit 1

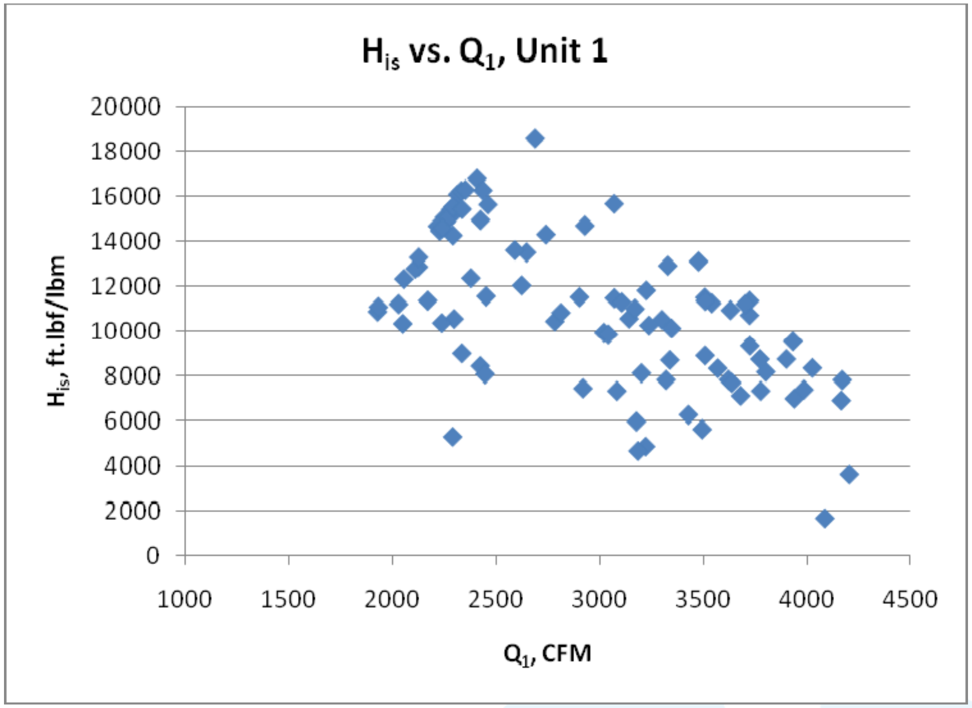
Type: centrifugal, 2 stages, impeller dia. 12"

Driver: gas turbine, ISO power 3.5 MW

-Operating data collected during 2010 were analyzed

-Operating points plotted on H_{is}-Q_1 chart suggests a complete coverage of compressor map

-Overall process efficiency will be analyzed using distribution functions and the Process Specific Heat Rate,



$$\frac{Btu_{gas\_turbine\_fuel}}{MMSCF * H_{is}}$$

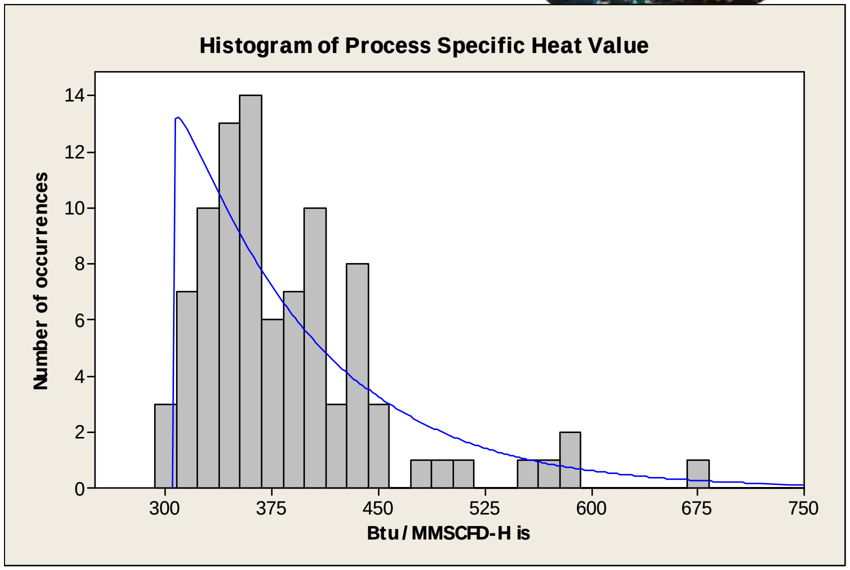
Example 2.1

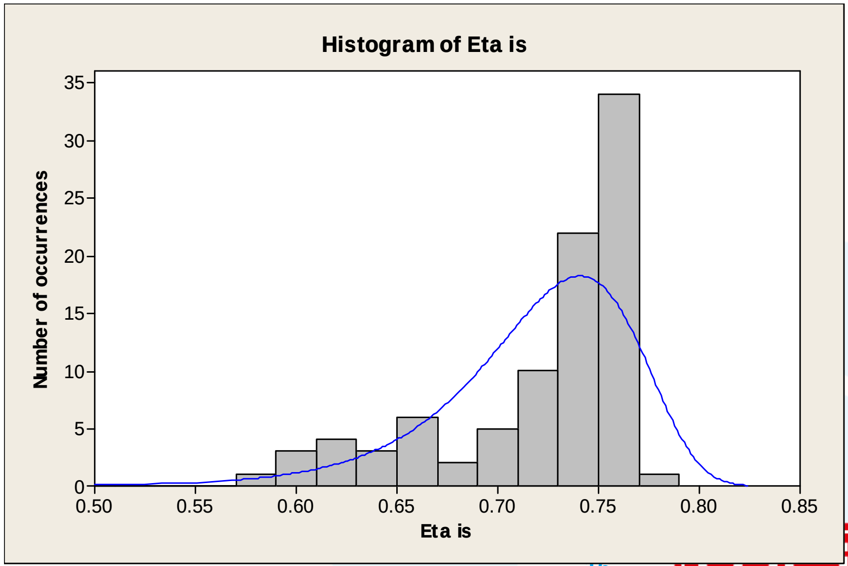
Conclusions

-The best efficiency this equipment reached in 2010 was 300 Btu/1MMSCF-1ft.lbf/lbm H_{is}

