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Technology qualification for IGCC power plant with CO2 Capture

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MASTER THESIS

for

Stud.techn. Yasir Baig
Spring 2011

Technology qualification for power plants with CO_2 capture

Kvalifisering av teknologi for gasskraftverk med CO2-fangst

Background and objective.

Carbon dioxide is indetified as the major contributor to man-made global warming. CO2 capture and storage (CCS) from power plants represents the biggest potential for reduction of CO_2. CCS is associcated with high risk, both technically and economical. When investing a lot of money in CCS technologies, it is required that the risk can be evaluated and quantified before actually large investemets can be done. The risk assessment challenge is to find the risk related to novel technologies, and technologies used on larger scale than previously. The risk assessment can be used as an element for the qualification of a technology, which forms an important part of the investment decision.

The objective of this project is to carry out a technology qualification procedure, including a risk assessment, for one plant concept; IGCC with CO_2 capture.

A basis for this work is a project work done by the candidate during autumn 2010.

The following questions should be considered in the project work:

1. Based on a selected power cycle with CO2 capture; Integrated Gasification Combined Cycle (IGCC), define a mass and heat balance and performance characteristic.
2. Make a qualification plan for the defined IGCC with CO_2 capture
3. Carry out a FMECA (Failure Mode, Effects and Criticality Analysis) and a HAZOP for the IGCC with CO_2 capture.

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Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct.

In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

Pursuant to "Regulations concerning the supplementary provisions to the technology study program/Master of Science" at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

One – 1 complete original of the thesis shall be submitted to the authority that handed out the set subject. (A short summary including the author's name and the title of the thesis should also be submitted, for use as reference in journals (max. 1 page with double spacing)).
Two – 2 – copies of the thesis shall be submitted to the Department. Upon request, additional copies shall be submitted directly to research advisors/companies. A CD-ROM (Word format or corresponding) containing the thesis, and including the short summary, must also be submitted to the Department of Energy and Process Engineering

Department of Energy and Process Engineering, 18. Febraury 2011

Trygve M. Eikevik
Department Deputy Head

Olav Bolland
Academic Supervisor

Co-Supervisor: Dr. Tore Myhrvold, DNV

Problem Description:

The objective of this thesis work is to carry out a technology qualification procedure, including a risk assessment, for one plant concept; IGCC with CO_2 capture.

The following questions should be considered in the project work:

1) Based on a selected power cycle with CO_2 capture; integrated gasification combined cycle, define a mass balance, heat balance and performance characteristics.
2) Make a qualification plan for the defined IGCC with CO_2 capture.
3) Carry out a FMECA(Failure Mode, Effects and Criticality Analysis) and a Hazop analysis for the IGCC with CO_2 capture

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At the end I wish to express my deepest gratitude to my aunty Nimo and my father Mirza Nasir Baig for their countless love and care throughout my life. Without their spiritual love this work would never have come into existence.

Nomenclature:

^0C	Degree centigrade, measure of temperature
Anova	Analysis of variance
ASU	Air separation unit
CCS	CO_2 capture and storage
FMECA	Failure modes effect and criticality analysis
GT	Gas turbine
Hazop	Hazard and operability analysis
HRSG	Heat recovery steam generator
HEX	Heat exchanger
IGCC	Integrated gasification combined cycle
MW	Molecular weight
QB	Qualification basis
RAM	Reliability, availability, and maintainability
RPN	Risk priority number
ST	Steam turbine
WGS	Water gas shift reactor

List of chemical symbols**:**

Ar	Argon
CO_2	Carbon dioxide

CH_4	Methane
CO	Carbon monoxide
H_2O	Water
H_2	Hydrogen
H_2S	Hydrogen sulfide
N_2	Nitrogen
O_2	Oxygen
SO_2	Sulfur dioxide

Summary:

This thesis presents the technology qualification plan for the integrated gasification combined cycle power plant (IGCC) with carbon dioxide capture based on DNV recommendations. Objectives of the thesis work were development of a qualification plan, heat balance, material balance and performance characteristics for IGCC with CO_2 capture. GT PRO software by thermoflow was used for the development of heat balance, material balance and performance characteristics of power plant.

IGCC with pre-combustion capture is a process of generating power with very low CO_2 emissions. The IGCC process gasifies coal to a syngas, converts the CO to CO_2 in the shift reactors, separates the CO_2 in the capture subsystem, and the resulting fuel is used for the gas turbine (GT) in a combined cycle setup. A comparison is also made between the enriched air blown gasification combined cycle power plant with CO_2 capture and shell gasification combined cycle power plant with CO_2 capture.

For the case of this thesis, technology qualification steps obtained from DNV guidelines are implemented on the enriched air blown integrated gasification power plant with CO_2 capture. First step of the technology qualification was to establish a qualification basis for the IGCC power plant with CO_2 capture. In this step detailed process description of power plant is done in order to define what technology should do and what its functional requirements are?

Next step of the technology qualification was technology assessment. The main purpose of this step was to divide the IGCC power plant with CO_2 capture into manageable elements that involve the aspects of new technology and identify key challenges and uncertainties associated with those novel elements.

Threat assessment was the third step in the technology qualification. Risks and failure modes associated with the commercialization of IGCC with CO_2 capture are identified by applying risk assessment techniques like (Failure Mode Effect & Criticality Analysis (FMECA) and Hazard and Operability Analysis (Hazop). Analysis of variance was used in order to give priority to more critical failure modes.Faiure modes like surge problem of gas turbine,fouling,metal dusting and tube vibration for the heat exchanger, deactivation of catalyst for shift reactor, maldistribution of the solvent for the absorber, contaminated supply of steam to steam turbine have been identified.

Qualification plans were developed for the identified failure modes of concern obtained from FMECA and Hazop analysis .The main objective of this step was to select qualification activities that adequately address the identified failure modes of concern with respect to its risk and determination of sufficient performance margins.

Activities like integration of gas turbine to air separation unit, chemical treatment of water in order to avoid contaminated supply of water to HRSG and contaminated supply of steam to steam turbine, better understanding of distributor design and packing development for the absorber were suggested.

After the selection of these qualification activities, execution of selected qualification activities was done in a systematic manner to document performance margins for the failure modes of concern.

Last step of the technology qualification plan was concept improvement. The objective of the concept improvement step was to implement improvements that have been found necessary or beneficial during the failure mode identification and risk ranking or in the performance assessment.

The focus of this work was to reduce uncertainties in these parameters in order to improve the confidence in the IGCC power plant with CO_2 capture.

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Chapter 1: Introduction:

1.1 Project background & motivation:

The topic of this thesis was suggested by DNV in order to develop a qualification plan for integrated gasification combined cycle power plant with carbon dioxide capture. The world's population is growing at a constant rate, as are its energy requirements. It is believed that the large portion of world' future demand for electrical energy and heat will come from the burning of fossil fuels, implying increased emissions of carbon dioxide to the atmosphere.CO_2 capture and storage (CCS) from power plants represents the biggest potential for the reduction in CO_2 from the atmosphere. The main motivation of this report was to reduce the emission of carbon dioxide to the atmosphere as a result of power production.

1.2 Objective:

The overall aim of this thesis was to establish a technology qualification plan for the integrated gasification combined cycle power plant with CO_2 capture. When investing a lot of money in CCS technologies, it is required that the risk can be evaluated and quantified before actually large investments can be done. The risk assessment challenge is to find the risk related to novel technologies, and technologies used on larger scale than previously.

Specifically for this thesis work the objectives were:

1) Development of heat balance, material balance and performance characteristics of Integrated Gasification Combined Cycle Power Plants with CO_2 Capture.
    - GT Pro by thermoflow was used in order to establish the heat balance, mass balance and performance characteristics of the power plant.
2) Make a qualification plan for the defined IGCC with CO_2 capture.
    - The main concept of this part of the project was taken from the Technology Qualification Plan based on DNV recommendations.
3) Carry out a FMECA (Failure Mode, Effects and Criticality Analysis) and Hazop Analysis.

- The main aim of this step was to identify the possible risks associated with the implementation of pre-combustion carbon dioxide capture to the IGCC power plant. The risk assessment can be used as an element for the qualification of a technology, which forms an important part of the investment decision.

1.3 Methodology:

Following is a brief description of methodologies that will be used in this master thesis:

1.3.1 Process description:

A detailed description of the IGCC power plant with CO_2 capture for shell gasifier and IGCC with CO_2 capture for Mitsubishi gasifier is done. Material balance, energy balance and performance characteristics were developed for both power plants by using GT Pro software. A comparison is also made between these two power plants.

1.3.2 Technology qualification steps:

Implementation of the technology qualification step is done on the IGCC with CO_2 capture (Mitshibishi gasifier case).This technology qualification process is based on the systematic risk based approach. Following steps are carried out on the IGCC power plant with CO_2 capture:

- Step1: Qualification basis for IGCC power plant with CO_2 capture

The first step in the technology qualification is the qualification basis .Qualification basis defines how technology will be used and what will be the acceptance criteria in terms of a fully qualified product.

- Step2: Technology assessment of IGCC power plant with CO_2 capture

Technology assessment of IGCC with CO_2 capture is done. IGCC power plant with CO_2 capture is divided into manageable elements in order to assess which elements involve aspects of new technology and identify key challenges and uncertainties.

- Step3:Threat assessment of IGCC power plant with CO_2 capture

Threat assessment of power plant is also carried out. The main purpose of this step is to identify all relevant threats defined as failure modes of concern, for elements defined as new technology in the technology assessment and for each judge the associated risks by performing FMECA and Hazop analysis. The main inputs to the failure mode identification are qualification basis and list of the new technology elements developed in the technology assessment.

- Step4: Development of qualification plan

A qualification plan is developed in order to address the identified failure modes of concern with respect to its risk and determination of sufficient performance margin. The selected qualification activities will be input to a technology qualification plan where various issues will be outlines as qualification activities need to be executed.

- Step5:Execution of qualification plan for failure modes of IGCC power plant with CO_2 capture

Execution of the technology qualification plan has been done by performing the qualification activities in the qualification plan.

- Step6: Performance assessment of IGCC power plant with CO_2 capture

Performance assessment of the power plant has been carried out in order to confirm that the functional requirements as stated in the qualification basis are met.

- Step7:Concept improvement of IGCC power plant with CO_2 capture

In this part of the technology qualification implementations of improvements found necessary during FMECA, Hazop and performance assessment are carried out.

1.4 Structure of thesis:

The thesis comprises four chapters. Chapter 2 gives a description of technical background and literature survey of the technology qualification of IGCC with CO_2 capture .Chapter 3 describes process description of IGCC with CO_2 capture with shell and Mitsubishi gasifiers.Within chapter 3 a comparison is also made between two power plants. Chapter 4 contains the heart of the thesis in which implementation of the technology qualification steps on power plant is done.Conclusions and future work are described in chapter 5.

Chapter 2: Technical background and literature survey:

2.1 IGCC power plant with CO_2 capture:

IGCC makes use of combined cycle unit for the efficient production of power. For the reduction of carbon dioxide emission it is by far the most advanced technology and within next coming years it is believed to be demonstrated in the large scale. Currently quite a large number of projects are in continuous progress all over the world (K.Christian et al., 2008).

There is an indication that the numbers of large point sources are likely to increase in the future, and that, by 2050, given expected technical limitations, around 20–40% of global fossil fuel CO_2 emissions could be technically suitable for capture, including 30–60% of the CO_2 emissions from electricity generation and 30–40% of those from industry (Metz.B et al., 2005).

An expansion in the recent power plant fleet is assured because of the continuous growing demand of electricity. The achievement of the efficient power production with reduction of greenhouse gas emissions is a daunting task. Among all other coal based power plants integrated gasification combined cycle power plant has the lowest emission of carbon dioxide. A substantial reduction in the green house gas emissions can be obtained by the implementation of physical absorption process in the integrated gasification combined cycle power plant. When combined with a CO_2 physical absorption system, substantial GHG emissions reductions can be attained. Depending on the degree of capture, the emissions can match or become less than those of natural gas fired combined cycle (NGCC) power plants (Ordorica-Garcia, et al., 2005).

2.2 IGCC and traditional coal fired power plant:

Integrated gasification combined cycle as compared to the traditional coal fired power plants has the advantage like high thermal efficiency, ultra low NOx ,SOx and solids emissions as well as marketable by products are factors making it commercially more competitive against conventional coal fired power plants. In addition to that by incorporating a catalyzed water gas shift reaction in the process reliably Hydrogen and carbon dioxide can be produced (Ordorica-Garcia et al., 2005).

2.3 Reliability, availability, and maintainability of IGCC:

Improvement of IGCC reliability, availability, and maintainability (RAM) is the most fundamental achievement needed for IGCC technology to become more competitive and more readily accepted in the marketplace. One cannot fully understand or substantially improve IGCC reliability, availability and maintainability without access to precise, dependable, and broad-based data that document the factors that decrease reliability and availability by increasing the frequency and duration of maintenance activities in IGCC plants. Currently there are no formal mechanisms for acquiring and tracking IGCC RAM (J.Phillip, 2007).

2.4 Commercialization of IGCC with CO_2 capture:

Commercially there is no IGCC plant with CO_2 capture has been built yet. However, all of the required technology is already proven in ammonia production and other industrial processes.Selexol is used as solvent for the simultaneous capture of H_2S and CO_2 from coal syngas in commercial ammonia production.Selexol gives the best result as a physical solvent for CO_2 removal from IGCC fuel gases due to its relatively lower energy requirements and lower investment costs (Ordorica-Garcia et al., 2005).

