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Process Compatibility Analysis of an Integrated Gasification Combined Cycle

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Abstract

IGCC - Integrated Gasification Combined Cycle - is an innovative electric power generation concept that combines modern coal gasification technology with both gas turbine (Brayton cycle) and steam turbine (Rankine cycle) power generation. The technology is highly flexible and can be used for new applications, as well as for repowering older coal- fired plants, significantly improving their environmental performance. IGCC provides feedstock and product flexibility, greater than 40 percent thermal efficiency, and very low pollutant emissions. The first commercial IGCC plants, put into service in the U.S., through DOE's cooperative Clean Coal Technology program, have proven capable of exceeding the most stringent emissions regulations currently applicable to coal-fueled power plants. IGCC is a process system that allows the structural integration of a gasification unit with a standard combined cycle power component. After gasification, coal or other solid or liquid feedstock (e.g., biomass, various oils, etc.) are converted into synthetic gas (also known as syngas), which is comprised predominantly of hydrogen (H2) and carbon monoxide (CO). The combustible syngas is first typically treated for the removal of sulfur dioxide (SO2), nitric oxide, mercury, and particular matter and then used in a gas turbine (GT) to produce electricity, whereas the assorted exhaust heat is used to generate steam for a second generation. In this study, Process capability study is applied combining the statistical tools developed from the normal curve and control charts with good engineering judgment to interpret and analyze the data representing the IGCC plant process. Also, this study seeks to determine the variation spread and to find the effect of time on both the average and the spread. The results from this study, it is hoped, would set a pace in administration, analysis and use of the process capability study as an integral part of the quality engineering function; as the input to the work is temperature and pressure at the ten streams of the plant. Results could be used for new design applications, inspection planning and evaluation techniques. All the process capability performance indices were all gotten for all the processes, except the Cpm, which, from the plots, was reported to be undefined. From a visual examination of the process spread, it is observed that the data in the histogram in relation to the lower and upper specification limits is not outside limits. Ideally, the spread of the data is narrower than the specification spread, and all the data are inside the specification limits. Data that are outside the specification limits represent nonconforming items. From visual examination of all results (figures 2 to 10), it is observed that Cpk $\ll$1.33. The implication of the indices is that there is need for a process improvement, such as reducing its variation or shifting its location. Compare Ppk to a benchmark value that represents the minimum value that is acceptable for your process. Many industries use a benchmark value of 1.33. (https://support.minitab.com/en-us/minitab/18/help-and-how-to/quality-and-process-improvement/capability-analysis/how-to/capability-analysis/normal-capability-analysis/interpret-the-results/key-results/). Since all the Ppk are lower than the benchmark, engineers as well as operators of the IGCC plant should consider ways to improve the process.
Keywords: Histogram, Normal Curves, Capability Indices, IGCC - Integrated Gasification Combined Cycle, Process Capability

I. INTRODUCTION

In recent years, integrated gasification combined cycle (IGCC) power plants have gained increasing interest in the field of industrial power production, allowing the use of low-grade fuels (coal, heavy petroleum liquids, orimulsion, etc.) with potential high efficiencies and limited environmental impact. Several commercial-size IGCC power plants are now in operation worldwide and others are under construction Carapellucci et. al. (2001).

IGCC - Integrated Gasification Combined Cycle - is an innovative electric power generation concept that combines modern coal gasification technology with both gas turbine (Brayton cycle) and steam turbine (Rankine cycle) power generation. The technology is highly flexible and can be used for new applications, as well as for repowering older coal- fired plants, significantly improving their environmental performance. IGCC provides feedstock and product flexibility, greater than 40 percent thermal efficiency, and very low pollutant emissions. The first commercial IGCC plants, put into service in the U.S., through DOE's cooperative Clean Coal Technology program, have proven capable of exceeding the most stringent emissions regulations currently applicable to coal-fueled power plants. (Ratafia-Brown, 2012).

IGCC is a process system that allows the structural integration of a gasification unit with a standard combined cycle power component. After gasification, coal or other solid or liquid feedstock (e.g., biomass, various oils, etc.) are converted into synthetic gas (also known as syngas), which is comprised predominantly of hydrogen (H2) and carbon monoxide (CO). The combustible syngas is first typically treated for the removal of sulfur dioxide (SO2), nitric oxide, mercury, and particular matter and then used in a gas turbine (GT) to produce electricity, whereas the assorted exhaust heat is used to generate steam for a second generation cycle through a steam turbine Zhang, (2015).

In an IGCC, the coal gasifier integrates into the highly efficient and proven gas turbine combined cycle. This makes it possible to use coal also in the combined cycle mode. What makes an IGCC efficient is the integration of energy balance of the gasifier with the combined cycle. The IGCC has different configurations Johnzactruba, (2009): Steam / or water for the gasifier is taken from the HRSG steam cycle; Air for the gasifier or the air for the Air separation unit is taken for the gas turbine compressor to save energy ; The Nitrogen from the Air separation unit is send back into the gas turbine combustor for dilution. This dilution reduces NOx emissions from the Gas turbine; The hot gas from the gasifier is cooled in one or more heat exchangers to produce steam, which integrates with the HRSG steam cycle; Lower temperature heat exchangers are used to further heat the condensate in the steam cycle while cooling the gas; CO2 from the syngas generation is ready for capture.

(Ratafia-Brown, 2012), Carapellucci et. al. (2001) , Xiao, (2012) and Zhu and Frey, (2006) highlighted the advantages of IGCC plants: achieved the lowest levels of criteria pollutant air emissions (NOx, SOx, CO, PM10) of any coal- fueled power plants in the world. Discharge of solid byproducts and wastewater is reduced by roughly 50% versus other coal-based plants, and the by-products generated (e.g., slag and sulfur) are environmentally benign and can potentially be sold as valuable products. Another significant environmental benefit is the reduction of carbon dioxide (CO2) emissions, by at least 10% per equivalent net production of electricity, due to a higher operating efficiency compared to conventional pulverized coal- fired power plants.

Johnzactruba, (2009) comparative analysis between the IGCC and the PC plant: The performance of an IGCC is compared to the highly efficient Natural gas fired combined cycle and the Ultra Supercritical pulverised coal fired plants; The overall thermal efficiency of the IGCC power plant is almost same with that of an Ultra supercritical coal fired power plant but still less than an Natural Gas fired CC plant. However, it is considerably higher than the conventional coal fired power plants; a part of the CO2 as output of the gasifier can be easily captured. CO2 generation per unit output will be around 20 % less than a Pulverized Coal fired unit. This could go a long way in meeting Carbon emissions and CO2 capture costs; the startup times of IGCC will be more than Pulverized Coal fired power plant due to the large number of sub systems. This makes the IGCC suitable only for base load operation; The biggest advantage of the IGCC is its capability to use a wide range of coals and other fuels; Cleaning of the Syngas from the gasifier removes most of the emissions like sulphur dioxide and PM10. In addition, dilution by using Nitrogen in the gas turbine combustor reduces the formation of NOx. The volume of gas to be handled is comparatively much less for emission control.

However, as a demerit, the cost of IGCC systems is perceived to be too high compared with PC plants, in most cases. Zhu and Frey, (2006). Johnzactruba, (2009) highlighted, further, demerits of IGCC plants: Current cost of IGCC is higher than the Ultra supercritical pulverised coal fired plants without CO2 capture; More components, more heat exchangers increase maintenance costs and outage times; Ash forms as slag which when quenched is a lot easier and less voluminous to handle and dispose than fly ash from coal fired power plants.