-The value the equipment was mostly operated was 360 Btu/ft.lbf/lbm (20% higher than the best value) and a spread up to 550 (80% above the best value)

-The best compressor isentropic efficiency was 0.79, and the value the compressor was mostly operated was 0.76





Example 2.2

ATMOS ENERGY Unit 2

Type: centrifugal, 3 stages, impeller dia. 12”

Driver: gas turbine, ISO power 3.5 MW

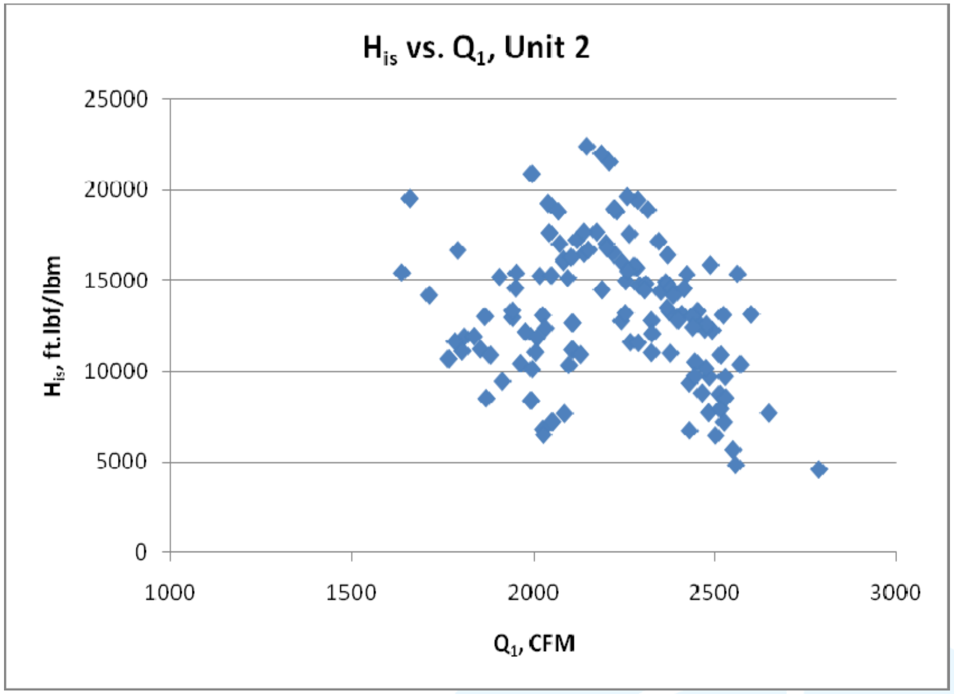
Operates in parallel with Unit 1

-Operating data collected during 2010 were analyzed

-Operating points plotted on H_{is}-Q_1 chart show a lower range of flow

-Overall process efficiency will be analyzed using distribution functions and the Process Specific Heat Rate,