2.5 Efficiency of IGCC power plant with CO_2 capture:

Energy conversion systems such as IGCC which are based on gasification can provide affordable, stable, high-efficiency energy production with minimal environmental impact. Strict air pollution emission standards, production of H_2O effluent within environmental limits, production of environmentally benign slag with good potential as a salable product can be economically achieved by the use of IGCC system. Life-cycle analyses performed on IGCC power plants have identified CO_2 release and natural resource depletion as their most significant lifecycle impacts, which testifies to the IGCC's low pollutant releases and benign byproducts. Recent studies have also shown that these plants can be built to efficiently accommodate future CO_2 capture technology that could further reduce their environmental impact. The outstanding environmental performance of IGCC makes it an excellent technology for the clean production of electricity. IGCC systems also provide flexibility in the production of a wide range of products including electricity, fuels, chemicals, hydrogen, and steam, while utilizing low-cost, widely available feedstock. Gasification systems based on coal can provide an energy production alternative that is more efficient and environmentally friendly than the competing coal fueled technologies (Jay A. et al., 2002).

The concept studied in this report is capture of carbon dioxide prior to the combustion in an Integrated Gasification Combined Cycle (IGCC) power plant by means of a physical absorption process using selexol as solvent. Qualification of this concept is highly necessary in order to reduce uncertainty, mitigate risks, and ensure feasibility. The objective of this thesis report is to develop qualification procedure based on DNV recommendations for the integrated gasification combined cycle power plant with carbon dioxide capture.

But it should be noted that in order to perform technology qualification procedure on integrated gasification combined cycle power plant with carbon dioxide capture, in depth knowledge of reliability engineering, risk management and all the technical details associated with the IGCC power plant is essential.

2.6 Failure analysis

A central part of technology qualification is identifying all the ways in which the system can fail to perform as required, that is, experience unreliability. This is the case when one or more required functions are terminated (i.e. exceeding the acceptable limits). The event when this happens is called a failure; the resulting state is termed a fault. A fault can be observed as a failure mode. Each function may have several failure modes, and each failure mode may have several different causes, mechanisms and effects (Rausand.M, 2004).

Failure modes, effects, and criticality analysis (FMECA) is an extensively used qualitative technique for reliability analysis. This technique can be used to identify critical areas during the design stage of the system. When the criticality of failures is not investigated, the FMECA is sometimes called failure mode and effect analysis (FMEA).For the case of this report FMECA is used in order to identify the most critical failure modes of concern and then consequently provide corrective action to mitigate the affect of failure (Olof Nord, L et al., 2009).

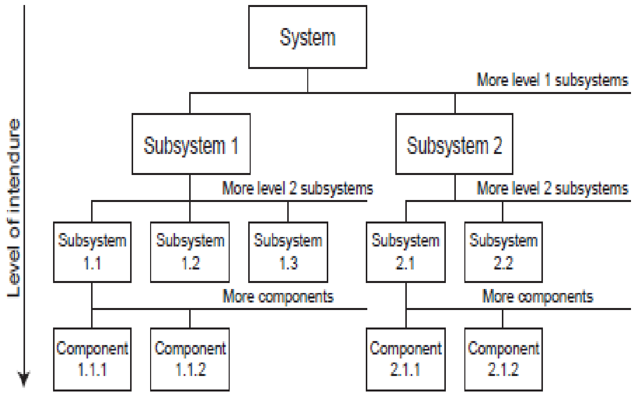

Figure 1: Division of components into subcomponents (Rausand.M, 2004)

2.7 Hazard and operability (Hazop) analysis:

The objective of Hazard and Operability Studies (Hazop) is to facilitate smooth, safe, and prompt commissioning of new plant, without extensive last-minute modifications, followed by trouble-free continuing operation. Hazop is widely accepted as the method of studies for safety assessment of process industries. Thermal power plant involves a wide scope of Hazop study and it is also an extra hazardous industry. To ensure safe operation, safety assessment is very important proactively to identify potential safety problems, recommend possible solutions and eliminate potential hazards. There are many methods of safety assessment for thermal power plants (Y.Chun, 2009). A detailed Hazop analysis was carried out on IGCC with CO_2 capture so that possible deviations from the process conditions can be analyzed.

HAZOP is a well recognized and commonly applied technique, but it has some limitations associated with it. For example it is not well suited for identifying component failures and environmental stresses as causes for deviation. Unforeseen hazards are not included in the study, and the results rely heavily on the team's composition (Rausand.M, 1991).

A schematic description of the Hazop analysis is given below:

Definition

- Define scope and objectives
- Define responsibility
- Select team

↓

Examination

- Divide system into parts
- Select a part and define design intent
- Identify deviation by using guide words on each element
- Identify consequences and causes
- Identify whether a significant problem exists
- Identify protection, detection, and indicating mechanisms
- Identify possible mitigating measures
- Agree action
- Repeat on each element and then on part of the system

↓

Preparation

- Plan study
- Collect data
- Agree style of recording
- Estimate the time
- Arrange a schedule

↓

Documentation and follow-up

- Record the examination
- Sign off the document
- Produce the report of the study
- Follow that actions are implemented
- Re-study any parts of the system if necessary
- Produce final output report

Figure 2: Schmetic description of Hazop analysis (Y.Chun, 2009)

HAZOP is a well known and extensively applied technique, but some limitations are also associated with it. It is for example not well suited for identifying component failures and environmental stresses as causes for deviation. Unexpected hazards are not included in the study, and the results rely a lot on the team’s composition

(Rausand.M, 1991). Combining HAZOP with other techniques, such as FMECA and Fault Tree analysis, is therefore suggested.

If data is available in limited amount for qualifying a new technology then it is very important to gather as much qualitative expert judgment on the potential ways in which a system fail as possible. A technique for systematically doing this is the HAZOP technique. This technique usually applied in the concept design phase of process plants to analyze the risks involved in the system, its most important objective is to identify potential problems that can arise during operation and maintenance of the system. HAZOP is a managed creative process carried out through a series of sessions by a team usually built up by 5-7 experts of relevant disciplines, a secretary and a HAZOP facilitator charged with managing the process. Creative potential of the team's members can be fully utilized to identify all possible ways the system can conceivably fail by conducting the sessions as brainstorm sessions, (Rausand, 1991).

Implementation of new technology with as low risk as possible will be of great interest of technology vendors, operators, as well as governments and that they will work as intended over the lifetime of the project. Qualification of technology is a systematic set of activities that aim to reduce the risks associated with the implementation of new technology. Technology qualification holds the key in increasing the confidence in new and scaled-up CO_2 capture technologies. (Myhrvold.T, et al., 2009).

2.8 Technology qualification:

The main technological concepts for CO_2 capture contain a majority of processes and components that are commercially available today. These are mainly developed and used for other purposes, such as within the food and beverage industry, natural gas processing, ammonia production or fire extinguishing equipment. The existing processes used in these systems are at smaller scale and/or used with other conditions than those that are planned built in the near future within the power generation industry. The CO_2 capture technologies that are available today need considerable efforts to integrate, optimize, and to scale up the process components to an industrially matured process. There are also some novel CO_2 capture concepts that use new components that are not known in the industry today. These novel technologies need a longer development and qualification program before commercialization.

2.9 Overall objective of technology qualification:

New technology is generally not sufficiently covered by well-known codes and procedures. It is of great importance that new technology must therefore be qualified by an organized process where the required functionality and reliability is obtained by identifying risks that need to be minimized through adequate qualification methods, such as analyses and testing.

Hence, the main goal of technology qualification is twofold:

a. Identify all ways in which the new technology can possibly fail; calculate risks, that is, the combination of likelihood and consequence of failure.

b. Minimize the time and capital penalty on the development project due to qualification.

Figure 3: Technology qualification steps (DNV, 2010).

2.10 Fundamental pillars of technology qualification:

Generally speaking, qualification of new technology rests on two basic pillars of knowledge: For one, qualification makes use of knowledge and different analytical methods developed in various academic fields, such as safety and reliability engineering, risk management and project management. Secondly, an in depth understanding of the technology at hand is compulsory.

The qualification process can be carried out throughout the development of the new technology, or can be started at any time in the development. However, if a significant change or modification (physical or operational) is planned during operation, a review should be made with regards to revisiting the qualification process. Examples of project development phases include strategy, feasibility and concept selection, design, construction, installation and commissioning, operation and life extension, and decommissioning. The standard description of the Technology Qualification can found in the DNV Technology Qualification Plan (DNV, 2010).

2.11 Initial phase of technology development:

The initial phase of any technology development project is a specification of the intentions or requirements of the intended user of the technology in terms of reliability and functional requirments.Governmental regulations and relevant standards should also be considered while specifying the requirements of the technology. The developer of the technology should be able to document that the new technology will live to the specifications. This is done through technology qualification, which is defined as “confirmation by examination and provision of evidence that the new technology meets the specified requirements for the intended use” (DNV, 2001).

A technology is qualified when it is documented that the specified performance criteria are met. A prerequisite for technology qualification is therefore that the requirements are clearly communicated in writing, which is done in a specification. A specification may define general characteristics or it may be specific to the reliability and maintainability features of a product, such as service life at various performance levels, conditions of use, installation, acceptance/rejection criteria and definitions of failure. The function of a specification is to provide a basis of understanding between two parties so that both agree on the criteria to be met (BS 5670).

With reliability requirements specified, the task of the technology developer is to confirm “by examination and provision of evidence that the new technology meets the specified requirements for the intended use” (DNV, 2001). In the case of new technology, the volume of data available is small, which means that the confidence of the evidence provided is reduced. Confidence is further reduced due to possible discrepancies between specification, design, manufacture, installation, commissioning and use. From this it can be concluded that the predicted performance demonstrated through the qualification process may be different from the actual performance realized in the field (Pecht, 1993). This is due to unexpected failure modes, unexpected operating conditions, unforeseen failure mechanisms and causes, epistemic uncertainties. Unanticipated operating conditions stem either from incorrect specification or from unexpected changes in the actual operating conditions. A thorough failure analysis is necessary to avoid uncertainties related to failure. Epistemic uncertainty occurs from the incapacity to obtain complete knowledge about a matter, while aleatory uncertainty arises from the inability (of the analyst) to provide perfect deterministic forecast of events. Epistemic and aleatory uncertainties are by nature of their definition impossible to totally remove, so the only way to lessen their impact is to enable the technology to cope with them. This is done by building robustness into the design, so as minimize the impact of any remaining uncertainty (Clausing, 2004). 'Examination and provision of evidence' is done through functional and failure analysis, and reliability testing, and can be supplemented with experience from proven, structurally similar technologies.

2.13 Reliability calculation

Information must be gathered to predict the probability and consequences of failure with the help of failure modes, mechanisms and causes identified. This can be new information based on results from tests and analysis of technology at hand or can be already existing knowledge about failure mechanisms of structurally similar technologies.

2.14 Structural similarity analysis

Collecting new information via analysis and in particular testing can be very costly and time consuming, and should therefore be preceded by checking the validity of existing information.

New technology may have features analogous to established technology in several ways. Given that the structural similarity can be validated, using knowledge about such structurally similar technologies will make significant contributions to simplifying qualification of the new technology. The technique is also widely used in the energy industry.

The structural similarity analysis process consists of six consecutive steps as shown Figure 10 (IEEE, 2003):

1. Select a working item that has similarities with the technology of interest. Inspect physical and functional characteristics of the technology to confirm satisfactory similarity. The appropriate system hierarchy for comparison is selected in this step. A close design and operational similarity will naturally improve reliability prediction accuracy.

2. Investigate and compare failure modes, mechanisms and root causes of the new and operating Technology. This information will normally come from failure analysis. Failure mechanisms and root causes of high criticality should be examined in detail, while those of lower criticality can be aggregated or approximated. Non-similar failure modes, mechanisms and root causes are studied further in Step 3, while those that are similar are followed by step 4.

3. Select suitable reliability prediction method. Structural similarity analysis does not apply for those failure modes, mechanism and causes that are not sufficiently similar.

4. Find out the field reliability prediction of new and operating technology. For similar failure modes, mechanisms and root causes, a field reliability prediction is performed for the in-service item. If the failure modes, mechanisms and root causes are identical, the field reliability prediction for the in-service item may used for the new item. If they are similar but not identical, field reliability prediction may be adjusted as described in Step 5.

5. Adjust field reliability prediction based on similarity between new and in-service items. This adjustment is done based on qualitative assessment of the direction in which the differences between the new and the in-service item is likely to influence system reliability.

6. Reliability prediction for the new technology can be done by combining reliability predictions from similarity analysis with reliability prediction from other methods.

In order to calculate reliability predictions for each specific failure mechanism, mathematical models are applied in 4th step of structural similarity analysis. Prediction will be empirical if the data used in statistical data from the operating technology or from the test of new technology. If the calculation is based on knowledge about physical material-load interactions and their influence on product reliability with respect to the use conditions, the prediction is deterministic. Accelerated aging tests can be used in order to test the validity of models .New models are developed using series of experiments, statistically designed to identify most important design and environmental factors governing failure and mathematical relationship linking those factor to time to failure if no models are available or if existing models are found to be erroneous.

2.15 Philosophy of reliable technology:

For a product to be acceptable it must be able to operate satisfactorily for a specific period of time in the actual application for which it is intended. Reliability assurance is therefore an important part of technology qualification. Reliability is defined as “the ability of an item to perform a required function, under given environmental and operational conditions and for a stated period of time” (ISO 8402). From this, it can be seen that function and failure are central part of reliability engineering; the main objective is to understand the mechanisms and impact of failure and make informed choices throughout the life cycle to maximize performance.