There are, however, hybrid IGCC – an option for IGCC with CO2 capture: Produce syngas in gasification area; use water shift reaction to produce high concentration of H2 and CO2; capture the CO2 from the syngas; methanate the syngas to synthetic natural gas, SNG; combust SNG to conventional combined cycle or send to pipeline; compress the CO2 for sequestration or use in enhanced oil recovery Jenkins and Booras, (2010).

There is need to study the process ability for power generation in these power plants that meets specifications. One of the powerful tools for such study is Process capability indices (PCIs) Chen et. al. 2001. Several capability indices including *Cp*, *Cpu*, *Cpl* and *Cpk* have been widely used in manufacturing industry to provide common quantitative measures on process potential and performance. Process yield, process expected loss and process capability indices (PCIs) are three basic means that have been widely applied in measuring product potential and performance. Chen et. al. 2001. Chen et. al. 2001 developed an effective and efficient method via a Product Capability Analysis Chart (PCAC) to evaluate the process capability of an entire product composed of multiple process characteristics.

Process mean μ, Process variance $\sigma 2$, and product specification are basic information used to evaluate process capability. However, the specifications are different in different products. A manager of a process can’t evaluate process performance from μ and σ right away. Subsequently, univariate process capability indices cannot meet the requirements stated above. Furthermore, the other important problem is focusing on many bilateral products with asymmetric tolerances. Chen et. al. (2006). A number of researchers have developed a multi-process capability analysis chart.

Judge process distribution and evaluate capability of production system’s flowchart of the process Chen et. al. (2006) as:

1) Step 1: Decide on the values of the product capability index c and $C0 = \Phi[(t \sqrt{2}\Phi(3c)-1+1)/2]/3)$.
2) Step 2: Collect a data set of quality characteristics.
3) Step 3: Judge the distribution. Use the MPCAC if the distribution is a normal distribution, and use the NMPCAC when it is a non-normal distribution.
4) Step 4: Compute process capability indices of respective quality characteristics in a product.
5) Step 5: Plot the points on an MPCAC or an NMPCAC.
6) Step 6: Find the points which are not qualified, and improve them.

Process capability study is a method of combining the statistical tools developed from the normal curve and control charts with good engineering judgment to interpret and analyze the data representing a process. The purpose of the process capability study is to determine the variation spread and to find the effect of time on both the average and the spread. The administration, analysis and use of the process capability study should be an integral part of the quality engineering function. The results could be used for new design applications, inspection planning and evaluation techniques. It is a type of tool that can be used to prevent defects during the production cycle through better designs, through factual knowledge of machine or process limitations and through knowledge of process factors that can or cannot be controlled. In any manufacturing operation there is a variability which is manifested in the product made by the operations .Quantifying the variability with objectives and advantages of reducing it in the manufacturing process is the prime activity of the process management Wooluru and Swamy, (2014).

II. THE BASIC CAPABILITY INDICES COMMONLY USED CP, CPK CPM & CPMK

Cp: It simply relates the Process Capability to the Specification Range and it does not relate the location of the process with respect to the specifications. Values of Cp exceeding 1.33 indicate that the process is adequate to meet the specifications. Values of Cp between 1.33 and 1.00 indicate that the process is adequate to meet specifications Values of Cp exceeding 1.33 indicate that the process is adequate to meet the specifications. Values of Cp between 1.33 and 1.00 indicate that the process is adequate to meet specifications Wooluru and Swamy, (2014).

Process capability analysis can determine how the process performs relative to its requirements or specifications, where an important part is the use of process capability indices Lundkvist, (2012). This study seeks to study how an IGCC plant performs using the plants temperature and pressure as its specification.

Capability analysis, or process capability analysis, is the comparison of the distribution of sample values to the specification limits, and possibly also the specification target. One basic measure of the capability of the process is the proportion of values falling inside (or outside) the specification limits. Another measure of capability is the proportion of values that would fall inside (or outside) the specification limits if the data are assumed to follow the normal distribution. Several capability ratios, or capability indices, have been developed to summarize how well the process yields measurements within the specification limits. Those produced in this procedure are Cp, Cpk, Cpm, and Cpkm. Cpm and Cpkm additionally take into account the nearness of the process to the specification target. Process data are typically gathered as samples or individual measurements taken from the process at given times (hours, shifts, days, weeks, months, etc.). If more than one value is taken at a time, the measurements of the samples at a given time constitute a subgroup. Some of the other procedures in NCSS that may be useful for analyzing process capability are X-bar and R (or s) charts, IM-R Charts, Descriptive Statistics, Stem-and-Leaf Plots (for smaller samples), Normality Tests, Outlier Tests, Distribution Fitting, Box-Cox Transformation, and the Data Simulation Tool. NCSS Statistical Software guide, (2018)

III. PROCESS CAPABILITY MODELING

Process capability modeling NCSS Statistical Software guide, (2018).

A. Estimating the Mean-Subgroup Data

Suppose we have *k* subgroups, each of size *n*. Let x_{ij} represent the measurement in the j_{th} sample of the i_{th} subgroup. The i_{th} subgroup mean is calculated using

$$\bar{x}_i = \frac{\sum_{j=1}^{n} x_{ij}}{n} \quad [1]$$

The model for the overall mean is thus

$$\bar{\bar{x}} = \frac{\sum_{i=1}^{k}\sum_{j=1}^{n_i} x_{ij}}{\sum_{i=1}^{k} n_i} \quad [2]$$

If the subgroups are of equal size, the above equation for the grand mean reduces to

$$\bar{\bar{x}} = \frac{\sum_{i=1}^{k} \bar{x}_i}{k} = \frac{\bar{x}_1 + \bar{x}_2 + \cdots + \bar{x}_k}{k} \quad [3]$$

1) Estimating the Mean – Individual Values Data

Suppose we have *k* individual values. The estimate of the overall mean is given by

$$\bar{x} = \frac{\sum_{i=1}^{k} x_i}{k} \quad [4]$$

B. Estimating Sigma – Subgroup Data

In this procedure, sigma can be entered directly, or there are three options for estimating sigma from subgroup data: sample ranges, sample standard deviations, and the weighted approach. Suppose we have *k* subgroups, each of size *n*. Let x_{ij} represent the measurement in the j_{th} sample of the i_{th} subgroup.

2) Estimating Sigma – Subgroup Data – Sample Ranges

If the standard deviation (sigma) is to be estimated from the ranges, *Ri*, it is estimated as

$$\ddot{\sigma} = \frac{\bar{R}}{d_2} \quad [5]$$

Where $\bar{R} = \frac{\sum_{i=1}^{k} R_i}{k}, d_2 = \frac{E(R)}{\sigma} = \frac{\mu_R}{\sigma}$

The calculation of *E(R)* requires the knowledge of the underlying distribution of the x_{ij}'s. Making the assumption that the *xij*'s follow the normal distribution with constant mean and variance, the values for *d2* are derived through the use of numerical integration. It is important to note that the normality assumption is used and that the accuracy of this estimate requires that this assumption be valid. In the procedure, this calculation is performed if Sigma Estimation is set to From Data – R-bar or s-bar Estimate, and Range or SD Estimation is set to Range.