$$\frac{Btu_{gas\_turbine\_fuel}}{MMSCF * H_{is}}$$



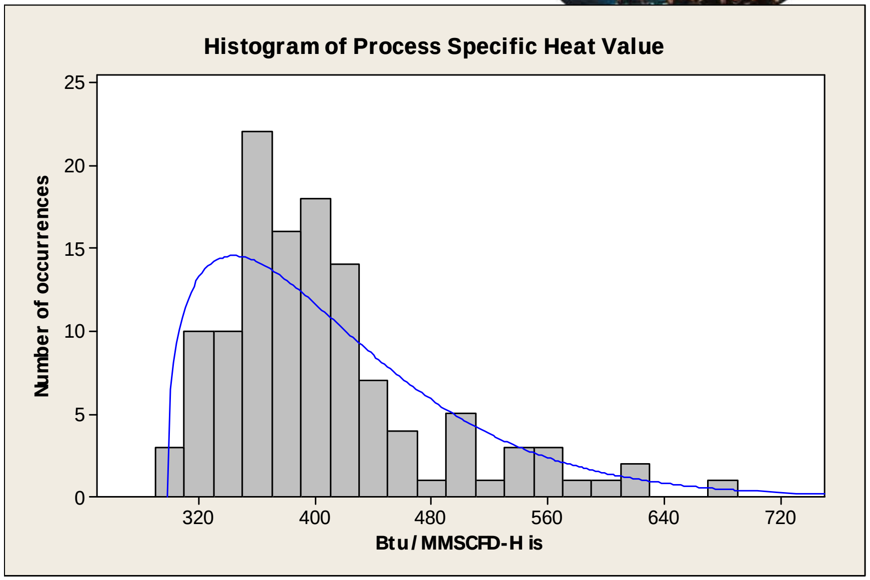
Example 2.2

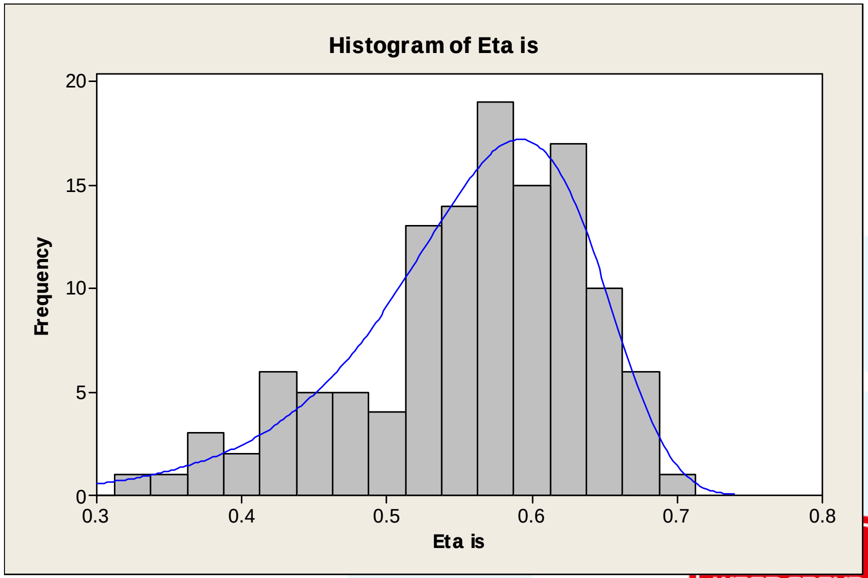
Conclusions

-The best efficiency this equipment was capable of was 310 Btu/1MMSCF-1ft.lbf/lbm H_{is}

-The value the equipment was mostly operated was 360-370 Btu/ft.lbf/lbm (almost 20% higher than the best value) with the spread up to over 600, 900% above the best value

-The compressor isentropic efficiency was max 0.75 with most operated value below 0.7, which is low for this type of compressor and may indicate a problem.





Example 2.3

ATMOS ENERGY Unit 3

Type: centrifugal, 3 stages, impeller dia. 15”

Driver: gas turbine, ISO power 5.2 MW

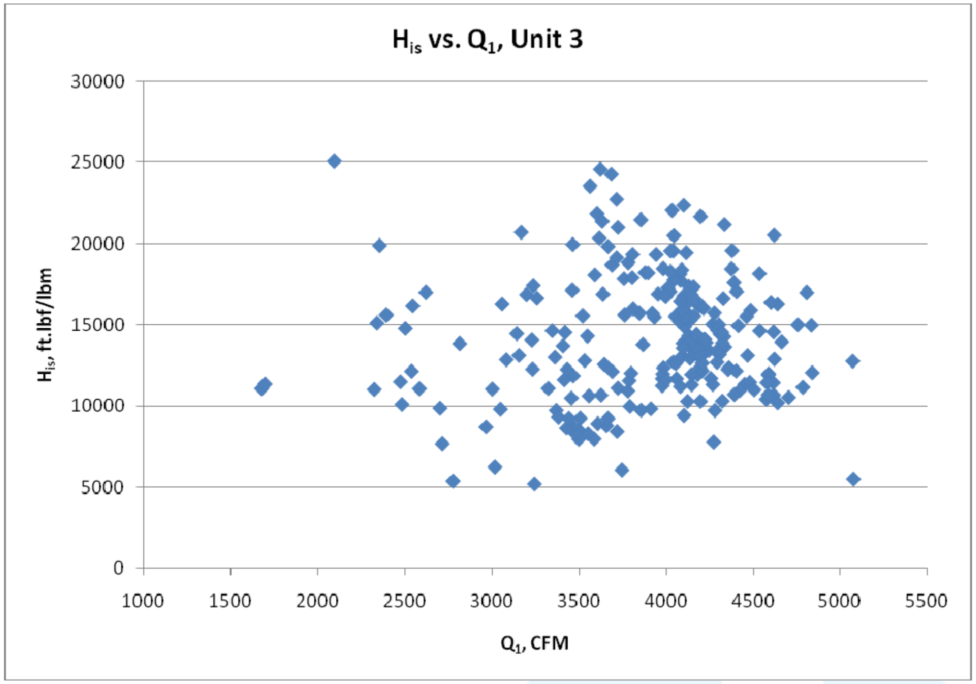
Operates in parallel with Unit 1 and 2

-Operating data collected during 2010 were analyzed

-Operating points plotted on H_{is}-Q_1 chart show a wider range of flow

-Overall process efficiency will be analyzed using distribution functions and the Process Specific Heat Rate,