Chapter 3: Process description

3.1 IGCC with CO_2 capture shell gasifier

3.1.1 Fuel preparation

Pittsburgh No.8 is used as fuel for the gasifier .It is mixed with compressed nitrogen (stream7) and uncompressed nitrogen (stream5) in the fuel preparation section. Nitrogen used for the preparation of fuel is produced in the Air Separation Unit (ASU). Nitrogen is used as transportation gas. The specifications of the coal and nitrogen used for the fuel preparation are given in **table 21 in Appendix A.**

3.1.2 Gasification island:

Fuel (stream2) mixed with nitrogen having mass flow rate of 104 ton/hr is sent to gasifier where the main gasification reaction takes place. Oxygen required for the Gasification reaction is produced in the Air Separation Unit which after compressing (stream9) is sent to gasifier. In the Gasifier when fuel and compressed oxygen comes in contact gasification reaction takes place and as a result of this gasification reaction syngas production takes place. High pressure steam(stream 29& 30) from Heat Recovery Steam Generator is also added to the gasifier. Hot raw syngas (stream11) leaving the gasification zone is cooled with recycled product gas (stream14) to convert any entrained molten slag to a hardened solid material prior to entering the syngas cooler(HEX1). The syngas cooler(HEX1) recovers high level heat from the raw syngas by generating high pressure steam(stream33) .Steam(stream32) used for the cooling of raw syngas in syngas cooler(HEX1) comes from HRSG.

3.1.3 Gas clean up system:

Raw syngas (stream11) from the gasifer is at temperature 900 °C.It is cooled in HEX1 from 900 °C to 350 °C by the use steam from HRSG at 319 °C &115.9 bar. Then Syngas is added to the wet scrubber where particles and chlorine removal take place. This scrubbing action takes place in the presence of water. Water (stream34) used for scrubbing purposes has the temperature of 100 °C and mass flow of 22 ton /hr. From the wet scrubber syngas is sent to the COS unit &Water Gas Shift Reactor which generates H_2S which is later remove in the Acid Gas removal plant. In COS unit syngas passes through the catalyst where COS react with water vapor present in the syngas to produce H_2S and CO_2.The quantity of water in syngas for water gas shift reaction is not sufficient, so steam from HRSG is used to overcome this deficiency.

After passing through the scrubber and COS unit syngas is passed through the battery of the three heat exchangers (HEX2, HEX3, HEX4) where cooling of syngas takes place before entering into the H_2S absorber. At the exit of COS unit, temperature of the syngas is 260°C.In the HEX2 syngas (stream17) is cooled by the clean syngas (stream22) from the CO_2 absorber to 174°C.In the HEX3 syngas (stream18) is further cooled to 146.6 °C and this cooling of syngas is done by condensate from the condenser (stream37) .Where as in the HEX4 cooling is done by heat rejection to external source and after this heat exchanger temperature of the syngas (stream20) is 37.78 °C.

3.1.4 Removal of CO_2 &H_2S:

Two stage selexol process is used for the removal of CO_2 and H_2S.Removal of H_2S is done in the absorber where H_2S is absorbed in counter current physical absorption process.Syngas (stream20) is entered in the H_2S absorber at 37.78 °C and 30.47 bar. In the absorber it comes into the contact with the solvent (selexol).From the bottom of the H_2S absorber rich solvent (stream61) is sent to stripper where the regeneration of the solvent takes place. From the stripper lean solvent (stream63) is fed to the top of the CO_2 absorber for further contact with the syngas .From top of the H_2S absorber syngas is sent to the CO_2 absorber.CO_2 rich solvent (stream57) from the bottom of the CO_2 absorber is sent to the flash drums where regeneration of the solvent takes place as shown in the process flow diagram. Semi-lean solvent (stream 60) from the bottom of the flash drum1 is sent back to the CO_2 absorber to make further contact with the syngas in the CO_2 absorber. Clean syngas (stream22) is taken out from the top of the CO_2 absorber. From the top of the stripper vapor liquid mixture (stream69) is sent to KO drum. In this drum separation of the liquid and H_2S vapor take place. Clean Syngas (stream22) after exchanging heat with raw syngas in (HEX1) is fed to the gas turbine as a fuel (stream 23).

3.1.5 Power island:

GE 7251FB gas turbine is used for the production of electricity. Compressor of the GT takes air from the atmosphere (stream 26) and after compression this air is sent to the combustor of the gas turbine .In the combustor compressed air (stream 27) and syngas (stream 23) are combusted. This combustion product (stream24) has temperature of 1374 °C and pressure 16.56 bars, entered into the gas turbine section, where production of electricity takes place.

Exhaust of the gas turbine (stream 25) at 642.5 °C and 1.043 bars is sent to the Heat Recovery Steam generator, where steam is produced at the different pressure levels for different purposes. Steam produced from HPB of the HRSG is mixed with the steam generated in the syngas cleaning system is sent to the HP section of the steam turbine at 554 °C and 111.6 bar after superheating. Cold reheat steam at about 351°C and 27.62 bar exit the high pressure turbine flows through the HRSG reheater .Hot reheated gas at 552 °C and 24.13 bars is routed to IP steam turbine section.

From the LP section of the steam turbine part of the steam (stream40) at 298 °C and 3.611bar is extracted and sent to the AGR by combining it with the LPB steam (stream41) of the HRSG. The exhaust of the steam turbine (stream52) at 32.27 °C and .0483 bars is sent to the condenser. With the help of cold water condensate is cooled down and is sent to HEX3 for cooling of syngas.The detailed material balance, energy balance and plant summary of this power plant can be found in the **Appendix A.**

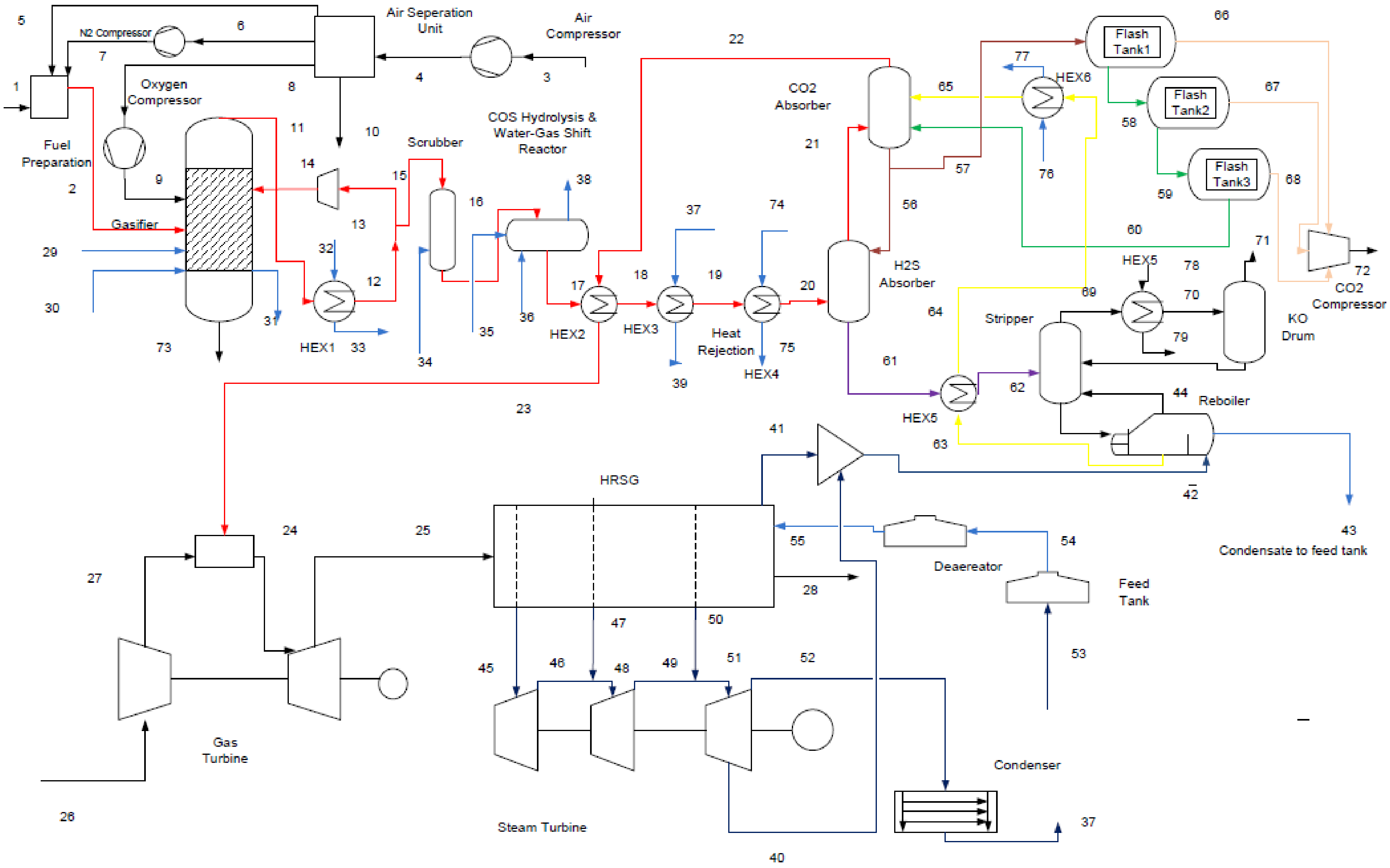

Figure 4: Process flow diagram of IGCC power plant oxygen blown gasifier

3.2 IGCC with CO_2 capture Mitshsubishi gasifier:

3.2.1 Fuel preparation:

Pittsburgh No.8 is used as fuel for the gasifier .It is mixed with compressed nitrogen (stream7) and uncompressed nitrogen (stream 8) in the fuel preparation section. Nitrogen used for the preparation of fuel is produced in the Air Separation Unit (ASU). Nitrogen is used as transportation gas. The specifications of the coal and nitrogen used for the fuel preparation are given in **table 25 in Appendix B**

3.2.2 Gasification island:

Fuel mixed with nitrogen is sent to the Enriched air blown gasifier where the main gasification reaction takes place. Fuel is fed at two separate points in the gasifier.In the first stage of the gasifer fuel is fed along with compressed air (stream 14) which is mixed with compressed oxygen (stream 10).Steam from HPB of Heat recovery Steam Generator is also added to the first stage of the gasifier.Temperature in the first stage of the gasifer is 1817 °C under this high temperature coal in the presence of mixed air and oxygen mixture is burned to produce syngas.The temperature in the combustor section(first stage) of the gasifier is sufficiently high to melt the coal ash. The molten slag falls from the bottom of the gasifier. The gas produced in the first stage of the gasifer rises upwards where more fuel is added without any air. In the second stage of the gasifer heat produced in the first stage is used to drive the endothermic gasification reaction. The temperature in the second stage of the gasifer is 1100 °C.

3.2.3 Gas cleanup system:

Raw syngas (stream 15) from the Gasifer is at a temperature of 1100 °C.It is cooled in HEX1 from 1100 °C to 350 °C by the use steam from HRSG.Then Syngas is added to the wet scrubber where particles and chlorine removal take. This scrubbing action takes place in the presence of water. After scrubbing of dissolved gases COS removal and shift reaction take place in conjuction.This is sour shift conversion in which shift reaction take place before the removal of H_2S.This reaction requires the presence of water. Steam produced in the HPB and LTE of the HRSG is used to support the reaction. CO shift reaction is exothermic reaction due to which production of steam take place .The produced steam is sent to the HPB of the HRSG.After the shift reaction cooling of syngas take place with the help of battery of three heat exchangers.

3.2.3 CO_2 and H_2S removal:

For the removal of H_2S and CO_2 capture a two stage physical absorption process is used with selexol as a solvent. Untreated syngas is entered into the H_2S absorber where H_2S preferentially removed with CO_2 rich solvent from the CO_2 absorber. Then the gas exiting the H_2S absorber passes next through the CO_2 absorber where CO_2 is removed first by contact with flash-regenerated, chilled solvent, then by thermally-regenerated solvent added near the top of the column.

As the CO_2 loaded solvent exits the CO_2 absorber, a portion of it is sent to the H_2S absorber and the remainder is sent to a series of flash drums for solvent regeneration. The CO_2 product stream is obtained from the flash drums. After flash regeneration the solvent is chilled and pumped back to the CO_2 absorber. Removed CO_2 is compressed to 150 bars and sent to further use. From the top of the CO_2 absorber clean syngas (stream 23) after exchanging heat is sent to the Gas Turbine as a fuel (stream 44).

3.2.4 Power island:

GE 7251FB gas turbine is used for the production of electricity. Compressor of the GT takes air from the atmosphere (stream 11) compress it and sent it to the combustor of the gas turbine .In the combustor compressed air (stream 12) and syngas (stream 44) are combusted. This combustion product has temperature of 1374 °C and pressure 16.56 bars is entered into the gas turbine section. Hence electricity is produced from the gas turbine. Part of the compressed air (stream14) from the Gas turbine is sent to the Gasifer

Exhaust of the gas turbine (stream 46) at 642.5 °C and 1.043 bars is sent to the Heat recovery Steam generator. Where steam is produced at the different pressure levels for different purposes. Steam produced from HPB of the HRSG is mixed with the steam generated in the syngas cleaning system is sent to the HP section of the steam turbine at 554 °C and 111.6 bar after superheating. Cold reheat steam at about 351°C and 27.62 bar exit the high pressure turbine flows through the HRSG reheater .Hot reheated gas at 552 °C and 24.13 bars is routed to IP steam turbine section.