3) *Estimating Sigma – Subgroup Data – Sample Standard Deviations*

If the standard deviation (sigma) is to be estimated from the standard deviations, it is estimated as

$$\ddot{\sigma} = \frac{S}{c_4} \quad [6]$$

Where

$$\bar{s} = \frac{\sum_{i=1}^{k} s_i}{k} \quad [7]$$

$$c_4 = \frac{E(R)}{\sigma} = \frac{\mu_R}{\sigma} \quad [8]$$

The calculation of *E(s)* requires the knowledge of the underlying distribution of the x_{ij}'s. Making the assumption that the x_{ij}'s follow the normal distribution with constant mean and variance, the values for c_4 are obtained from

$$c_4 = \sqrt{\frac{2}{n-1}} \frac{\Gamma\left(\frac{n}{2}\right)}{\Gamma\left(\frac{n-1}{2}\right)} \quad [9]$$

In the procedure, this calculation is performed if Sigma Estimation is set to From Data – R-bar or s-bar Estimate, and Range or SD Estimation is set to SD Approach.

4) *Estimating Sigma – Individual Values Data – Overall Standard Deviation*

If there is only one observation per time point, and the process is assumed to be in control, sigma may be estimated using the sample standard deviation

$$\hat{\sigma} = \sqrt{\frac{\sum_{i=1}^{k}(x_i - \bar{x})^2}{k-1}} \quad [10]$$

In the procedure, this calculation is performed if the data are individual values data, and if Sigma Estimation is set to From Data – SD Approach.

IV. PROCESS CAPABILITY INDICES MODELING

Montgomery (1997); Scrucca, L. (2004) and Huang and Chen, (2003) modeled process capability:

A. *Process Capability Ration, C_p is*

$$C_p = \frac{USL - LSL}{6\sigma} \quad [11]$$

Where USL and LSL are the upper and lower specification limits, respectively. An estimate of *Cp* is produced by substituting a suitable estimate of σ , namely σˆ .

B. *Confidence Intervals for Cp are*

$$C_{plower} = C_p \sqrt{\frac{\chi^2{}_{n-1,\alpha/2}}{n-1}} \quad [12]$$

$$C_{pupper} = C_p \sqrt{\frac{\chi^2{}_{n-1,1-\alpha/2}}{n-1}} \quad [13]$$

C. C_{pl} & C_{pu}

The one-sided capability ratios C_{pl} and C_{pu} are defined as

$$C_{pl} = \frac{\mu - LSL}{3\sigma} \quad [14]$$

$$C_{pl} = \frac{ULS - \mu}{3\sigma} \quad [15]$$

These are estimated by substituting mean and standard deviation estimates.

D. C_{pk}

C_{pk} is the lesser of C_{pl} and C_{pu} *or*

$$C_{pk} = \min(C_{pl}, C_{pu}) \quad [16]$$

The lower and upper confidence limits for C_{pk}

$$C_{pk_{lower}} = C_{pk} - z_{1-a/2}\sqrt{\frac{n-1}{9n(n-3)} + \left(\frac{C_{pk}^2}{2n-6}\right)\left(1 + \frac{6}{n-1}\right)} \quad [17]$$

$$C_{pk_{upper}} = C_{pk} + z_{1-a/2}\sqrt{\frac{n-1}{9n(n-3)} + \left(\frac{C_{pk}^2}{2n-6}\right)\left(1 + \frac{6}{n-1}\right)} \quad [18]$$

E. C_{pm}

$$C_{pm} = \frac{USL - LSL}{6\sqrt{\sigma^2 + (\mu - T)^2}} \quad [19]$$

Where *T* refers to the specification target. A suitable estimate of *Cpm* is made by substituting estimates of the mean and standard deviation.

F. C_{pmk}

$$C_{pmk} = \frac{C_{pk}}{\sqrt{1 + \left(\frac{\mu - T}{\sigma}\right)^2}} \quad [20]$$

Where *T* refers to the specification target. A suitable estimate of C_{pmk} is made by substituting estimates of the mean and standard deviation.

V. NON-NORMAL MULTI-PROCESS CAPABILITY ANALYSIS CHART

Liao et al. (2002) suggested that index N_{pl} is more accurate than C_{pl} in measuring process capability in the larger-the-better-type quality characteristics with non-normal distribution. They replaced the process mean μ by the process median M, and the process standard deviation σ by $(F99.865 - F0.135)/6$ in the definition of the index N_{pl} to suit the larger-the better type quality characteristics with non-normal distribution as follows:

$$N_{pl} = \frac{M - LSL}{(F99.865 - F0.135)/2} \quad [21]$$

Schneider et al. (1996) proposed that *Cpu* fails to measure process capability in smaller-the-better-type quality characteristics with non-normal distribution. Chen et. al (2003) defined N_{pu} to replace C_{pu} according to Liao et al. (2002).

$$N_{pu} = \frac{USL - M}{(F99.865 - F0.135)/2} \quad [22]$$

In revising the Liao et al. (2002), Chen et. al (2003) modified C_{pn} to N_{pn} order to evaluate bilateral specification, thus:

$$N_{pn} = min(N_{du}, N_{du}) \quad [23]$$

Where

$$N_{du} = \frac{USL - M}{\sqrt[3]{[(F99.865 - F0.135)/6]^2 + [M - T]^2}} \quad [24]$$

$$N_{dl} = \frac{M - LSL}{\sqrt[3]{[(F99.865 - F0.135)/6]^2 + [M - T]^2}} \quad [25]$$

The integrated process capability is C_T when the process is a normal distribution, but we change C_T to N_T when the process is a non-normal distribution. N_T can be defined as follows Chen et. al (2003)

$$N_T = \left(\frac{1}{3}\right)\phi^{-1}\left\{\left[\left(\prod_{i\epsilon S}\prod_{j=1}^{n_i}\left[2\phi(3N_{pij}) - 1\right]\right) + 1\right] \div 2\right\} \quad [26]$$

$$S = \{u, l, n\} \quad [27]$$

$$N_{pij} = \begin{cases} \frac{USL - M}{(F99.865 - F0.135)/2}, i = u, j = 1, 2, \dots, t_u \\ \frac{M - LSL}{(F99.865 - F0.135)/2}, i = u, j = 1, 2, \dots, t_l \\ \frac{\min(USL - M, M - LSL)}{\sqrt[3]{[(F99.865 - F0.135)/6]^2 + [M - T]^2}} \; i = n, j = 1, 2, \dots, t_n \end{cases} \quad [28]$$

Process Capability Index and Process Yield for a Multi-Process Product:
There is s direct or proportional relationship between the index S_{pk} and process yield. when S_{pk} = c, process yield Boyles, (1994)

$$\&yeild = 2\Phi(3c) - 1 \qquad [28]$$

The index S_{pk} was defined Huang and Chen, (2003) thus

$$S_{pk} = \frac{1}{3}\Phi^{-1}\left\{\frac{1}{2}\Phi\left(\frac{USL-\mu}{\sigma}\right) + \frac{1}{2}\Phi\left(\frac{\mu - LSL}{\sigma}\right)\right\} \qquad [29]$$

Where Φ denotes the standard normal cumulative distribution function.
Huang and Chen, (2003) opined that since *C*3*pmk* _ *Spk*, *C*3*pmk* = *c* guarantees *Spk* _ *c* and implies that *Pj* _ 2_(3*c*) _ 1. Although the Sea island micro-fiber product is illustrated in this paper, for general application, a product with *w* quality characteristics is introduced in this section. The process yield of the end product consists of the number of *w* quality characteristics and can be expressed as *PT* _ 2_(3C″*pmk*) _ 1, *j* = 1, 2,..., *w*.

$$pr \geq 2\Phi(3C''_{pmk} - 1, j = 1,2,\dots,w \qquad [30]$$

It was intended to define an integrated process capability index *CT k* to express the integrated process capability of the entire product with *w* quality characteristics Huang and Chen, (2003)

$$C_k^T = \left(\frac{1}{3}\right)\phi^{-1}\left\{\left[\left(\prod_{j=1}^{w} 2\Phi(3C_{pmk}^{w}\right) - 1\right] \div 2\right\} \qquad [31]$$