$$\frac{Btu_{gas\_turbine\_fuel}}{MMSCF * H_{is}}$$



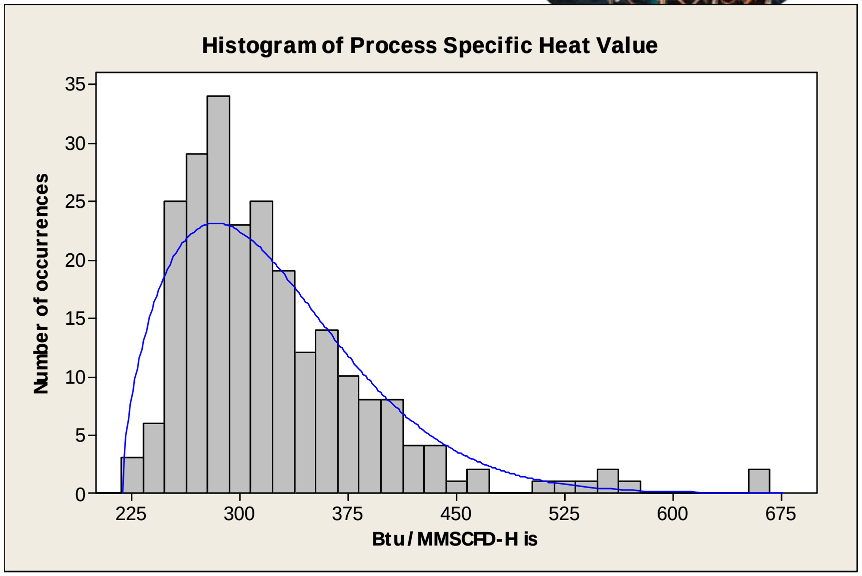
Example 2.3

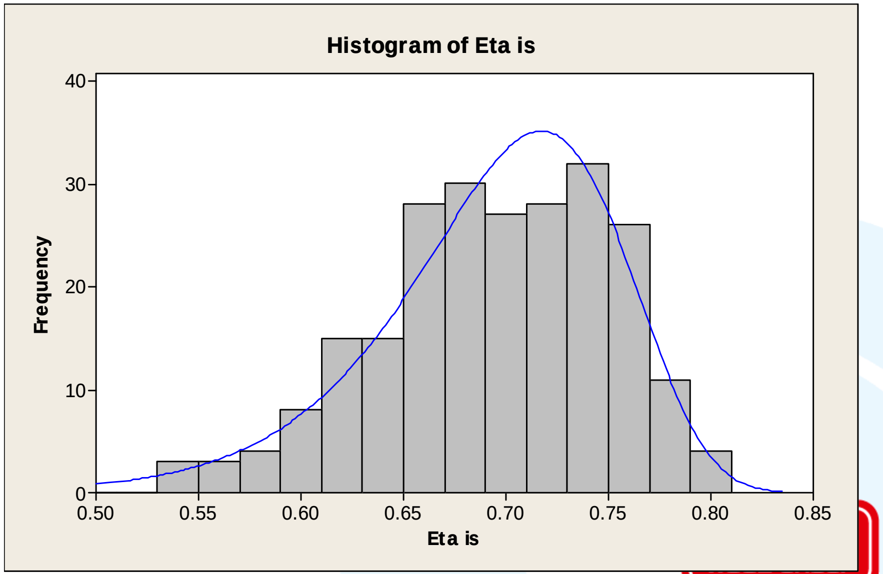
Conclusions

-The best efficiency this equipment was capable of was 225 Btu/1MMSCF-1ft.lbf/lbm H_{is} – with 25% better than Unit 1

-The value the equipment was mostly operated was 285 Btu/ft.lbf/lbm (27% higher than the best value) with a spread up to 550, which is 140% above the best value

-The compressor isentropic efficiency was max 0.83, with mostly operated value at 0.74





Example 2.4

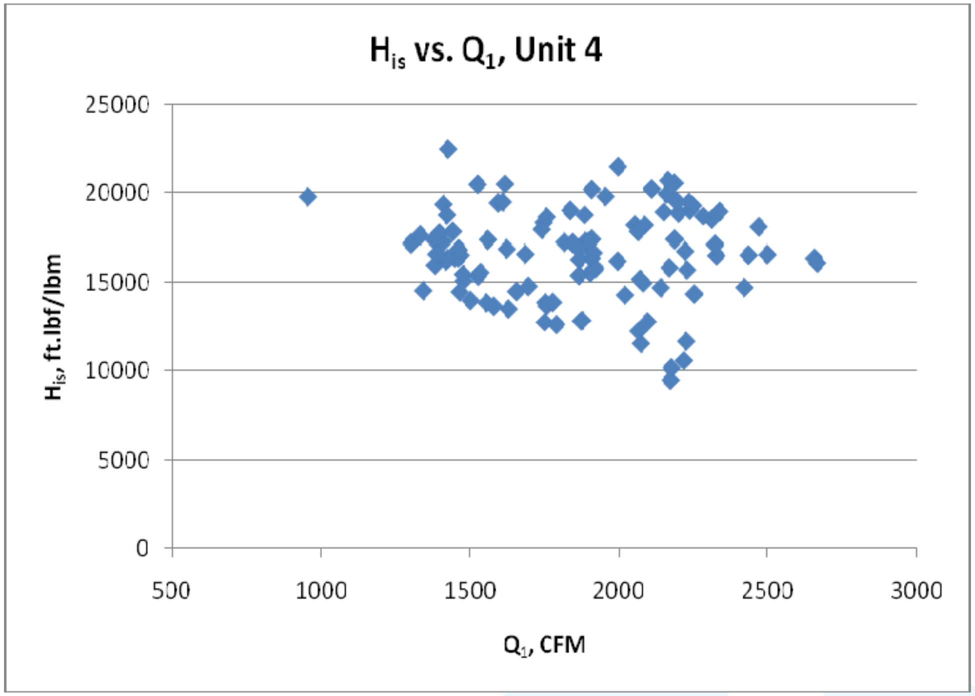
ATMOS ENERGY Unit 4

Type: reciprocating compressor driven by reciprocating engine

-Operating data collected during 2010 were analyzed

-Operating points plotted on H_{is}-Q_1 chart show a flow range similar to Unit 2

-Overall process efficiency will be analyzed using distribution functions and the Process Specific Heat Rate,