From the LP section (stream55)of the steam turbine part of the steam at 298 °C and 3.611bar is extracted and sent to the AGR by combining it with the LPB steam(stream56) of the HRSG.The exhaust of the steam turbine at 32.27 °C and .0483 bar is sent to the condenser. With the help of cold water condensate is cooled down and is sent to HEX3 for cooling of syngas. The detailed material balance, energy balance and plant summary can be found in the **Appendix B.**

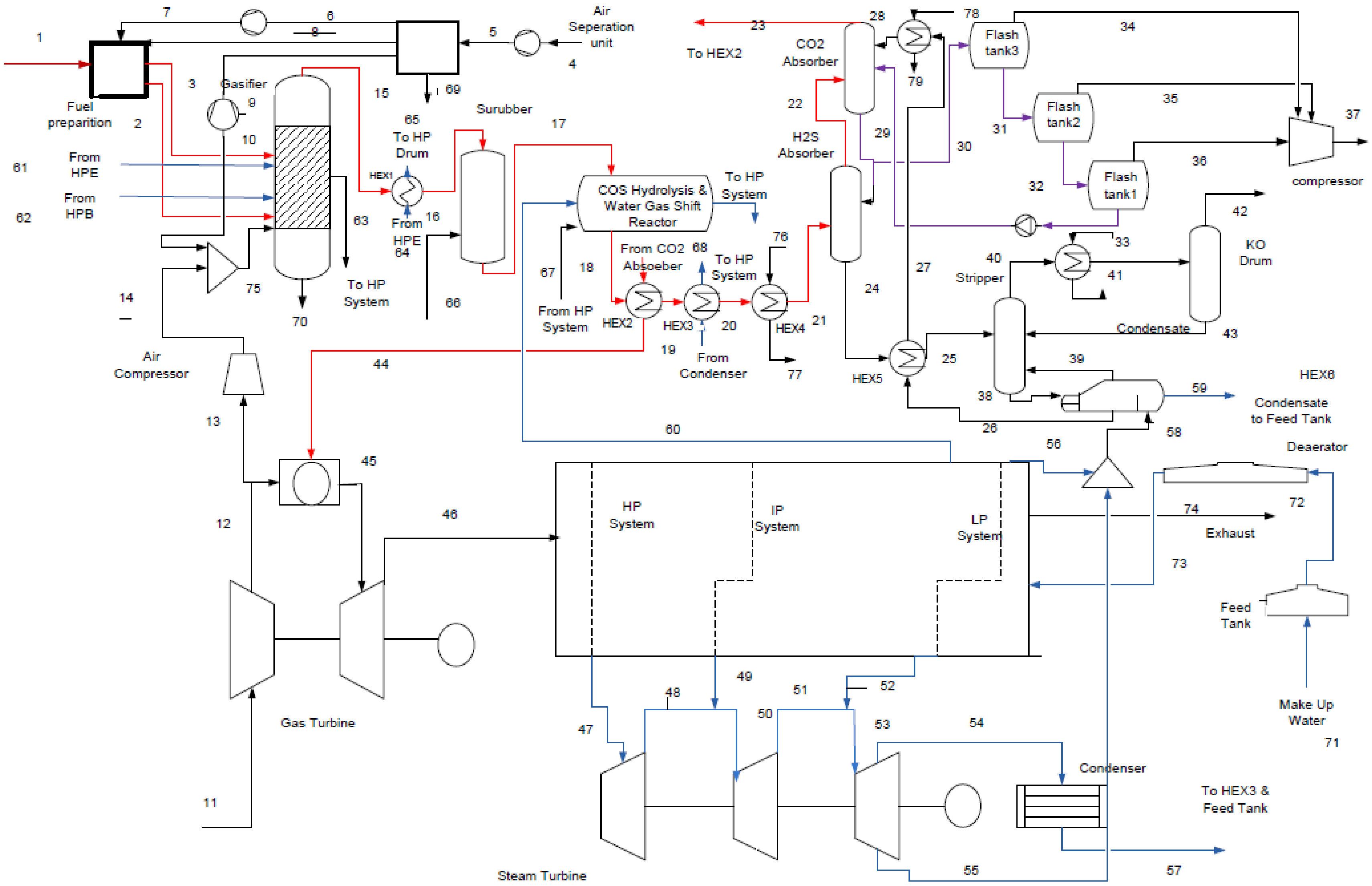

Figure 5: Process flow diagram of IGCC power plant with CO$_2$ capture enriched air blown gasifier

3.3 Comparison cases:

3.3.1 Gasification Island:

The following table shows the variations in the consumption of the steam and composition of the syngas in the Shell Gasification Island and enriched air blown Gasification Island. As it can be seen from the table that the enriched air blown gasifier has significantly higher amount of nitrogen .The reason for this higher amount of nitrogen in the gasifier is the air which is extracted from the gas turbine compressor for the purpose of gasification.

Table 1: Comparison of shell and enriched air blown gasifier composition

Gasifier(Shell)		Gasifier(Enriched Air Blown)	
Steam from Gasifier Cooling(ton/hr)	16.96	Steam from Gasifier Cooling(ton/hr)	33.86
Syngas Composition (Vol%)		Syngas Composition (Vol%)	
CO	55.21	CO	34.59
CO_2	3.545	CO_2	1.6
CH_4	.0032	CH_4	.3370
H_2	27.66	H_2	17.94
H_2S	.867	H_2S	.5408
COS	.064	COS	.0339
N_2	5.16	N_2	42.46
Ar	.45	Ar	.57
H_2O	7	H_2O	1.83

3.3.2 Gas cleaning system:

How composition of the syngas varies at the end of syngas cleaning process for shell gasifier syngas cleaning system and enriched air blown gasifier is shown in the following table2.Syngas produced by the shell gasifier has significantly higher vol% of H_2 than enriched air blown gasifier. Consumption of the steam for the water gas shift reaction for the shell gasification case is higher than enriched air blown gasification process.

Table 2: Comparison of shell (oxygen blown) and enriched air blown gasifier

Shell		Enriched Air Blown	
Clean Syngas		Clean Syngas	
Composition (vol %)		Composition (vol %)	
CO	1.18	CO	.64
CO_2	5.19	CO_2	2.7
CH_4	.0035	CH_4	.31
H_2	87.56	H_2	48.1
H_2S	.0099	H_2S	.0053
COS	.0013	COS	.0006
N_2	5.52	N_2	39.4
Ar	.48	Ar	.53
H_2O	.034	H_2O	8.2
Steam addition to CO shift reaction(ton/hr)	150	Steam addition to CO shift reaction (ton/hr)	138.3

3.3.3 Power island:

The following table shows the comparison of power blocks of two power plants. The detailed summary of these two power plants can be found in **Appendix (A & B).**

Table 3: Comparison of oxygen blown and air blown gasifier, Power Island

Shell		**Enriched Air Blown Gasifier**	
Gross Power Output	200653	Gross Power Output	190546
Exhaust Mass Flow	1638	Exhaust Mass Flow	1584.2
Exhaust Temperature	636.7	Exhaust Temperature	642.5
HRSG Efficiency	84.93	HRSG Efficiency	84.46
Steam Turbine Gross Power	136160	Steam Turbine Gross Power	130996
Plant Total Power Output @ generator terminal	336813	Plant Total Power Output @ generator terminal	321543
Plant Net Power Output	273867	Plant Net Power Output	262695

Chapter 4: Technology qualification steps:

The standard description of the technology qualification steps based on the DNV description can be found on (DNV, 2010). In the following discussion how these steps are implemented on the IGCC with CO_2 capture Enriched air blown gasifier is described.

4.1 Qualification basis:

In this step of the technology qualification, process description and functional requirements of the IGCC with CO_2 capture are described in full detail. The detailed process description of the IGCC with CO_2 capture is described earlier in the report. In the following discussion Functional requirements and Critical parameter list which govern the performance of plant are established.

Table 4: Critical parameter list

Critical Parameter List	Goal values
Plant net power output	262MW
Power out put from Gas turbine (Gross)	190.5MW
Power out from Steam turbine (Gross)	130MW
CO_2 Capture rate	4743 ton/day
Heat consumed in Capturing CO_2 &H_2S	20933 KJ/Kg
Power consumption in CO_2 Capture	15.7MW

Table 5: Functional requirement of IGCC with CO_2 capture enriched air blown gasifier case

Subsystem	Equipment	Functions	Functional Requirements
Gasification	Gasifer	Convert Coal to Fuel	Ist stage T_{15}=1815 °C, 2nd stage T=1100°C
Power Cycle	Gas Turbine	Generate Power	190.5(Gross Power)
Power Cycle	Gas Turbine	Produce Hot Gases	T_{25}>642C
Power Cycle	Gas Turbine	Provide Air	m_{12}= 207.7ton/hr, 396.7C
Power Cycle	Steam Turbine	Produce Power	P≥130MW
Power Cycle	Steam Turbine	supply Steam to AGR	m_{55}≥8.4ton/hr
HRSG	LP	Generate LP Steam	m =8.4ton/hr
HRSG	IP(Reheat)	Generate IP Steam	m= 70ton/hr
HRSG	HP	Generate HP Steam	m =70ton/hr
Gas Cleaning	scrubber	Remove dissolved gases	Remove dissolved gases
COS hydrolysis Water Gas Shift	WGS Reactor	Convert CO to CO_2	T_{exit}=285 ^{0}C
Heat Exchanger Net Work			
HEX1	Raw SynGas Cooler	Cool Raw SynGas	T_{16}=350 ^{0}C
HEX2	SynGas Cooler	Cool Raw SynGas	T_{19}=163 ^{0}C
HEX3	SynGas Cooler	Cool Raw SynGas	T_{20}=136 ^{0}C
HEX4	SynGas Cooler	Cool Raw SynGas	T_{21}=37.7 ^{0}C
Heat Exchanger Net Work	Condenser	Condenses Steam	p≤.0483 bar
Pre Combustion Capture	Gas Separation	Separate CO_2	
Pre Combustion Capture	CO_2 Absorber	Absorb CO_2	m_{23}=4743 ton/day
Pre Combustion Capture	H_2S Absorber	Absorb H_2S	69 ton/day
Compression	Compressor	Compress CO_2	p_{37}≥150 bar
Compression	Air Compressor	Compress Air for Gasifer	T_{14}≥642^{0}C

4.2 Technology assessment:

In this step of the technology qualification, IGCC power plant with CO_2 Capture is divided into subparts and subsequently each of the subpart is divided into its components. This way of dividing the technology into manageable elements helps to scrutinize the novel elements involved in the technology; IGCC with carbon dioxide capture has the following subparts:

- Air separation unit
- Gasification unit
- Gas clean up
- Water gas shift reaction
- Capture of CO_2 and H_2S
- Power block

Now for further elaboration of these subparts of IGCC with CO_2 Capture, they are divided into components as shown below:

Air separation unit:
ASU can be divided into the sections of air compressor, cryogenic heat exchanger, cryogenic distillation unit, oxygen compressor and nitrogen compressor.

Gasification unit:
Gasification is divided into fuel preparation section and gasifier and air compressor.

Gas cleaning system:
Gas cleaning system is divided into scrubber, COS hydrolysis and water gas shift reaction.

CO_2 & H_2S capture unit:
This section can be divided into CO_2 absorber,H_2S absorber, Stripper, KO drum,CO_2 compressor, Flash tanks, Heat Exchanger(5), Pump.

Power block unit:
This section of the power plant contains Gas Turbine, Steam Turbine, HRSG, KO drum.

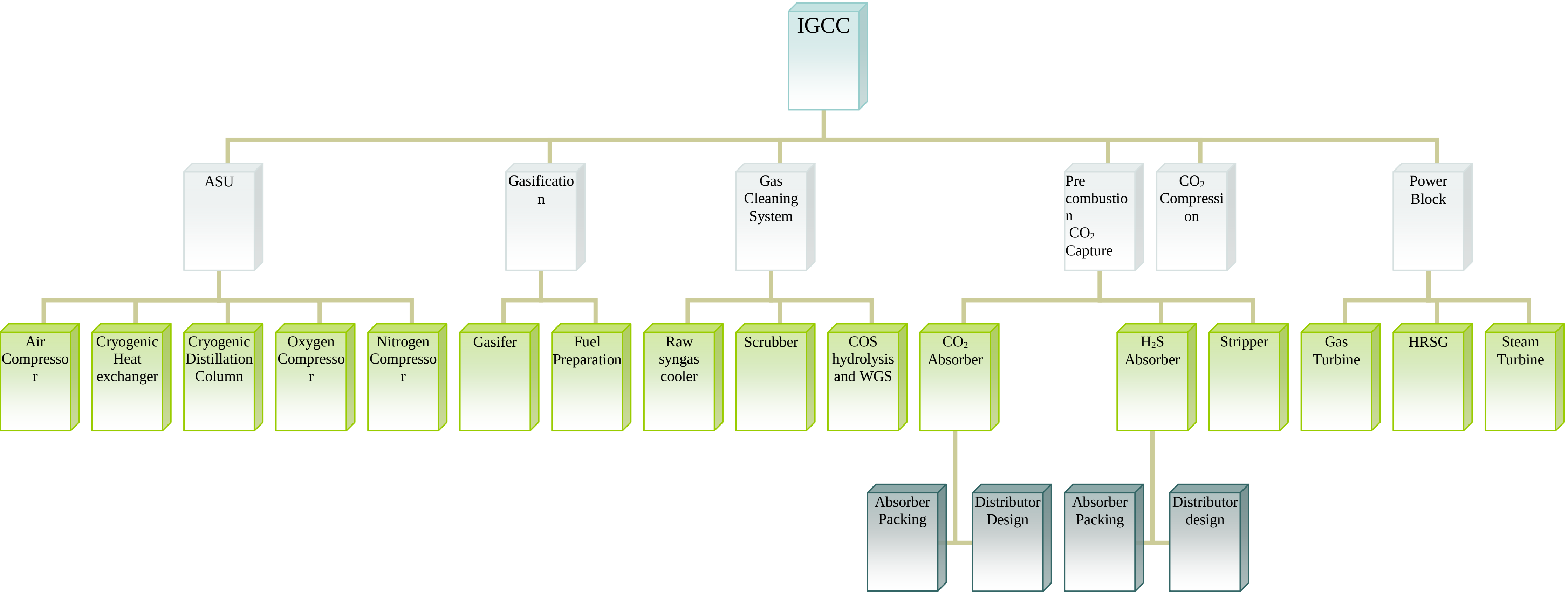

Figure 6:Division of IGCC power plant into subcomponents

4.2.1 Technology classification:

After the technology is divided into manageable elements classification of the technology with respect to its application area and maturity is given below. The main reason for assigning this rating to the technology is to identify the uncertainty associated with the new elements .Rating is assigned according to the following criterion.