When $C_k^T = v$, solving the above equation we have

$$\prod_{j=1}^{w} 2\Phi(3C''_{pmk}) - 1 = 2\Phi(3v) - 1 \qquad [32]$$

Plant Process flow chart: A flowchart is a visual representation of the sequence of steps and decisions needed to perform a process. Each step in the sequence is noted within a diagram shape. Steps are linked by connecting lines and directional arrows. This allows anyone to view the flowchart and logically follow the process from beginning to end. With proper design and construction, it communicates the steps in a process very effectively and efficiently. https://www.smartdraw.com/flowchart/. The IGCC process flow chart is a logical sequence of the process involved in the IGCC plant. Figure 1.0 shows Modified Block Flow Diagram Gasifier-Based IGCC Reference Plant

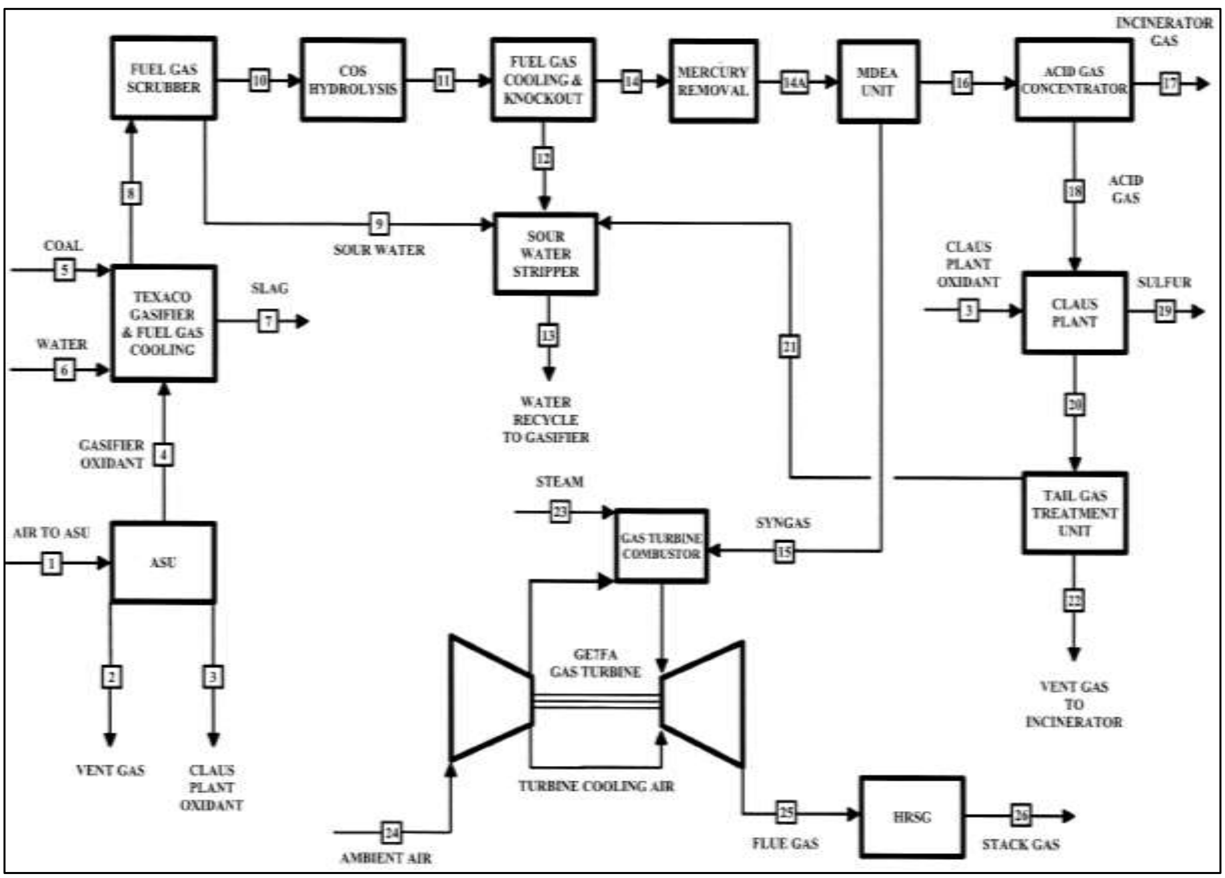

Fig. 1: Modified Block Flow Diagram Gasifier-Based IGCC Reference Plant (DOENETL, 2002)

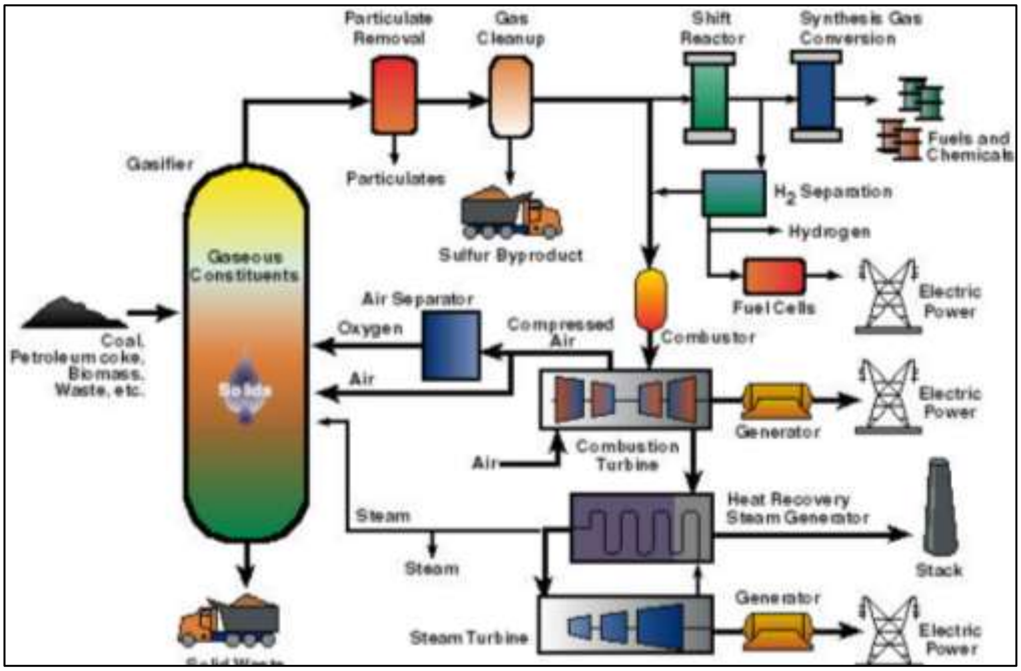

Fig. 2: Gasification-Based Energy Production System Concepts (Ratafia-Brown et. Al 2002)

VI. Results & discussions

A. *Process Capability*

A comparison of the solid overall curve to the bars of the histogram to assess whether the data is approximately normal is carried out for temperature (figure 3). It can be seen that the bars doesn't vary greatly from the curve; it, therefore, can be inferred that the data is normal and the capability estimates is reliable for the IGCC plant process. Between an LSL of 1.131 and USL of 500, a sample mean of 192.39, 26 events, a standard deviation (within) of 119.317 and a standard deviation (overall) of 143.919 were shown as results(figure 3). Furthermore, potential (within) capability are thus: Cp = 0.70, CPL = 0.53, CPU = 0.86, Cpk = 0.53. Also, for the overall capability, Pp = 0.58, PPL = 0.44, PPU = 0.71, Ppk = 0.44, Cpm = undefined. . By visual examination of the data in the histogram (figure 4) in relation to the lower and upper specification limits; it is observed that, the spread of the data is narrower than the specification spread, and all the data are inside the specification limits. Since no data are outside the specification limits, therefore there are no nonconforming items. Also, since Cp and Cpk differ, then the process is not centered. All the Ppk are lower than the benchmark of 1.33, engineers as well as operators of the IGCC plant should consider ways to improve the process.