$$\frac{Btu_{gas\_turbine\_fuel}}{MMSCF * H_{is}}$$

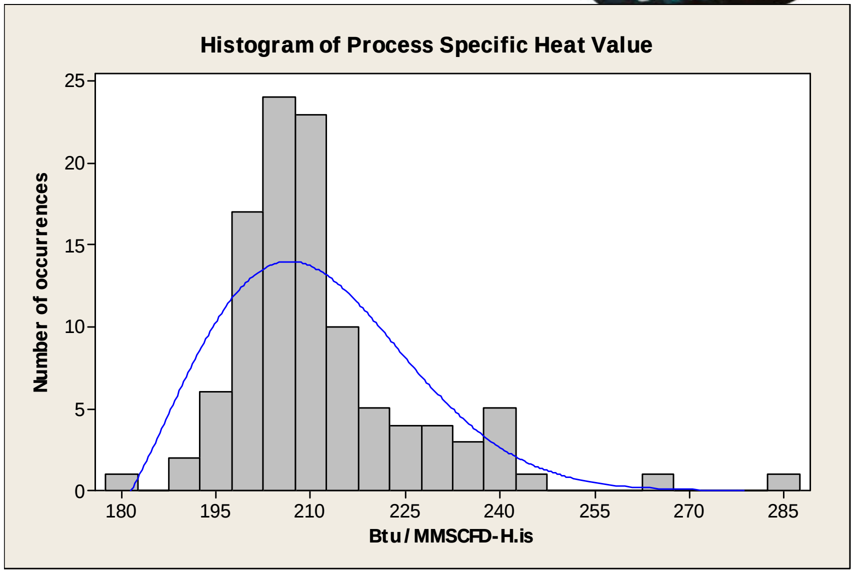
Example 2.4

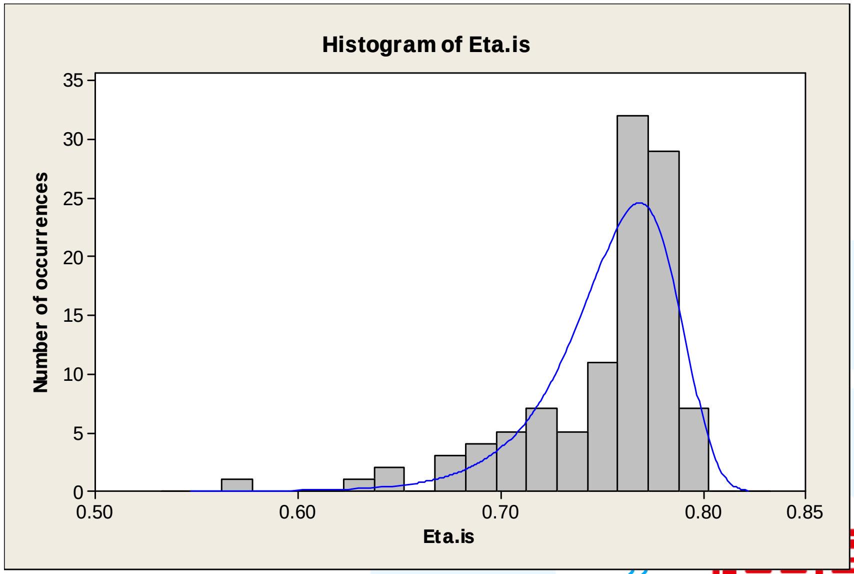
Conclusions

-The best efficiency this equipment was capable of was 180 Btu/1MMSCF-1ft.lbf/lbm Had, which is 20% better than Unit 3 and 40% better than Unit 1

-The value the equipment was mostly operated was 205 Btu/ft.lbf/lbm (14% higher than the best value), with a spread up to 250 (40% above the best value)

-The compressor isentropic efficiency was max 0.795, with mostly operated value at 0.765





Example 2.5

ATMOS ENERGY Unit 5

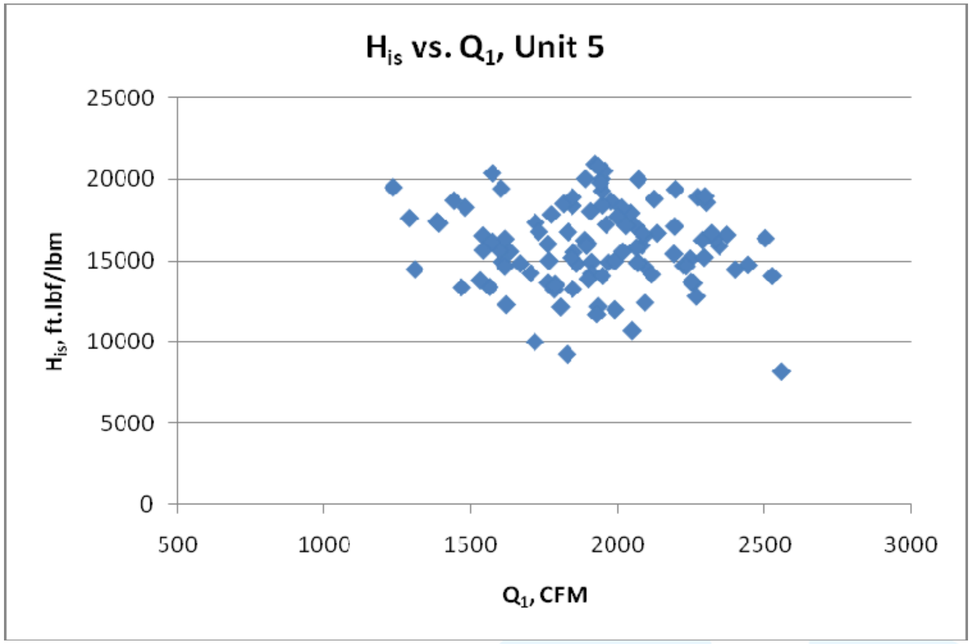
Type: reciprocating compressor driven by reciprocating engine, similar to Unit 4, operating in parallel with units 1-4

-Operating data collected during 2010 were analyzed

-Operating points plotted on H_{is}-Q_1 chart show a flow range similar to Unit 1

-Overall process efficiency will be analyzed using distribution functions and the Process Specific Heat Rate,