Technology rated as 1 is proven technology without any new aspects.

Technology rated as 2 is technology with limited knowledge

Technology rated as 3 is technology is without any knowledge what so ever

Following is the example how this classification concept is applied to the IGCC with carbon dioxide capture.

- **ASU:**

Cryogenic air separation unit which is used for the production of oxygen is well proven technology (C.Gen, 2011).And these are the most common units for the large scale production oxygen (Bolland, 2010). So on the basis of high field experience and availability of relevant data rating of 1 is assigned to the ASU.

- **Gasification:**

Production of syngas with gasification is also proven technology with lots of field data and relevant experience so it is also rated as 1. Syngas for the production of electricity is commercially available technology ELCO power plant in the Spain is example of that. (Lancha A.M, et al., ?)

- **Gas clean up:**

Cleaning of syngas is also a well known phenomenon with lots of field data and relevant experience. It is also rated as 1(C.Gen, 2011).

- **Gas turbine:**

Currently, GE gas turbines are operating in IGCC plants that have a total installed capacity of more than 2,500 MW, while another 1,000 MW of GE gas turbines are operating with process fuels from steel mills (Szwgroup,2010).But there are some issues like gas turbine (GT) technology is, much more mature for natural gas. Also, a GT designed for an IGCC plant typically needs to be more fuel flexible, which requires special attention to the burner design and the control system firing than for firing a hydrogen-rich fuel (Olof Nord.L, et.al 2009) .These figures shows that in terms of relevant field experience and previous history data Gas turbine can be rated as 2 in terms of technology classification.

- **Pre-combustion CO_2 capture:**

Pre-combustion capture of CO_2 from IGCC is not commercially available yet. (Guillermo Ordorica-Garcia et al., 2005). So there is high degree of uncertainty involved in terms of the availability of relevant data and past experience. So in this case it is rated as 3.

Technology classification of each equipment of IGCC power plant with CO_2 capture can be found in **Appendix C**.

4.3 Threat assessment:

There are following two inputs to the threat assessment steps:

- Critical parameter list established in the qualification basis
- Elements which are identified as new elements in the technology classification

Although it should be noted that these parameters can be changed or to be more precise can be modified according to the situation.

In order to identify failure modes of concern of the technology which are rated as new technology in the technology classification part and critical parameters, FMECA and Hazop analysis are performed. The procedure for applying the FMECA and Hazop analysis to the integrated gasification combined cycle power plant with carbon dioxide capture is given below.

4.3.1FMECA for IGCC power plant with CO_2 capture:

Failure mode, effects and criticality analysis is a methodology to identify and analyze (Rausand.M, 2004):

- All potential modes of various parts of a system
- The effects these failure may have on the system
- How to avoid the failure and mitigate the effect of the failure system

This technique is used to identify, prioritize and eliminate potential failures from the system. It can be used to solve the problems in a system before they occur. Functional requirement of the process is given in the Qualification basis. For FMECA description of the process should be done in two ways one is process flow diagram which is already described and second is functional description of the process which is given below.

4.3.2 Functional requirement of IGCC with CO_2 capture Mitsubishi gasifier:

The purpose of the plant is to generate fossil fuel power with low emission. Input to the system include coal, ambient air, make up water and cooling water where as output across the system include compressed CO_2,water that has been separated out, exhaust from the HRSG that originated in the Gas Turbine as well as power. The functionality and description of each of the equipment is given below.

Air separation unit:

Function: Separation of oxygen and nitrogen from the air. Nitrogen is used as transportation gas while O_2 is mixed with air and send to the gasifer.

Gasifier:

Function: The gasification reaction take place in the gasifier. Raw syngas is produced. Composition and temperature information are already described in the material and energy balance **(Appendix A and B).**

Raw syngas cooler:

Function: Cools down the raw syngas from the gasifier.

Scrubber:

Function: It is used to clean up the gas from the particulate material.

COS hydrolysis and water gas shift unit:

Function: This sour gas water shit unit converts the sulfur present in syngas to the H_2S and CO to CO_2 in the presence of catalyst.

Syngas cooler:

Function: This heat exchanger cools the syngas for the separation purposes.

CO_2 and H_2S absorbers:

Function: To capture the CO_2 and H_2S from the syngas and produce a hydrogen rich fuel.

Flash tanks:

Function: They are used for the regeneration of the solvent for the absorption of CO_2.

Stripper:

Function: Regeneration of the solvent.

Gas turbine:

Function: To provide compressed air to gasifier, provide hot gases to HRSG, generate power.

HRSG:

Function: To generate steam.

Steam turbine:

Function: To generate power and supply steam to gas cleaning system.

CO_2 Compressor:

Function: To compress CO_2

Condenser:

Function: To condense the steam. After exiting the last low pressure turbine stage the steam is condensed in the condenser.

Air Compressor:

Function: To compress the air for the gasifier.

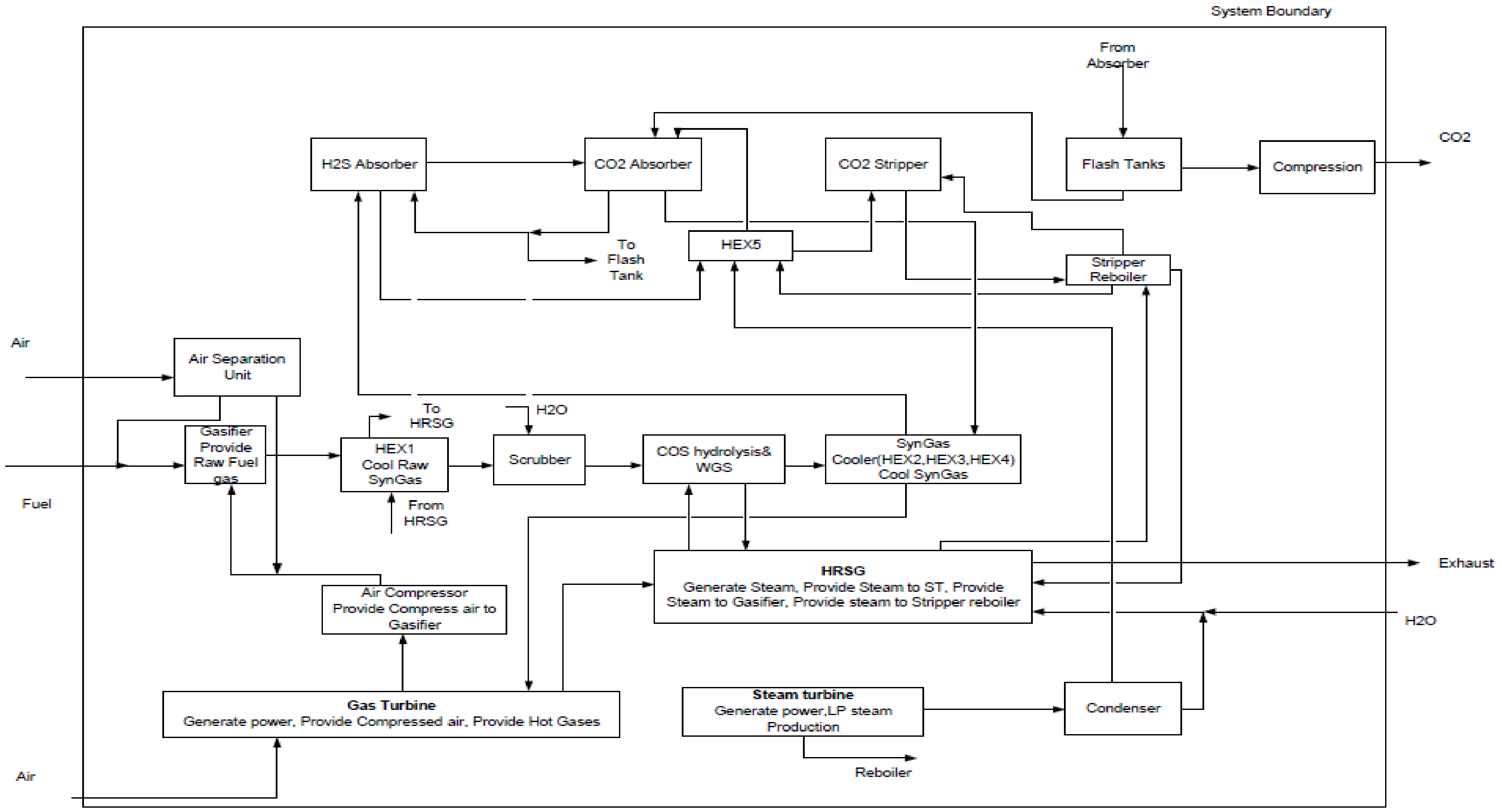

Figure 7: Block diagram of IGCC power plant

4.3.3 Methodology for FMECA:

The FMECA approach that was selected for IGCC with CO_2 capture is shown in the following figure. In this methodology a risk number is given to each and every failure mode as a risk priority number. The Risk Priority Number is calculated based on the evaluation of the factors; detection, failure Rate, and severity of a failure mode. This RPN is used to identify the most critical failure mode, leading to corrective action.

$$RPN=S^{*}\ O^{*}\ D$$

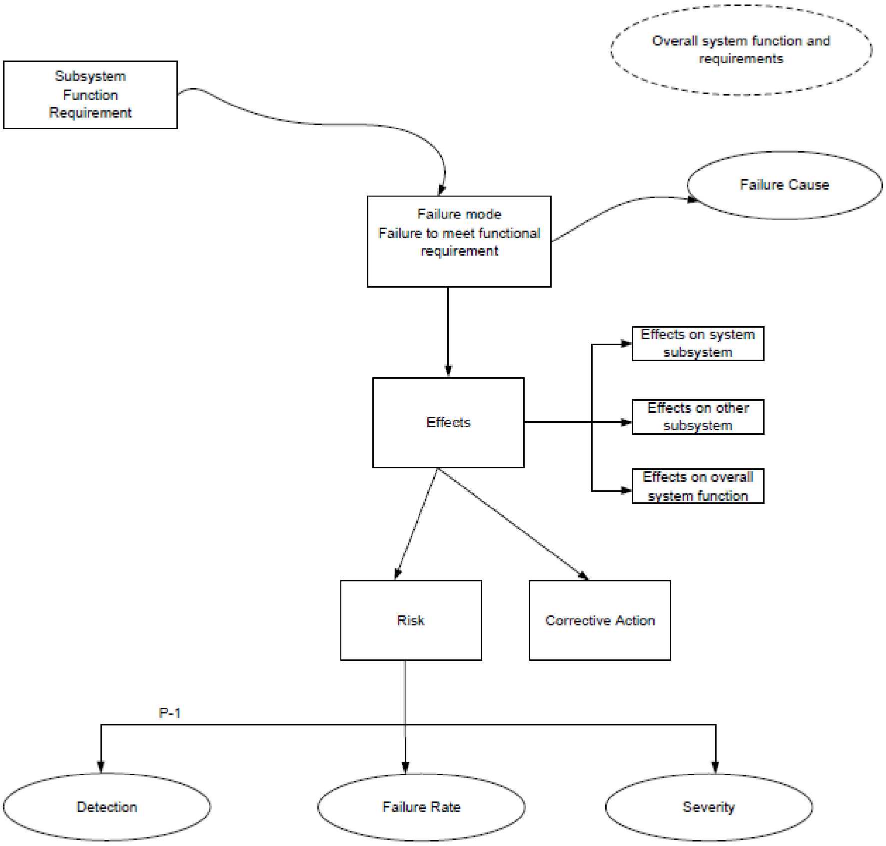

Figure 8: Methdology for failure mode effects and criticality analysis

Table 6: Failure rate

Effect	Rank	Criteria
Almost Never	1	Failure unlikely
Remote	2	Rare number of failure likely
Very slight	3	Very few failure likely
Slight	4	Few Failure likely
Low	5	Occasional Number of failure likely
Medium	6	Medium numbers of failure likely
Moderately High	7	Moderately high numbers of failure likely
High	8	High numbers of failure likely
Very High	9	Very High Numbers of Failure Likely
Almost Certain	10	Failure Almost Ceratin