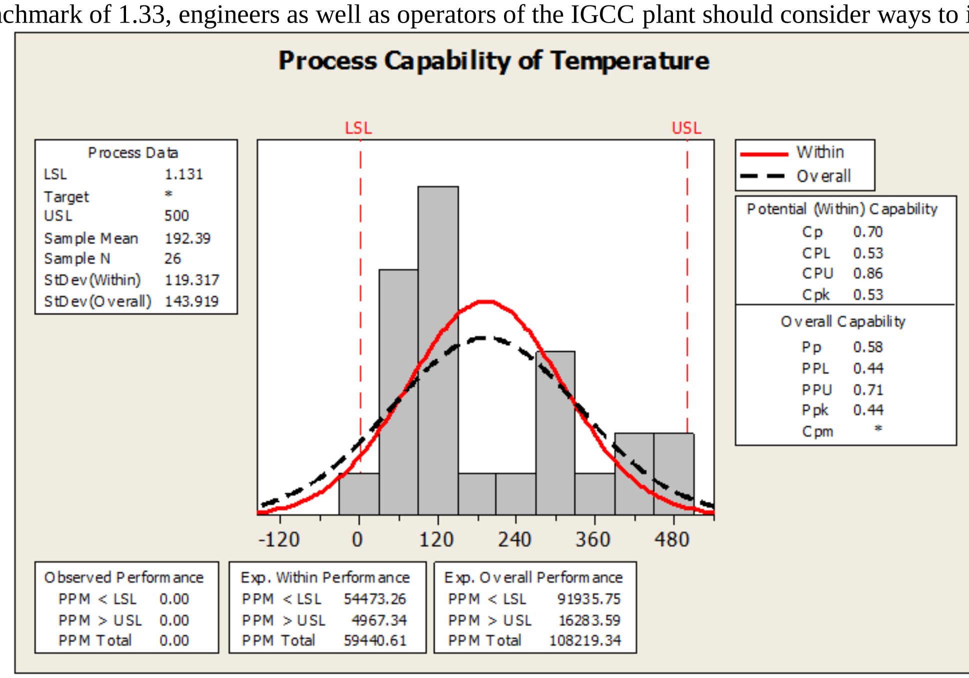

Fig. 3: Process Capability of Temperature

A comparison of the solid overall curve to the bars of the histogram to assess whether the data is approximately normal is carried out for pressure (figure 4). It can be seen that the bars doesn't vary greatly from the curve; it, therefore, can be inferred that the data is normal and the capability estimates is reliable for the IGCC plant process. Between an LSL of 14.7 and USL of 650, a sample mean of 159.119, 26 events, a standard deviation (within) of 124.05 and a standard deviation (overall) of 201.513 were shown as results (figure 4). Furthermore, potential (within) capability are thus: Cp = 0.85, CPL = 0.39, CPU = 1.32, Cpk = 0.39. Also, for the overall capability, Pp = 0.53, PPL = 0.24, PPU = 0.81, Ppk = 0.24, Cpm = undefined. By visual examination of the data in the histogram (figure 4) in relation to the lower and upper specification limits; it is observed that, the spread of the data is narrower than the specification spread, and all the data are inside the specification limits. Since no data are outside the specification limits, therefore there are no nonconforming items. Also, since Cp and Cpk differ, then the process is not centered. All the Ppk are lower than the benchmark of 1.33, engineers as well as operators of the IGCC plant should consider ways to improve the process.

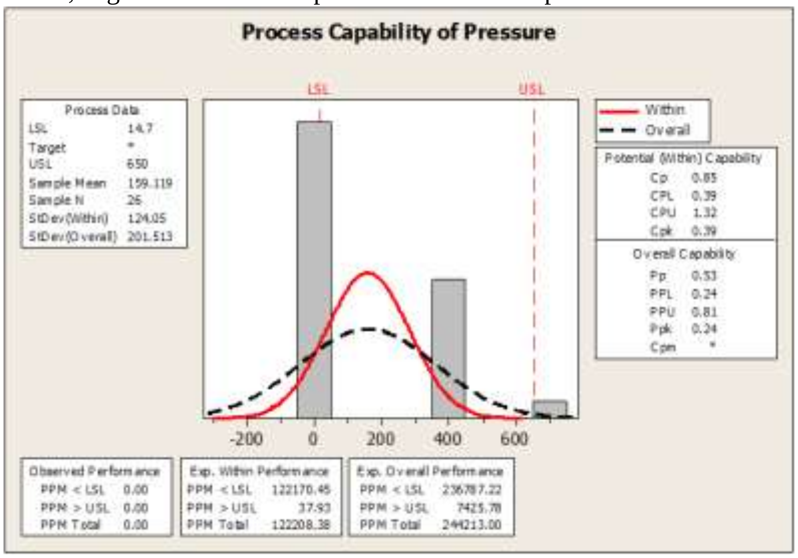

Fig. 4: Process Capability of Pressure

A comparison of the solid overall curve to the bars of the histogram to assess whether the data is approximately normal is carried out for Between/within capability of Temperature (figure 5). It can be seen that the bars doesn't vary greatly from the curve; it, therefore, can be inferred that the data is normal and the capability estimates is reliable for the IGCC plant process. Between an LSL of 1.131 and USL of 450, a sample mean of 192.39, 26 events, a standard deviation (between) of 30.0966, a standard deviation (within) of 150.081 and a standard deviation (overall) of 143.919 were shown as results (figure 5). Furthermore, potential (within) capability are thus: Cp = 0.49, CPL = 0.42, CPU = 0.56, Cpk = 0.42. Also, for the overall capability, Pp = 0.52, PPL = 0.44, PPU = 0.60, Ppk = 0.44, Cpm = undefined. . By visual examination of the data in the histogram (figure 4) in relation to the lower and upper specification limits; it is observed that, the spread of the data is narrower than the specification spread, and all the data are inside the specification limits. Since no data are outside the specification limits, therefore there are no nonconforming items. Also, since Cp and Cpk are approximately equal, then the process is centered between the specification limits. All the Ppk are lower than the benchmark of 1.33, engineers as well as operators of the IGCC plant should consider ways to improve the process.