$$\frac{Btu_{gas\_turbine\_fuel}}{MMSCF * H_{is}}$$



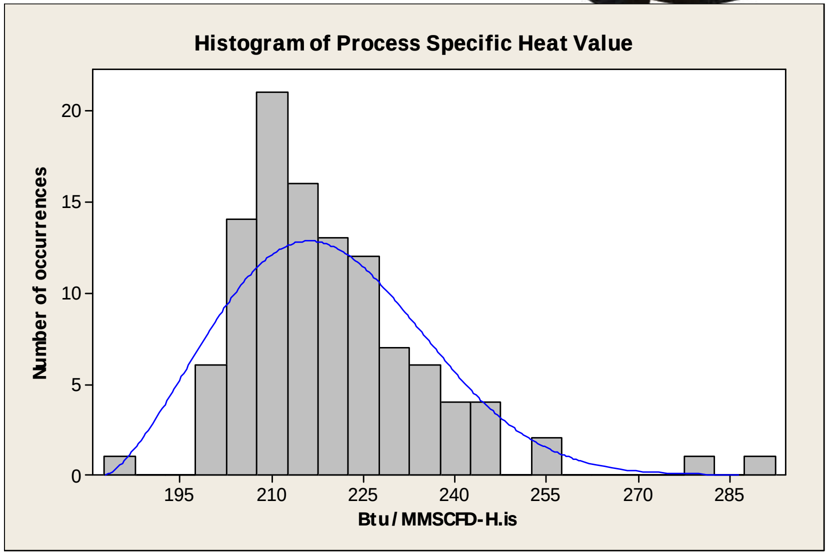
Example 2.5

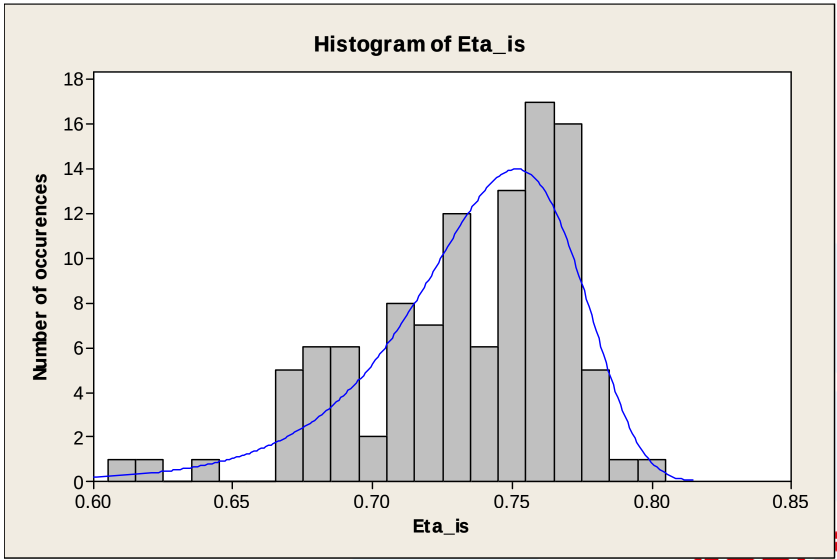
Conclusions

-The best efficiency this equipment was capable of is 180 Btu/1MMSCF-1ft.lbf/lbm H_{is} (like Unit 4)

-The value the equipment was mostly operated is 210 Btu/ft.lbf/lbm (16% higher than the best value) with a spread up to 280, which is 55% above the best value

-The compressor isentropic efficiency was max 0.80 and mostly operated value was 0.76





Application of the method to existing installations - Discussion

- When plotted as a histogram, the process specific heat value shows suggestively how efficiently the process is operated and how much of the time the process is off target.
- Instant data collection is simple and performed daily on most installations; reporting can be totally automatic
- The peak level in the histogram is a direct measurement of how the equipment is mostly operated
- The minimum value on the horizontal axis shows the best efficiency the equipment is capable of
- The spread in the histogram shows how well the machine is used in comparison to the peak performance.
- The operator will understand the differences in the process and if possible and opportune, attempt to operate in the best efficient mode
- Reducing variability of the process remains a general rule for improving efficiency
- Comparing machines based on best value achieved gives good indication for opportunities of restaging their components

Example 3 – Method applied in design phase

Type: centrifugal, 4 stages, impeller dia. 7”
Driver: gas turbine, ISO power 0.8 MW

Design parameters

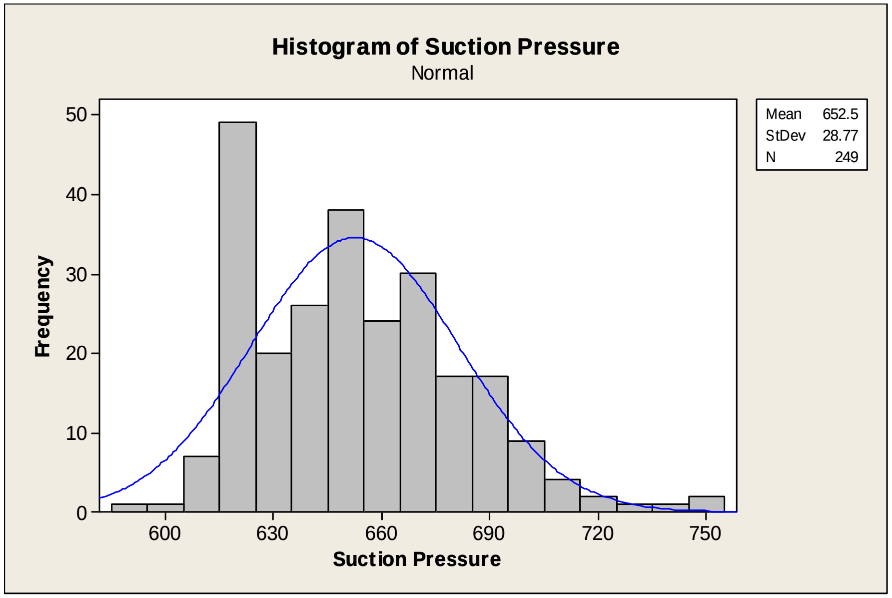
- **Suction pressure: 654.7 psia**
- **Discharge pressure: 960.7 psia**
- **Flow: 41 MMSCFD**
- **Suction temperature: 110 deg. F**
- **Ambient temperature: 95 deg. F**
- **In addition, a number of 250 different verification points were provided by the customer in order to analyze the off design operation of the compressor package.**
- **The approach was to start with an initial design and develop a model, and then running the model for all 250 different operating conditions.**
- **The results served for re-selecting the staging**