Table 7: Detection ranking

Effect	Rank	Criteria
Almost Certain	1	Current control(s) almost certain to detect failure mode. Reliable controls are known with similar processes
Very High	2	Very high likelihood current control(s) will detect failure mode
High	3	High likelihood current control(s) will detect failure mode
Moderately High	4	Moderately high likelihood current control(s) will detect failure mode
Medium	5	Moderate likelihood current control(s) will detect failure mode
Low	6	Low likelihood current control(s) will detect failure mode
Slight	7	Very low likelihood current control(s) will detect failure mode
Very slight	8	Remote likelihood current control(s) will detect failure mode
Remote	9	Very remote likelihood current control(s) will detect failure mode
Almost impossible	10	No known control(s) available to detect failure mode

Table 8: Severity ranking

Effect	Rank	Criteria
NO	1	No effect of failure on system
Very slight	2	Minor disruption to facility function. Repair to failure can be accomplished during trouble call
Slight	3	Minor disruption to facility function Repair to failure may be longer than trouble call but does not delay Mission..
Minor	4	Moderate disruption to facility function. Some portion of Mission may need to be reworked or process delayed.
Moderate	5	Moderate disruption to facility function. 100% of Mission may need to be reworked or process delayed.
Significant	6	Moderate disruption to facility function. Some portion of Mission is lost. **Moderate** delay in restoring function.
Major	7	High disruption to facility function. Some portion of Mission is lost. **Significant** delay in restoring func
Extreme	8	High disruption to facility function. **All** of Mission is lost. Significant delay in restoring function
Serious	9	Potential Safety, Health or Environmental issue. Failure will occur withwarning
Almost certain	10	Potential Safety, Health or Environmental issue. Failure will occur without warning

A failure mode is defined as a failure to meet a functional requirement of specific equipment. Once a failure mode has been specified, the causes and effects of the failure need to be identified. Regarding failure effects, the effects on the same equipment where the failure first occurred were analyzed secondly, the effects on other equipment in the system were investigated. Data sources like (Oreda, 2004), (NERC, 2007), (J.Phillip, 2007) were consulted in order to find the failure rates of equipments. Rating for the detection is based on the instrumentation and control knowledge of the process equipments.

4.3.4 Drawback of Traditional Approach:

The approach described above is a well accepted safety analysis method, however it has several shortcomings. The most critical drawback of this approach is that the various sets of S, D, and O may produce the identical value of RPN; however the risk implication may be totally different. The other disadvantage of this approach is taking the average in ranking scale for the three failure indexes, when the team has a disagreement in ranking scale. The above mentioned problems also occurred when FMECA is applied to the IGCC with CO_2 capture. In order to mitigate the influence of these shortcomings following methodology is used (Narayanagounder et al., 2009).

New Approach for Prioritization of failure Modes:

This methodology has the ability to deal with the situation when:

- Two or more failure modes have the same RPN
- The team has a disagreement in the ranking scale for severity, occurrence and detection
- It is assumed that the threes S,O,D are all equally important

A general method with “n” failure mode is discussed below with the same RPN.

Let Aij denote the ranks of “S”, “F”, and “D” respectively corresponding to the failure mode “a_i” where i=1,2,3…..n and j=1,2,3.Where≤1Aij≤10 for all (i,j).The Aij precisely takes the ranks {1,2,3,4,5,6,7,8,9,10}in some order, where the ranks 1,2,3….10 are given by combining of table 6, table 7,table 8 as follows:

Table 9: general form of failure mode indexes and RPN

Failure Mode	S	F	D	RPN
a_i	A_{11}	A_{12}	A_{13}	R_1
a_2	A_{21}	A_{22}	A_{23}	R_2
a_3	A_{31}	A_{32}	A_{33}	R_3
:				
a_k	A_{K1}	A_{K2}	A_{K3}	R_K
:	:			
:	:			
:	:			
a_n	A_{NI}	A_{N2}	A_{N3}	R_N

This method suggests three steps procedure (Narayanagounder,2009):

Critical Failure Mode Index

CFM index $I(a)=\min\{\max(A_{11},A_{21}\ldots\ldots A_{n1}),\max(A_{12},A_{22}\ldots\ldots A_{n2}),\max(A_{13}, A_{23}\ldots A_{n3})\}$……………………………………………. (1)

Risk Priority Code (RPC)

RPC (a_i) =N (ai)

Where, N (ai) be the number of places, in the row corresponding to "a_i" for which $A_{ij}>I$ (a).

Critical Failure Mode (CFM)

CFM (a) =Failure mode corresponding to $\max\{N(a_i)\}$………….(3)

If there is a tie situation, consider the set of all "a_i" for which N (ai) are equal, for such a_i we define:

$T(a_i)=\max\{|L_{i1}-L_{k1}|, |L_{i2}-L_{k2}|,|L_{i3}-L_{k3}|\}$……………………..(4)

CFM (a) =failure mode corresponding to max $\{T(a_i)\}$…………..(5)

In the case of this thesis report when FMECA is applied to the IGCC with CO_2 Capture, several failure modes with same RPN appeared. The following table shows those failure modes with the same RPN.The above mentioned steps were implemented in order to identify the critical failure mode among those failure modes which have the same RPN value.

Table 10: Comparison of failure modes

Number	Equipment	Failure Mode	S	F	D	RPN
1	WGS Reactor	85% conversion of CO to CO_2	5	7	6	210
2	WGS Reactor	85% conversion of CO to CO_2	10	5	7	210*

Critical Failure Mode Index

CFM index (I) = min {max (5, 10), max (7, 5), max (6, 7)}

= Min {10, 7, 7}

= 7

Risk Priority Code is found for each by using equation (2) from above methodology:

RPC $_{(1)}$ =0

RPC $_{(2)}$ =1

According to equation (3) from above methodology critical failure mode is 2 denoted by (*) in the above table.

Table 11: Comparison of failure modes

Number	Equipment	Failure Mode	S	F	D	RPN
1	Air Separation Unit	M_7<7.079 ton/hr T_7<100^0C	8	1	10	80*
2	WGS-Reactor	85%conversion of CO	5	4	4	80

Critical Failure Mode Index

CFM index (I) = min {max (8, 5), max (1, 4), (10, 4)}

= Min {8, 4, 10}

= 4

RPC $_{(1)}$ =2

RPC $_{(2)}$ =1

According to equation (3) from above methodology critical failure mode is 1 denoted by (*) in the above table.

Critical Failure Mode Index (CFM) Index (I) by using (1)

Table 12: Comparison of failure modes

Equipment	Failure Mode	F	D	S	RPN
Gasifier	$T_{15}<900^0C$ $M_{15}<300$ton/hr	3	8	5	120*
H_2S Absorber	M<45ton/day	4	6	5	120**
Gasifier	CO>60vol% $H_2<17$vol%	8	5	3	120***
HRSG	$M_{61}=2.5$ton/hr	10	6	2	120****

I = min{max (3,4,8,10),max(8,6,5,6),max(5,5,3,2)}

= min {10, 8, 5}

= 5

Calculate RPC for each failure mode by using equation (2)

$N_{(1)}=1$, $N_{(2)}=1$, $N_{(3)}=1$, $N_{(4)}=2$

In this case by using equation (3) the most critical failure mode is a_4.Then there is a tie between failure modes a_1, a_2, a_3.By using equation 4 we can easily discriminate this tie situation.

Critical Failure Mode (CFM)

$T_{(1)}$ =max {|3-4|, |8-6|, |5-5|}

= max {1, 2, 0}

=2

$T_{(2)}$ = max {|4-8|, |6-5|, |5-3|}

= max {4, 1, 2}

=4

$T_{(3)}$ =max {|8-3|, |5-8|, |3-5|}

= max {5, 3, 2}

=5

So by using equation (5), it can be concluded that the most critical failure mode is a_3 followed by a_2 and a_1.

Above table shows that the failure mode which has highest number of (*) is the most critical failure mode.

Case 2:
There was a disagreement and uncertainty in assigning the value of F, D, S for the following failure modes. This situation is tackled with the help of analysis of variance (ANOVA).

Table 13: Comparison of means of failure modes

Equipment	FM	F	D	S	RPN	Mean	Range
Gasifier	1	2 4	5 7	5 6	50,60, 70, 84 100, 120 140,168	99	118
Air Separation Unit	2	7 6	4 5	4 3	112, 84 140, 105 96, 72, 120, 90	102.375	68
CO_2 Absorber	3	6 5	3 4	7 8	126, 144 168, 192 105, 120 120, 140	144.375	87
Gasifier	4	4 3	5 7	4 6	80, 120 112, 168 60, 90 84, 126	105	108

By analyzing the above table it can be seen that the failure mode 3 is the most critical followed by the failure modes 4, 2, 1.

The general rule for the above case is stated as follows;” The higher the RPN mean is more severe. When the RPN means are same, the smaller the RPN range is more severe”.

Analysis of variance (ANOVA) is a statistical technique used to compare the means of two or more samples. The different types of ANOVA reflect the different experimental designs and situations for which they have been developed. In this study, SPSS statistical analysis software is used to compare the mean RPNs associated with four failure modes.

We want to test whether the data in Table11 provide sufficient evidence to conclude that the failure modes RPN mean differ. Thus, we want to test the null hypothesis

$$H_o : \mu_{fm1} = \mu_{fm2} = \mu_{fm3} = \mu_{fm4}$$

H_a: The mean RPN differ for at least two of the failure modes

The test statistic compares the variation among the four failure modes RPN means to the sampling variability within each of the failure modes.

Test statistic: F = MST/MSE

Rejection region: $F > F_\alpha = F_{.05}$, with $v_1 = (k - 1) = 3$ numerator degrees of freedom and $v_2 = (n - k - b + 1) = 21$ denominator degrees of freedom. From the percentage points of the F-distribution ($\alpha = .05$), we find $F_{.05} = 3.07$.Thus, we reject H_0 if $F > 3.07$. The assumptions necessary to ensure the validity of the test are as follows: (1) the probability distributions of the RPN for each failure mode are normal (2) the variances of the RPN for each failure mode are normal. The results of an analysis of variance (ANOVA) can be summarized in a simple tabular format. The general form of the table is shown in Table 14 where symbols df, SS and MS stand for degrees of freedom, Sum of Squares and Mean Square respectively.

Table 14: General form of ANOVA

Source	df	SS	MS	F
Treatment	k-1	SST	MST	MST/MSE
Block	b-1	SSB	MSB	
Error	n-k-b+1	SSE	MSE	
Total	n-1	SS(Total)		

SPSS is used to analyze the data in Table 13 and the result is shown in Table 15 and 16. The F-ratio for failure modes (highlighted in the Table 14) is F = 4.064, which exceeds the tabulated value 3.07. We therefore reject the null hypothesis at $\alpha = .05$ level of significance, concluding that at least two of the brands differ with respect to mean RPN for failure modes.

Following data is obtained when ANOVA is applied on the failure mode of table15:

Table 15: SPSS result of Anova analysis

ANOVA

Dependent Variable:PRN

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	20880.500[a]	10	2088.050	2.345	.048
Intercept	406351.125	1	406351.125	456.370	.000
FM	10855.125	3	3618.375	4.064	.020
COUNT	10025.375	7	1432.196	1.608	.188
Error	18698.375	21	890.399		
Total	445930.000	32			
Corrected Total	39578.875	31			

a. R Squared = .528 (Adjusted R Squared = .303)

Table 16: Summarized Anova analysis

Source	**Type III Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
FM	10855.125	3	3618.375	4.064	.020
COUNT	10025.375	7	1432.196	1.608	.188
Error	18698.375	21	890.399		
Total	39578.875	31			

Graphs of the relationship between RPN count and RPN value for the four failure modes considered in this study are displayed in the following figures;

Table 17: RPN count and RPN value

Count	FM1	FM2	FM3	FM4
1	50	112	126	80
2	60	84	144	120
3	70	140	168	112
4	84	105	192	168
5	100	96	105	60
6	120	72	120	90
7	140	120	140	84
8	168	90	160	126