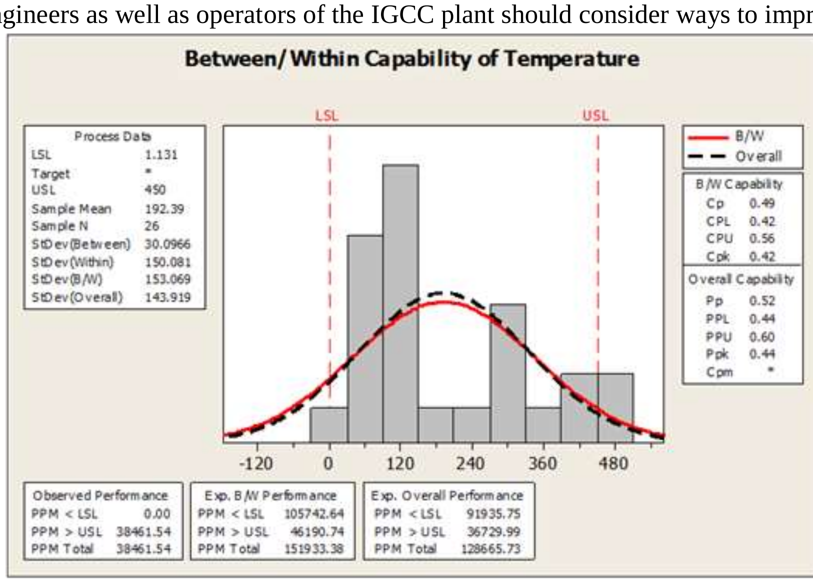

Fig. 5: Process Capability Between/Within Capability Temperature

B. Process Capability of Temperature Calculations based on Weibull Distribution Model

A comparison of the solid overall curve to the bars of the histogram to assess whether the data is approximately normal is carried out for Between/within capability of Temperature (figure 6). It can be seen that the bars doesn't vary greatly from the curve; it, therefore, can be inferred that the data is normal and the capability estimates is reliable for the IGCC plant process. Between an LSL of 1.131 and USL of 500, a sample mean of 192.39, 26 events, shape = 1.28261, scale = 206.591 were shown as results (figure 6). Also, for the overall capability, Pp = 0.55, PPL = 1.00, PPU = 0.46, Ppk = 0.46. . By visual examination of the data in the histogram (figure 4) in relation to the lower and upper specification limits; it is observed that, the spread of the data is narrower than the specification spread, and all the data are inside the specification limits. Since no data are outside the specification limits, therefore there are no nonconforming items. All the Ppk are lower than the benchmark of 1.33, engineers as well as operators of the IGCC plant should consider ways to improve the process.

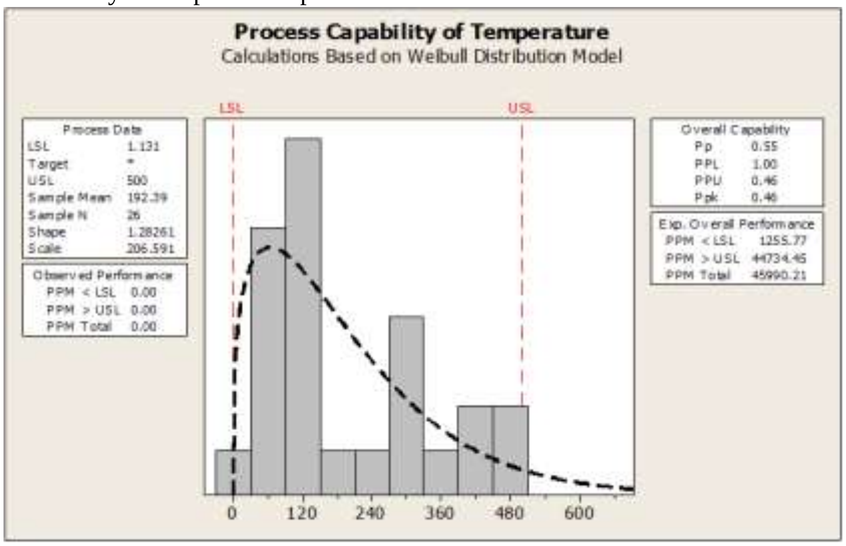

Fig. 6: Process Capability of Temperature Calculations based on Weibull Distribution Model

A comparison of the solid overall curve to the bars of the histogram to assess whether the data is approximately normal is carried out for Between/within capability of Temperature (figure 7). It can be seen that the bars doesn't vary greatly from the curve; it, therefore, can be inferred that the data is normal and the capability estimates is reliable for the IGCC plant process. Between an LSL of 14.7 and USL of 650, a sample mean of 159.119, 26 events, a standard deviation (between) of 107.569, a standard deviation (within) of 184.609 and a standard deviation (overall) of 201.513 were shown as results (figure 7). Also, for the overall capability, Pp = 0.53, PPL = 0.24, PPU = 0.81, Ppk = 0.24. . By visual examination of the data in the histogram (figure 4) in relation to the lower and upper specification limits; it is observed that, the spread of the data is narrower than the specification spread, and all the data are inside the specification limits. Since no data are outside the specification limits, therefore there are no nonconforming items. All the Ppk are lower than the benchmark of 1.33, engineers as well as operators of the IGCC plant should consider ways to improve the process.

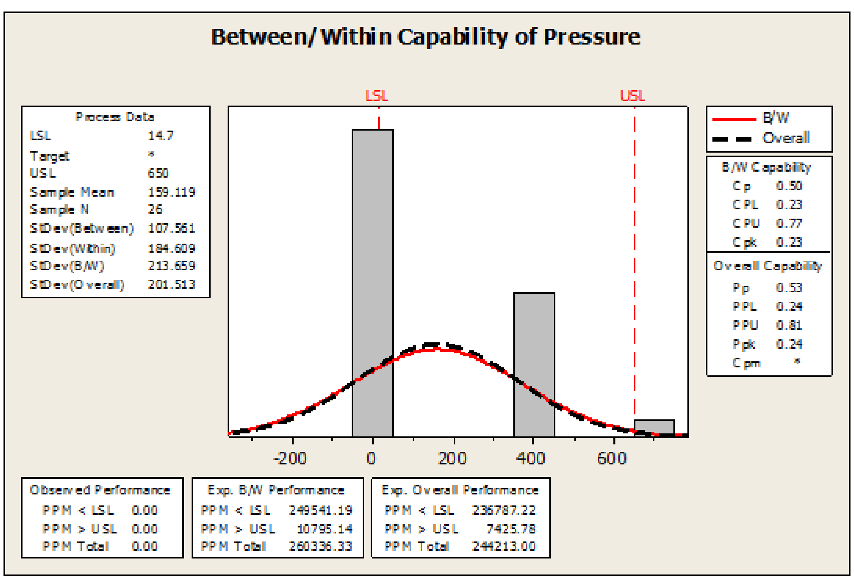

Fig. 7: Process Capability Between/Within Capability Pressure

C. Process Capability Six-Pack of Temperature

A comparison of the solid overall curve to the bars of the histogram to assess whether the data is approximately normal is carried out for Between/within capability of Temperature (figure 7). It can be seen that the bars doesn't vary greatly from the curve; it, therefore, can be inferred that the data is normal and the capability estimates is reliable for the IGCC plant process. Between an LSL of 1.131 and USL of 500, a sample mean of 150.4,26 events. It is observed, from the individual value plot (figure 8), that UCL =550.3, while mean = 192.4) and LCL = 165.6. For the moving range chart, it is observed that UCL = 439.7, $\overline{MR} = 134.6$ and LCL = 0. Within values of the capability plot, standard deviation of 119.3, a standard deviation (between) of 143.9 and a 513 were shown as results (figure 8). Also, for the overall capability, Pp = 0.58, Cpm = undefined, PPM = 108219.34, Ppk = 0.44. For within capability, standard deviation of 119.3, Cp = 0.70, Cpk = 0.53 and PPM = 59440.61. By visual examination of the data in the histogram (figure 8) in relation to the lower and upper specification limits; it is observed that, the spread of the data is narrower than the specification spread, and all the data are inside the specification limits. Since no data are outside the specification limits, therefore there are no nonconforming items. Also, since Cp and Cpk differ, then the process is not centered. All the Ppk are lower than the benchmark of 1.33, engineers as well as operators of the IGCC plant should consider ways to improve the process.