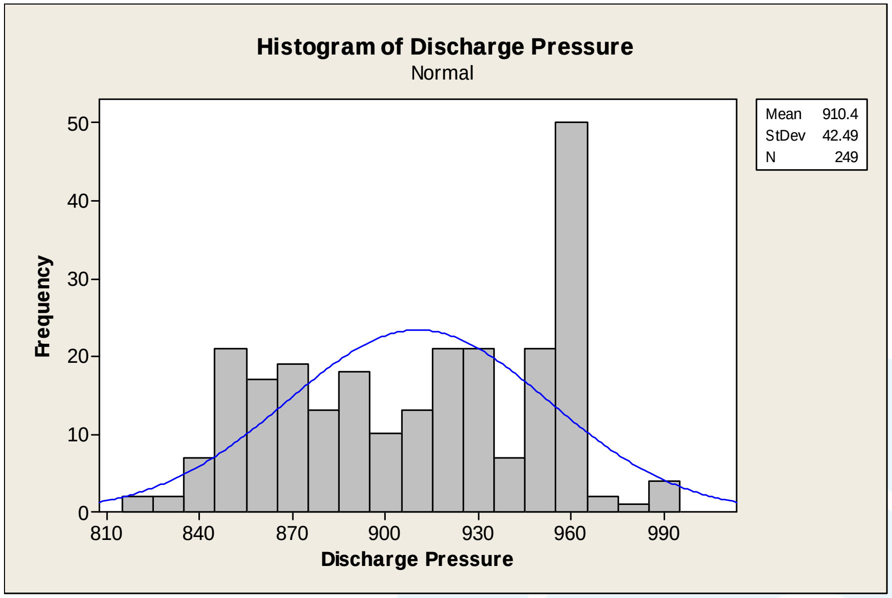
Example 3

The units analyzed after in factory test and before shipment to customer

Example 3

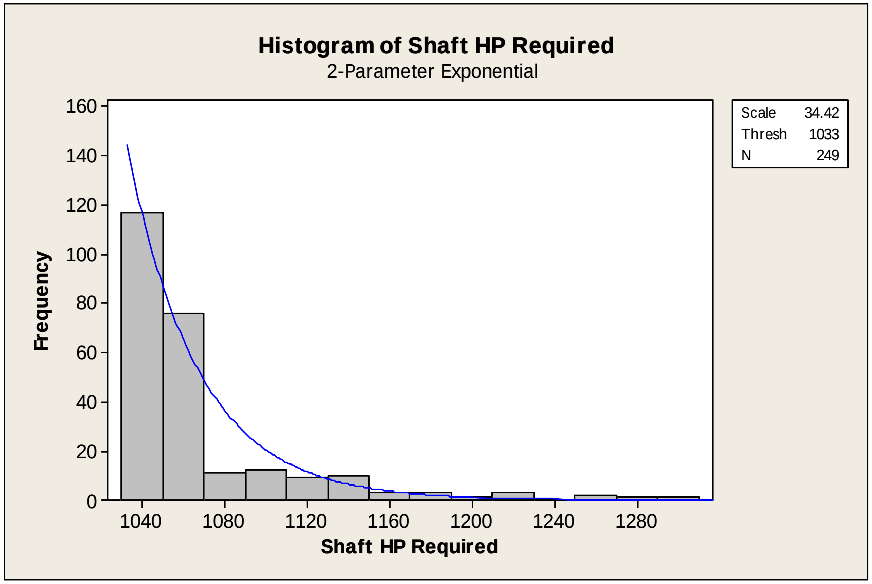
- **Input design parameters**
- **Suction pressure and discharge pressure are input parameters and historical records were provided with a range between 590 and 750 psia for suction pressure, and 810 to 990 psia for the discharge. The resulted ratio ranged from 1.22 to 1.56. For this model the distributions were estimated with normal, and the parameters were calculated from the historical data supplied.**