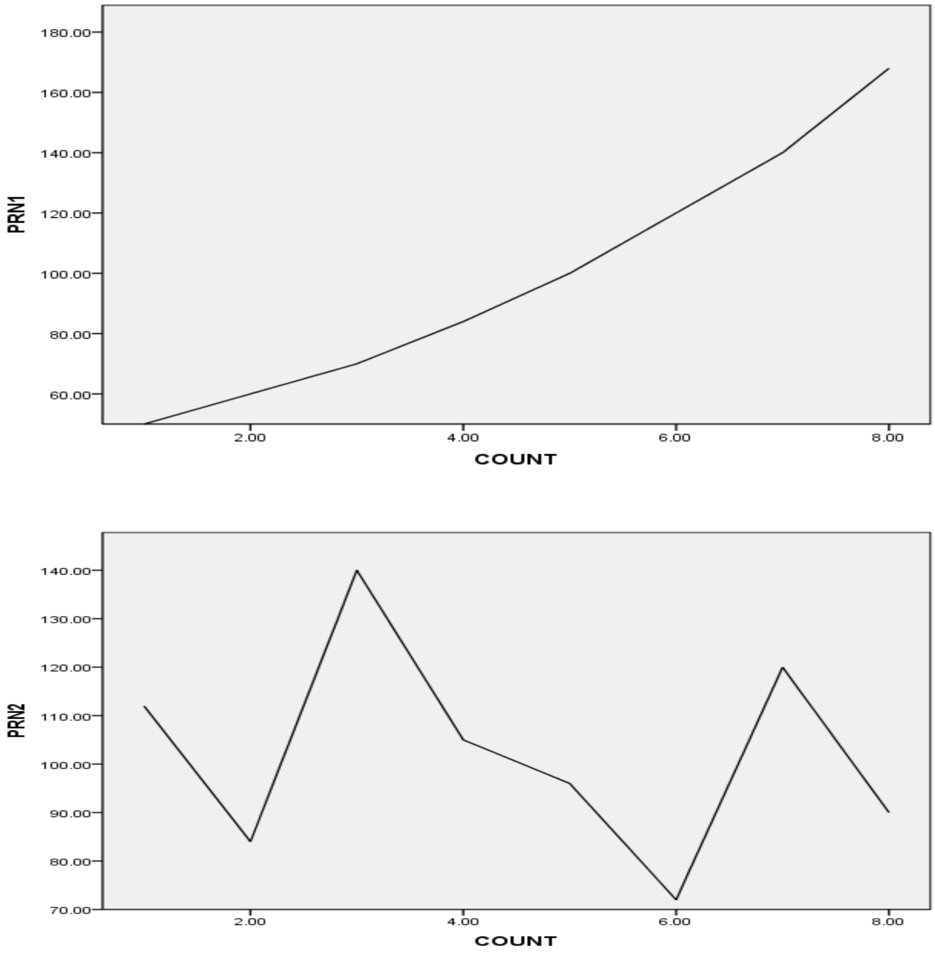

Figure 9: Graphs of RPN and RPN count

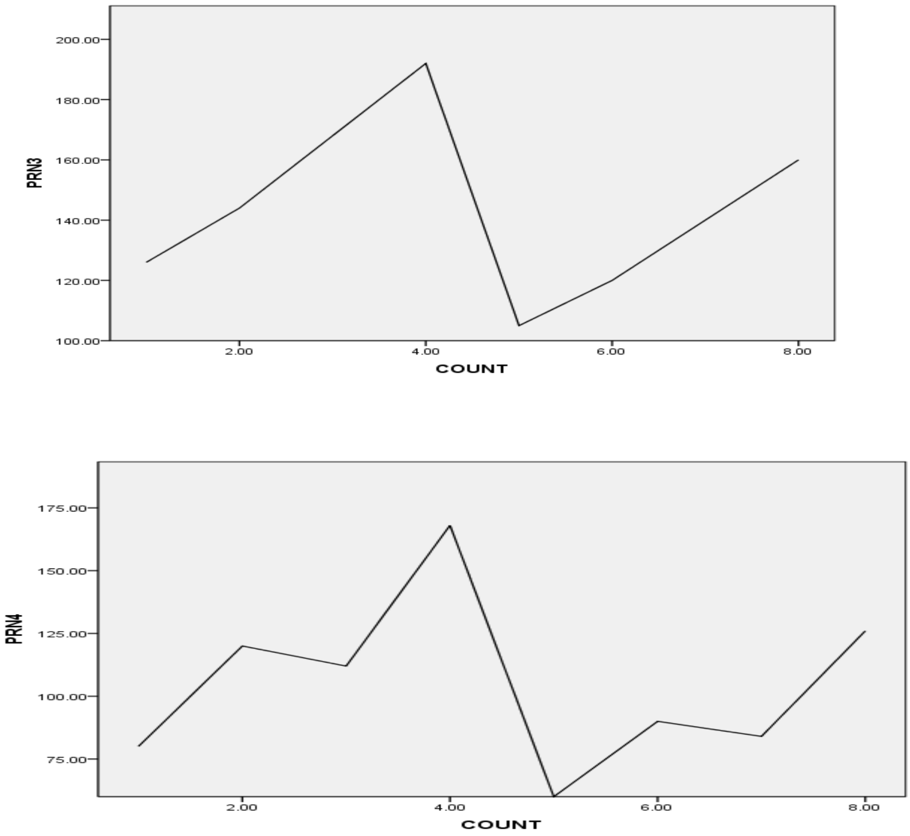

Figure 10: Graphs of RPN and RPN count

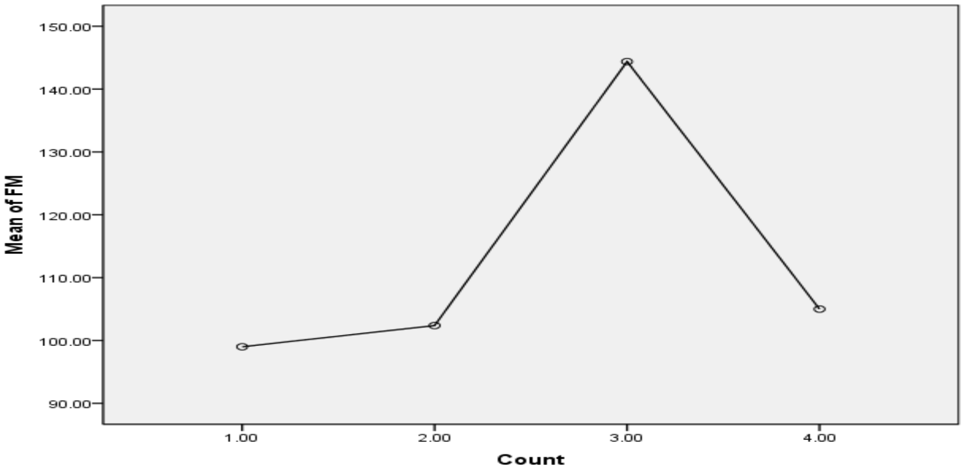

Figure 11: Graph of RPN count and mean RPN

Table 18: Failure modes effects and criticality analysis

Equipment	Function	Functional Requirement	Failure Mode	Failure cause	Effects on same equipment	Effects on other equipment	Effects on overall system	Failure Rate	Detection	Severity	RPN
Gasifier	To Produce Syngas	T_{15}=1100C m_{15}=329.4 ton/h	m_{15}<300.4 ton/h T_{15}<900^{0}C	Burner issues	Possibly lower temperature, Flame shape distortion, can damage gasifier wall	Undesired Syngas composition is transferred to shift reactor	Reduced plant load,CO_2 capture rate is reduced	4	5	4	80
Gasifier	To Produce Syngas	CO=34.57vol % H_2=17.93vol %	CO>60vol% H_2<17vol%	Combustion chamber	Unconverted coal is transferred to Reduction Chamber	Undesired Syngas composition is transferred to shift reactor	Reduced plant load,CO_2 capture rate is reduced	8	5	3	120
Scrubber	To Remove dissolved gases	Removal of dissolved gases	Failure to remove dissolved gases	Contaminated supply of water	Corrosion can take place	Undesired composition of syngas	Less Capture CO_2 results	5	5	4	100
Scrubber	To Remove dissolved gases	Removal of dissolved gases	Failure to remove dissolved gases	Less supply of water	Decrease in efficiency	Undesired composition of syngas	Performance of WGS is effected	4	6	4	96

Table18: Failure modes effects and criticality analysis

Equipment	Function	Functional Requirement	Failure Mode	Failure cause	Effects on same equipment	Effects on other equipment	Effects on overall system	Failure Rate	Detection	Severity	RPN
Gas turbine	Provide air to gasifier	T_{12}=396.7^{0}C m_{12}=207.7ton/hr	m_{12}<180 ton/hr	Fuel supply	GT not functioning at full load	Reduced production of steam in HRSG,Reduced power output from ST	Reduced plant load	5	5	2	50
Gas turbine	Generate Power	power@generator terminal=190.5MW	power@generator terminal<160MW	Trip	GT Trip	Shut down of the subsystem	Plant shut down	3	10	5	150
Gas Turbine	Generate Power	m_{45}=1584ton/hr T_{45}=642^{0}C	T_{45}<550 ^{0}C	Protective load shed	GT stop working	Shut down of the subsystem	Plant shut down	5	5	3	75
Gas Turbine	Provide hot gases	m_{45}=1584ton/hr T_{45}=642^{0}C	T_{45}<550^{0}C	Combustion related issues	GT stop working	Shut down of the subsystem	Plant shut down	7	4	6	168

Table18:Failure Modes Effects and criticality analysis

Equipment	Function	Functional Requirement	Failure Mode	Failure cause	Effects on same equipment	Effects on other equipment	Effects on overall system	Failure Rate	Detection	Severity	RPN
HRSG	Provide Steam to Gasifeir	m_{61}=3.48ton/hr $T_{61}=320^0C$	m_{61}=2.5ton/hr	Contaminated supply of water	Less production of steam, can cause corrosion	Supply of steam to gasifer is affected,	Part load operation of plant	10	6	2	120
Water-Gas Shift Reactor	CO to CO_2	98% conversion of COS	85%conversion of COS	Contaminated supply of steam	Lowe conversion of CO to CO_2	Undesired composition of Syngas	Increased load on absorber	7	5	6	210
Absorber	Capture CO_2	m_{37}=4743ton/day	m_{37}<4000ton/day	Maldistribution of solvent	Problem with packing	Insufficient supply of solvent	Less CO_2 is captured	4	4	4	64
Absorber	Capture CO_2	m_{37}=4743ton/day	m_{37}<4000ton/day	Maldistribution of solvent	Accumulation of solids within packing	Contaminated supply of solvent to H_2S absorber	Less CO_2 is captured	3	7	6	126
Absorber	Capture H_2S	m=65ton/day	m<45ton/day	Maldistribution of solvent	Accumulation of solids within packing	Supply of solvent to absorber is effected	Less H_2S is Captured	5	6	4	120

Table18: Failure Modes Effects and criticality analysis

Equipment	Function	Functional Requirement	Failure Mode	Failure cause	Effects on same equipment	Effects on other equipment	Effects on overall system	Failure Rate	Detection	Severity	RPN
Gas turbine	Generate Power	m_{45}=1584ton/hr T_{45}=642^{0}C	m_{45}<1585ton/hr T_{45}<550^{0}C	Fuel supply	GT not functioning at full load	Reduced production of steam in HRSG,reduced power output from ST	Reduced plant load	6	4	6	144
HRSG	Provide Steam to gasifier	m_{62}=1.475ton/hr T_{62}=319^{0}C	m_{62}<1.0ton/hr	Corrosion of HRSG tubes	Less production of steam	Reduced supply of steam to gasifer,syngas cooling system, syngas cleaning system	Less power production	6	6	4	144
Steam turbine	To produce power	Gross Power=131MW	Gross Power<100MW	Contaminated supply of steam	Less production of power	Less supply of steam to the reboiler of stripper	Less production of power, efficiency of stripper is reduced	5	5	5	125

Failure Modes Effects and criticality analysis

Equipment	Function	Functional Requirement	Failure Mode	Failure cause	Effects on same equipment	Effects on other equipment	Effects on overall system	Failure Rate	Detection	Severity	RPN
Steam Turbine	To provide steam to AGR	m_{55}=23 ton/hr T_{55}=287.5 C	m_{55}<23 ton/hr	Contaminted supply of stem	Less power production	Less supply of steam to reboiler stripper	Less power production	4	6	6	144
Air Separation Unit	To produce oxygen, Nitrogen	m_7=7.079ton/hr T_7=113.5C	m_7<7.079 T_7<100C	Cryogenic liquid Trap	over pressurization	Reduced production of oxygen, for gasifier,Reduced production of Nitrogen for fuel	Insufficient supply of oxygen can lead to undesired composition of Syngas	5	5	6	150
Water-Gas Shift Reactor	CO to CO_2	98% conversion of COS	85%conversion of COS	Contaminated supply of steam	Lowe conversion of CO to CO2	Undesired composition of Syngas	Increased load on absorber	7	5	6	210
Absorber	Capture CO_2	M_{37}=4743ton/day	M_{37}<4000 ton/day	Maldistribution of solvent	Problem with packing	Insufficient supply of solvent	Less CO_2 is captured	4	4	4	64

Table18: Failure Modes Effects and criticality analysis

Equipment	Function	Functional Requirement	Failure Mode	Failure cause	Effects on same equipment	Effects on other equipment	Effects on overall system	Failure Rate	Detection	Severity	RPN
Absorber	Capture CO_2	m_{37}=4743ton/day	m_{37}<4000ton/day	Maldistribution of solvent	Accumulation of solids within packing	Contaminated supply of solvent to H_2S absorber	Less CO_2 is captured	3	7	6	126
Absorber	Capture H_2S	m=65ton/day	m<45ton/day	Maldistribution of solvent	Accumulation of solids within packing	Supply of solvent to absorber is effected	Less H_2S is Captured	5	6	4	120
Gas turbine	Generate Power	m_{45}=1584ton/hr T_{45}=642C	m_{45}<1585ton/hr T_{45}<550C	Fuel supply	GT not functioning at full load	Reduced production of steam in HRSG,Reduced power output from ST	Reduced plant load	6	4	6	144
Air Separation Unit	To produce oxygen, Nitrogen	m_8=2.34ton/hr	m_8<2.34 ton/hr	Rapid oxidation	Source of Ignition, corrosion	Supply of Oxygen is affected to Gasifier	Threat to overall Safety of Plant	6	7	6	252