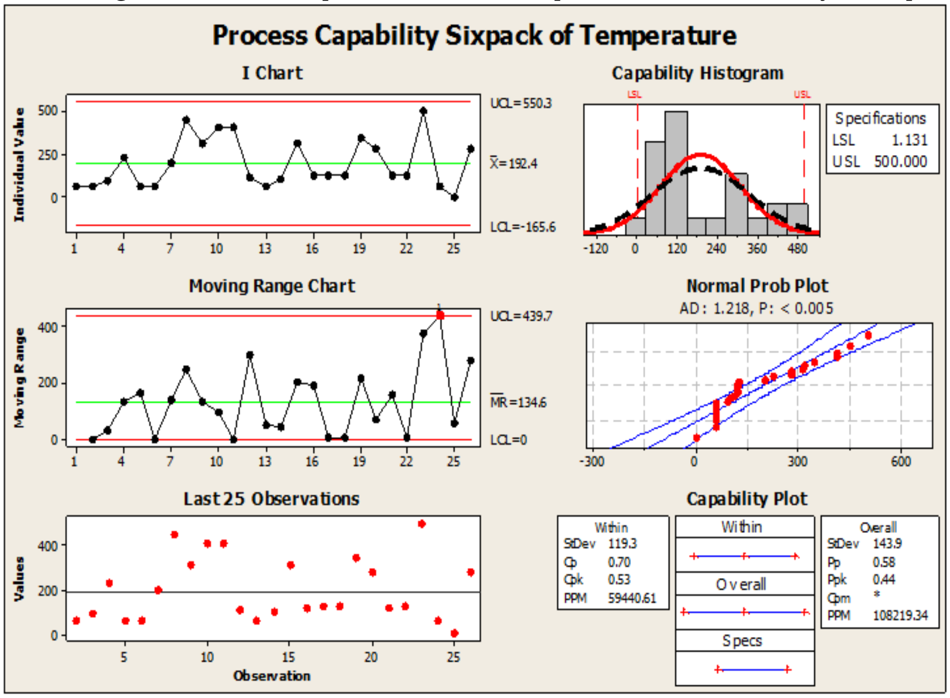

Fig. 8: Process Capability Six Pack of Temperature

A comparison of the solid overall curve to the bars of the histogram to assess whether the data is approximately normal is carried out for Between/within capability of Temperature (figure 9). It can be seen that the bars doesn't vary greatly from the curve; it, therefore, can be inferred that the data is normal and the capability estimates is reliable for the IGCC plant process. Between an LSL of 14.7 and USL of 650, a sample mean of 159.1, 26 events. It is observed, from the individual value plot (figure 9), that UCL =531.3, while mean = 159.1) and LCL = 213.0. For the moving range chart, it is observed that UCL = 457.2, $\overline{MR} = 139.9$ and LCL = 0. Within values of the capability plot, standard deviation of 124.0, a standard deviation (overall) of 201.5 were shown as results (figure 9). Also, for the overall capability, Pp = 0.53, Cpm = undefined, PPM = 244213.00, Ppk = 0.24. For within capability, standard deviation of 124.0, Cp = 0.85, Cpk = 0.39 and PPM = 122208.38. By visual examination of the data in the histogram (figure 9) in relation to the lower and upper specification limits; it is observed that, the spread of the data is narrower than the specification spread, and all the data are inside the specification limits. Since no data are outside the specification limits, therefore there are no nonconforming items. Also, since Cp and Cpk differ, then the process is not centered. All the Ppk are lower than the benchmark of 1.33, engineers as well as operators of the IGCC plant should consider ways to improve the process.

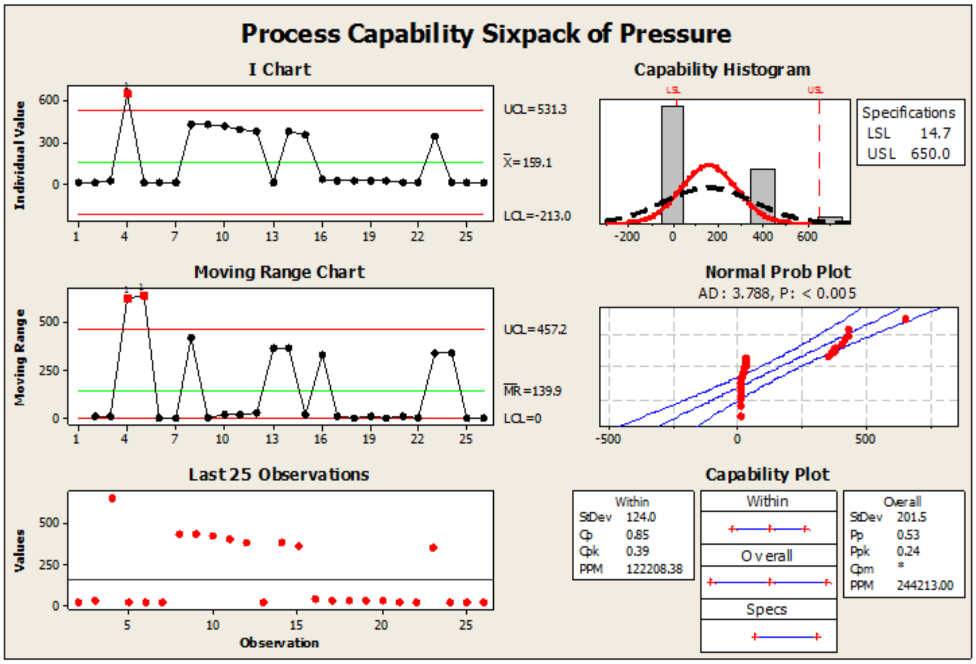

Fig. 9: Process Capability Six Pack of Pressure

Comparing the solid overall curve to the bars of the histogram to assess whether the data is approximately normal is carried out for Between/within capability of Temperature (figure 10). It can be seen that the bars doesn't vary greatly from the curve; it, therefore, can be inferred that the data is normal and the capability estimates is reliable for the IGCC plant process. Between an LSL of 1.131 and USL of 650, a sample mean of 192.4, 26 events. It is observed, from the individual value plot (figure 10), that UCL = 434.9, while mean = 192.4 and LCL = -50.2. For the moving range chart, it is observed that UCL = 298.0, $\overline{MR} = 91.2$ and LCL = 0. Within values of the capability plot, standard deviation of 150.3, a standard deviation (overall) of 143.9 were shown as results (figure 10). Also, for the overall capability, Pp = 0.75, Cpm = undefined, PPM = 92673.07, Ppk = 0.24. For within capability, standard deviation of 150.1, Cp = 0.71, Cpk = 0.42 and PPM (between) = 107139.51. while PPM (overall) =92673.07 By visual examination of the data in the histogram (figure 9) in relation to the lower and upper specification limits; it is observed that, the spread of the data is narrower than the specification spread, and all the data are inside the specification limits. Since no data are outside the specification limits, therefore there are no nonconforming items. Also, since Cp and Cpk differ, then the process is not centered. All the Ppk are lower than the benchmark, engineers as well as operators of the IGCC plant should consider ways to improve the process.