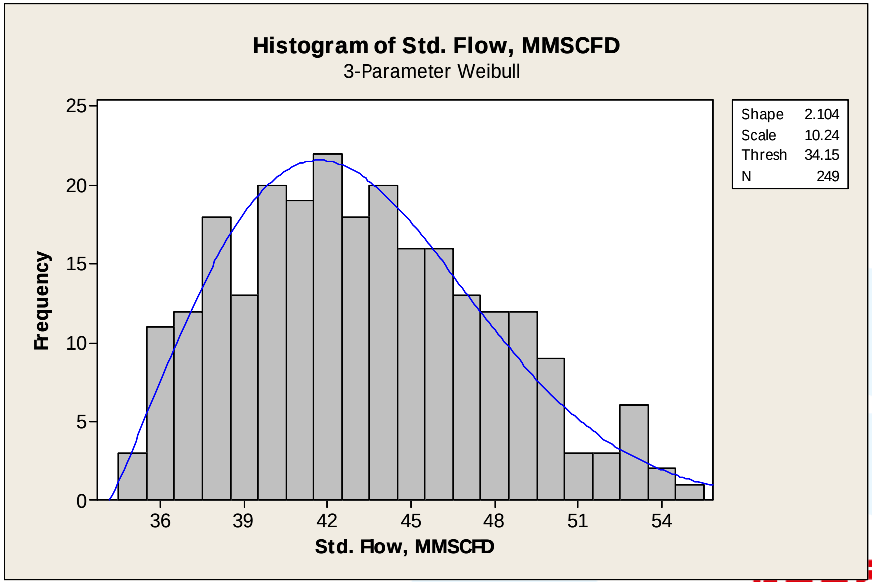




Example 3

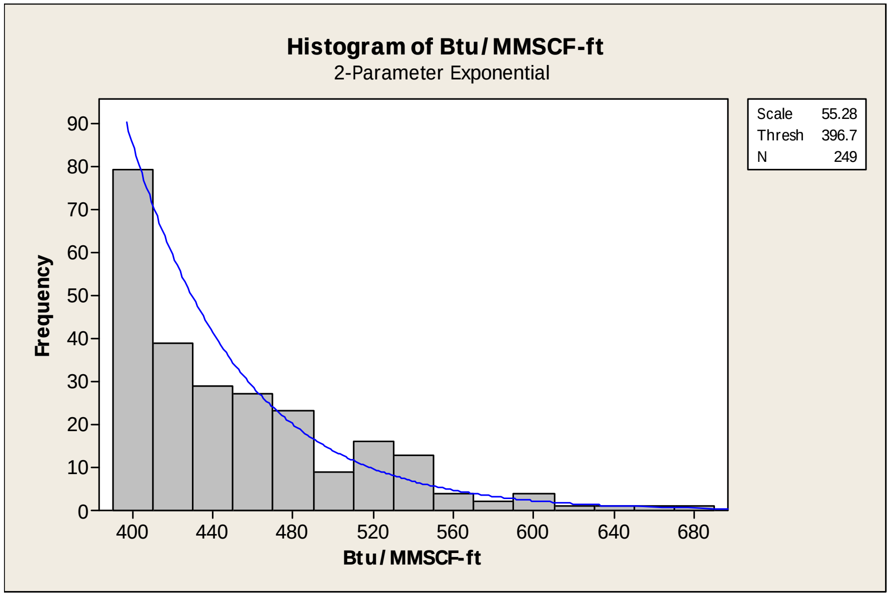
- **Output design parameters**
- **The package design included a gas turbine driver and a process gas compressor. The volume flow was required to be maximum all the time and to make complete use of available turbine power.**
- **Distributions for HP and std. flow were calculated. As expected the power (HP) distribution is exponential and strongly skewed to the right, showing that the process will require almost max power all the time. The standard flow was found slightly skewed to the right and for a better modeling an approximation with a Weibull distribution was used.**

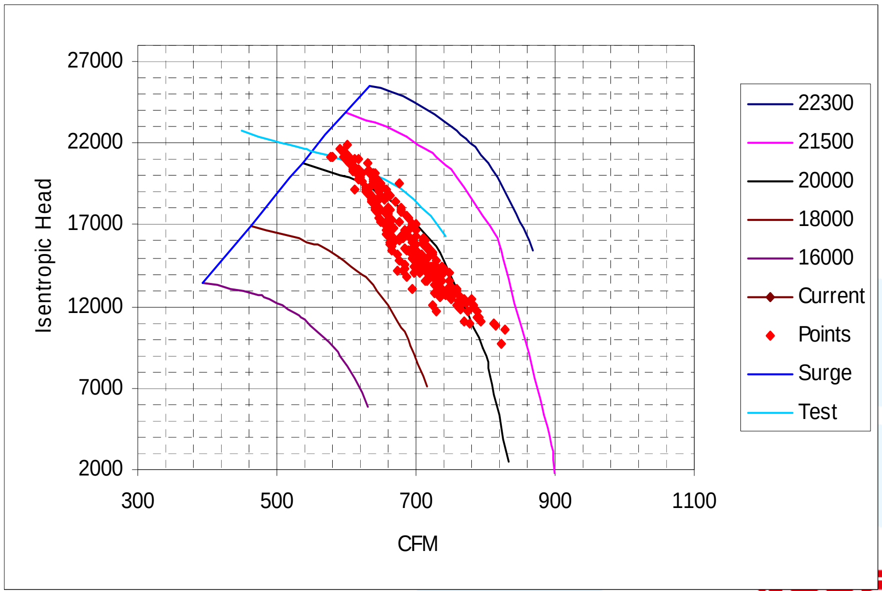




Example 3

- Output efficiency was calculated using the detailed model developed for design. It included gas turbine model as well as compressor geometry and characteristic curves. The ultimate parameter used in analysis is the *process specific heat* as previously defined and plotted as histogram. Its distribution is exponential and is strongly skewed to higher values.
- The compressor map in Figure 4b shows all analyzed operating points. It can be seen that their spread is very wide and this is the cause for which many points operate off max efficiency. It suggestively shows that by re-targeting the process the overall efficiency distribution can be improved.





Application of the method to designing a new installations - Discussion

- Simulating the input parameters (suction and discharge pressure, suction temperature etc.) both with their value and with frequency of apparition (as distribution functions) will provide estimates of real performances encountered in operation, as opposed to a single point design
- It is strongly desired that the shape of process specific heat value distribution is exponential with the most frequent value at or close to the best value
- The spread in the histogram shows how suited the design is for the actual variable conditions
- The points plotted on the compressor map shows how suited is the design for the operating range

Conclusions – Comparison of results

- -Specific heat best value varies from 180 to 400 for the packages analyzed
- -The max value is 30% to 160% higher than the best value the equipment is capable of
- -The median value is 10% to 27% higher than the best value
- **-All of the above can be used as tools to identify opportunities of improvement with the equipment or the process**

Btu/1MM SCFD-1ft.lbf/lbm	Centrif., 4 stages 12" dia., gas turbine 3.5 MW	Centrif., 2 stages 12" dia., gas turbine 3.5 MW	Centrif., 3 stages 12" dia., gas turbine 3.5 MW	Centrif., 3 stages 15" dia., gas turbine 5.5 MW	Recip, 6 cyl, 4 MW	Recip, 6 cyl., 4 MW	Centrif., 4 stages 7" dia., gas turbine 0.8 MW
Best value	**310**	**300**	**310**	**225**	**180**	**180**	**400**
Mostly seen	**330**	**360**	**365**	**285**	**205**	**210**	**400**
Max value	**400**	**600**	**640**	**550**	**250**	**255**	**620**

Questions?