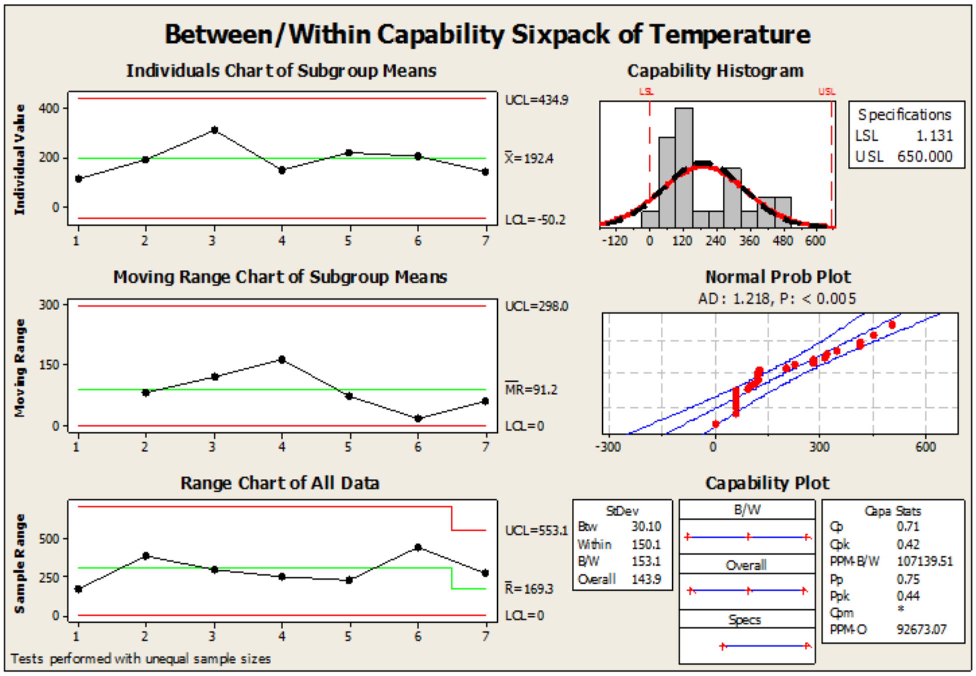

Fig. 10: Plot of Between/Within Capability Six Pack of Temperature

VII. CONCLUSION

Process capability study is applied combining the statistical tools developed from the normal curve and control charts with good engineering judgment to interpret and analyze the data representing the IGCC plant process by the following the algorithm, depicted by the flow chart:

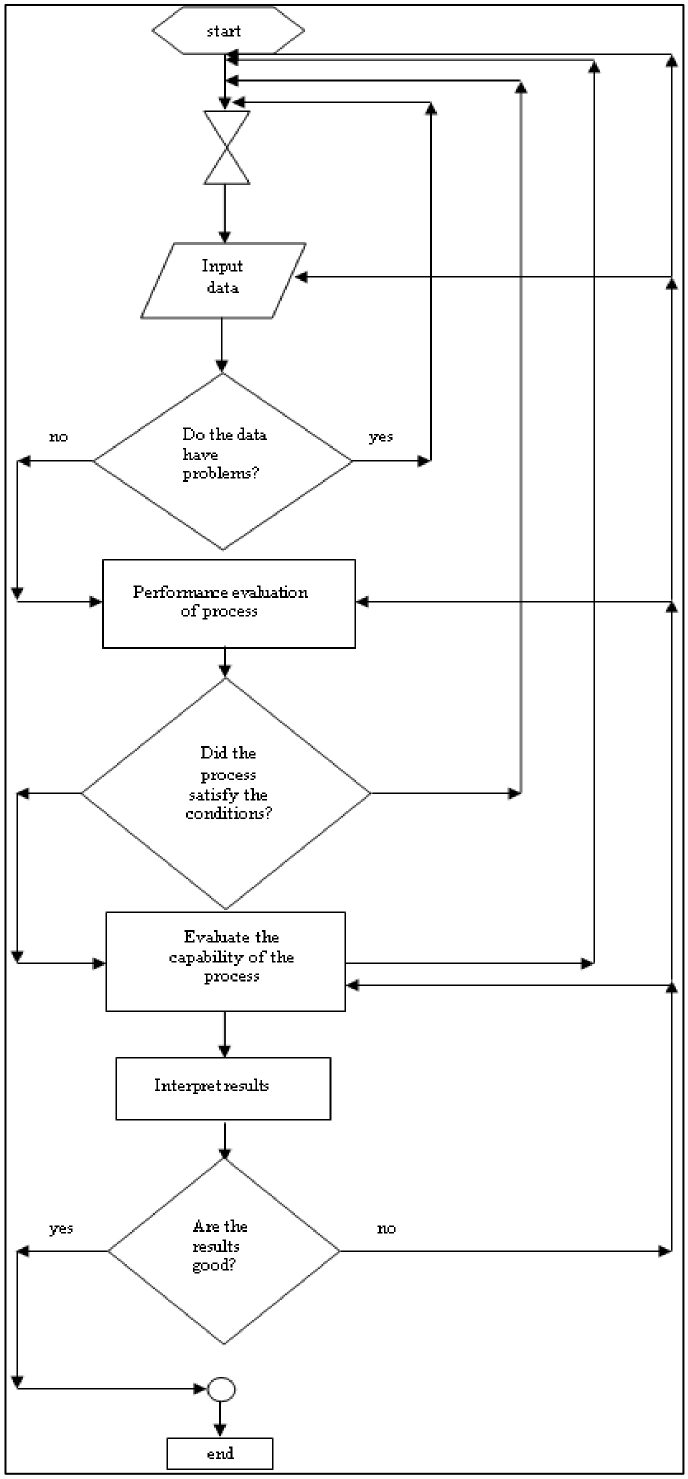

Fig. 11: Flowchart for Process Capability

All the process capability performance indices were all gotten for all the processes, except the Cpm, which, from the plots, was reported to be undefined. From a visual examination of the process spread, it is observed that the data in the histogram in relation to the lower and upper specification limits is not outside limits. Ideally, the spread of the data is narrower than the specification spread, and all the data are inside the specification limits. Data that are outside the specification limits represent nonconforming items. From visual examination of all results (figures 2 to 10), it is observed that Cpk $\ll 1.33$. The implication of the indices is that there is need for a process improvement, such as reducing its variation or shifting its location. Compare Ppk to a benchmark value that represents the minimum value that is acceptable for your process. Many industries use a benchmark value of 1.33. (https://support.minitab.com/en-us/minitab/18/help-and-how-to/quality-and-process-improvement/capability-analysis/how-to/capability-analysis/normal-capability-analysis/interpret-the-results/key-results/). Since all the Ppk are lower than the benchmark, engineers as well as operators of the IGCC plant should consider ways to improve the process.

REFERENCES

[1] M. L. Huang and K. S. Chen (2003), Capability Analysis for a Multi-Process Product with Bilateral Specifications, Int J Adv Manuf Technol 21:801–806, 2003 Springer-Verlag London Limited.
[2] https://www.brighthubengineering.com/power-plants/43234-advantagesof-an-integrated-gasification-combined-cycle-igcc/
[3] Montgomery, D.C. (1997). Introduction to Statistical Quality Control. Wiley.
[4] Scrucca, L. (2004). qcc: an R package for Quality Control Charting and Statistical Process Control. R News 4/1, 11-17.
[5] Liao SJ, Chen KS, Li RK (2002) Capability evaluation for process of the larger-the-better type for non-normal populations. Adv Appl Stat 2(2):189–198
[6] Schneider H, Pruett J, Lagrange C. (1995-1996) Uses of process capability indices in the supplier certification process. Qual Eng 8(2):225–235
[7] R. A. Boyles (1994), Process capability with asymmetric tolerances , Communications in Statistics Simulation and Computation, 23, pp. 615 – 643,
[8] https://support.minitab.com/en-us/minitab/18/help-and-how-to/quality-and-process-improvement/capability-analysis/how-to/capability-analysis/normal-capability-analysis/interpret-the-results/key-results/