Table18: Failure modes effects and criticality analysis

Equipment	Function	Functional Requirement	Failure Mode	Failure cause	Effects on same equipment	Effects on other equipment	Effects on overall system	Failure Rate	Detection	Severity	RPN
Air Separation Unit	To produce oxygen, Nitrogen	$m_{10}=29.31$ ton/hr $T=120.5^0C$	$m_{10}<20$ ton/hr	Contaminants	Production of O_2 and N_2 is reduced		Affects the supply of oxygen to the power plant	7	4	4	112
Gasifier	To produce Syngas	$T_{15}=1100^0C$ $m_{15}=329.4$ ton/hr	$T_{15}<900^0C$ $m_{15}<300$ ton/hr	Fuel Supply	Unwanted Reaction resulting undesirable composition of syngas	Affect on the combustion Process of Gas Turbine	Less Production of power	3	8	5	120
Gasifier	To produce Syngas	$T_{15}=1100^0C$ $m_{15}=329.4$ ton/hr	$T_{15}<900^0C$ $m_{15}<329$ ton/hr	Oxygen Supply	Unwanted Reaction resulting undesirable composition of syngas	Affect on the combustion Process of Gas Turbine	Less Production of power	2	5	5	50

Table18: Failure modes effects and criticality analysis

Equipment	Function	Functional Requirement	Failure Mode	Failure cause	Effects on same equipment	Effects on other equipment	Effects on overall system	Failure Rate	Detection	Severity	RPN
Gasifier	To Produce Syngas	$T_{15}=1100^0C$ $M_{15}=329.4ton/hr$	$M_{15}<300.4ton/hr$ $T_{15}<900^0C$	Burner issues	Possibly lower temperature, Flame shape distortion, can damage gasifier wall	Undesired Syngas composition is transferred to shift reactor	Reduced plant load, CO_2 capture rate is reduced	4	5	4	80
Gasifier	To Produce Syngas	$CO=34.57vol\%$ $H_2=17.93vol\%$	$CO>60vol\%$ $H_2<17vol\%$	Combustion chamber	Unconverted coal is transferred to Reduction Chamber	Undesired Syngas composition is transferred to shift reactor	Reduced plant load, CO_2 capture rate is reduced	8	5	3	120
Scrubber	To Remove dissolved gases	Removal of dissolved gases	Failure to remove dissolved gases	Contaminated supply of water	Corrosion can take place	Undesired composition of syngas	Less Capture CO_2 results	5	5	4	100

Table18: Failure Modes Effects and criticality analysis

Equipment	Function	Functional Requirement	Failure Mode	Failure cause	Effects on same equipment	Effects on other equipment	Effects on overall system	Failure Rate	Detection	Severity	RPN
Scrubber	To Remove dissolved gases	Removal of dissolved gases	Failure to remove dissolved gases	Less supply of water	Less efficiency	Presence of dissolved gases		4	6	4	96
Gasifier	To Produce Syngas	T_{15}=1100^{0}C M=329.4ton/hr	M<300.4ton/hr T_{15}<900^{0}C	Burner issues	Possibly lower temperature, Flame shape distortion, can damage gasifier wall	Undesired Syngas composition is transferred to shift reactor	Reduced plant load,CO_2 capture rate is reduced	4	5	4	80

4.3.5 Hazop analysis of IGCC with CO_2 capture:

"A hazard and operatabilty study is a structured and systematic examination of a planned or existing process or operation in order to identify and evaluate problems that may represent risk to personnel or equipment or prevent efficient operation."(Ross, 2011).

Methodology:

The following methodology is used in order to carry out Hazop analysis on the IGCC power plant with CO_2 Capture (Mitsubishi Gasifier Case):

- Divide the system into sections
- Choose a study node

Node:

A node is a specific location in the process in which (the deviation of) the process intent are evaluated e.g.; air separation unit, gasifier, and heat exchangers, gasifier, GT, ST, HRSG.

Process Parameter:

Relevant parameters for that specific equipment are selected.

Hazards:

Then possible deviations or hazards associated with that process parameter are studied.

Cause:

The reason why the deviation could occur. Several causes may be identified for one deviation. It is often recommended to start with the causes that may result in the worst possible consequence.

Possible Consequence:

Evaluations of the possible consequences have been performed in this section of Hazop analysis. Consequences may both comprise process hazards and operability problems, like plant shut-down or reduced quality of the product. Several consequences may follow from one cause and, in turn, one consequence can have several causes.

Detection:

How these deviations are detected.

Safeguards:

How to reduce the occurrence frequency of the deviation or mitigate its consequence are studied under safeguards.

The following figure represents the steps which needs to be performed in a general way:

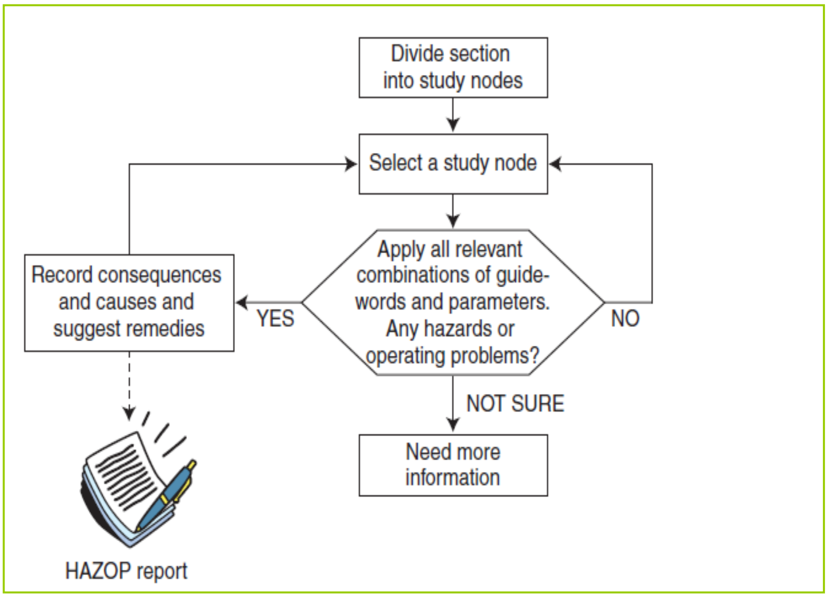

Figure 12: Schmetic description of Hazop analysis (Ross, 2011).

Table 19: Hazop analysis

ID	Function	Important Parameter	Hazard	cause	Possible consequence	detection	Safeguard
Air Separation Unit	Produce oxygen and Nitrogen	Contaminant	Plugging,Reaction,Corrosion	Airborne can originate from various sources like vents,flares,process leaks	Increase probability of fire, reduce production of oxygen	Analyze ambient air	Elevating air intake ,constant inspection of intake air
Air Separation Unit	Produce oxygen and Nitrogen	Abnormally low temperature	Can damage the expander of air separation unit	Malfunction of the expander ,presence of liquid droplets in the expander	Loss of expander effeiciency,Mechanical failure of the expander	Condition of the fluid at the discharge of expander should be checked	Inlet temperature of expander should be maintained as per manufacturer recommendation, temperature monitoring at the end of expander
Gasifier	Produce SynGas	Temperature	High temperature	Less steam supply, non-stoichiometric quantities of air and oxygen	Undesirable composition of syngas,high temperature of outlet syngas,less power production	Online chromatograph for monitoring composition	Temperature controller
			Low Temperature	Less steam supply, problem with fuel supply	Undesirable composition of syngas,low temperature of outlet syngas,less power production		Temperature controller

Table19: Hazop analysis

ID	Function	Important Parameter	Hazard	cause	Possible consequence	detection	Safeguard
Gasifier	Produce syngas	Composition	Undesirable composition	Fuel supply problems, Temperature runaway within reactor	Variation in syngas composition at gasifier outlet	Online chromatograph for monitoring composition	Monitoring of composition
Scrubber	Remove dissolved gases from syngas	Water supply	Contaminated supply of water	Malfunctioning of water clean up system	Efficiency of scrubber decreases,	Online Chromatograph	Monitoring of composition
Scrubber	Remove dissolved gases from syngas	Flow rate of Syngas	High flow rate	Malfunctioning of gasifier	Undesired composition ,degradation of WGS catalyst	Online Chromatograph	Monitoring of composition
			Less flow rate	Malfunctioning of gasifier,Compressor problem	Undesired composition	Online Chromatograph	Monitoring of composition
Shift Reactor	Convert CO to CO_2	Temperature	High Temperature	Catalyst issues, less steam supply, failure of steam supply	Less conversion of CO to CO_2,Undesirable composition of CO_2	Temperature controller	
			Low Temperature	Catalyst issues	Less conversion of CO to CO_2,Undesirable composition of CO_2	Online Chromatograph	

Table19:Hazop analysis

ID	Function	Important Parameter	Hazard	cause	Possible consequence	detection	Safeguard
Shift Reactor	Convert CO to CO_2	Contamination	Contaminated supply of steam	Malfunctioning of deaereator	Low conversion of CO, Catalyst degradation	Online Chromatograph	On-line chronatograph
Shift reactor	Convert CO to CO_2	Composition	Conversion of CO to CO_2 is affected	Catalyst issues, uncontrolled temperature and pressure	Less conversion of CO to CO_2,Undesirable composition of CO_2	Online Chromatograph	On-line chronatograph
Shift Reactor	Convert CO to CO_2	Flow Rate of Syngas	High Flow Rate	Malfunctioning of gasifier, failure of control valve	Non-stoichiometric ratio of steam and syngas causes deactivation of catalyst in reactor	Measurement of flow rate	Maintain Proper flow rate
Heat exchanger	Cool Syngas	Temperature	High Temperature	Less supply of steam,	High temperature of the syngas, uncontrolled production of syngas, increase in corrosion	Temperature Controller	Temperature Controller
			Low Temperature	Excessive steam of steam	Undesired temperature of syngas	Reduction in performance can be seen	Temperature Controller

Table19: Hazop analysis

ID	Function	Important Parameter	Hazard	cause	Possible consequence	detection	Safeguard
Absorber	Remove CO_2 from SynGas	Fluid flow	Maldistribution of liquid	Low liquid flow rate. High gas flow rate	Less efficient removal of CO_2, increase in pressure drop	Constant measurement of flow rate	Quality control during manufacturing and erection
Absorber	Remove CO_2 from SynGas	Fluid flow	Improper wetting	Very low liquid flow rate, fouling on packing, distributor not working at scale, need perfectly horizontal distributor, perfectly vertical column, high gas flow rate, high viscosity, gas diffusers	Less efficient absorption due to less effective area	Constant measurement of flow rate	Quality control during manufacturing and erection

Table19: Hazop analysis

I.D	**Function**	**Important Parameter**	**Hazard**	**Cause**	**Possible consequence**	**Detection**	**Safeguard**
Absorber	Remove CO_2 from SynGas	Fluid flow	Improper wetting	Very low liquid flow rate, fouling on packing, distributor not working at scale, need perfectly horizontal distributor, perfectly vertical column, high gas flow rate, high viscosity, gas diffusers	Less efficient absorption due to less effective area	Constant measurement of flow rate	Quality control during manufacturing and erection
		Pressure	High Pressure	Increased temperature, malfunctioning of condenser, high solution loading, malfunctioning of solvent recirculation pump	Decrease the efficiency of absorber, Less capture rate of CO_2	Pressure indicators along the length of the column	Pressure controller on the absorber

Table19: Hazop analysis

ID	Function	Important Parameter	Hazard	cause	Possible consequence	detection	Safeguard
Heat exchanger	Cool Syngas	Fluid Flow	Tube vibration	Increased flow of steam	Tubes of heat exchanger can be damaged, can cause excessive noise	Excessive noise from heat exchanger,	Accurate calculation of flow rate
Heat exchanger	Cool Syngas	Contamination		Contaminated steam supply	Corrosion ,fouling, leakage through tubes can contaminate syngas	Reduction in performance of heat exchanger	Proper maintaince and operation alert
Absorber	Remove CO_2 from SynGas	Temperature	High Temperature	Flow decrease, Malfunction of flash drums	Increased degradation of the solvent, Decreased the viscosity of the solvent, increased the corrosion	Reduction in efficiency of absorber, Decrease capture rate of CO_2 Reduction in efficiency of absorber,	Pressure controller on the condenser Pressure controller on the condenser
			Low Temperature	Increase flow, malfunction of condenser	Increased viscosity of solvent, flow related issues	Decrease capture rate of CO_2	

Table19: Hazop analysis

ID	Function	Important Parameter	Hazard	cause	Possible consequence	detection	Safeguard
Absorber	Remove CO_2 from SynGas	Pressure	Low Pressure	Low temperature, malfunctioning of the recirculation of the pump	Flow within the absorber is altered,	Pressure indicators along the length of the column	Pressure controller on the absorber
Absorber	Remove CO_2 from SynGas	Composition	Solvent Composition	Presence of the oxygen in the flue gas degrade the solvent,	Fouling can take place.	Corrosion inhibitors	Online chromatograph
Stripper	Remove CO_2 from Selexol	Temperature	High Temperature	Flow decrease, pressure increase, condenser malfunction, reboiler malfunction, malfunction of pressure controller on the condenser outlet		Pressure and temperature indicators along length of column.	Optimize the location of the transmitters

Table19: Hazop analysis

ID	Function	Important Parameter	Hazard	cause	Possible consequence	detection	Safeguard
Stripper	Remove CO_2 from Selexol	Temperature	Low Temperature	Increased liquid flow ,condenser malfunction (sudden draining of sump), reboiler malfunction, sudden decrease in pressure, pressure controller malfunction	Decreased separation, cost increase, reduce the CO_2 capture rate, decreased mass transfer rates, increased viscosity, increased flashing in the stripper, less opportunity for heat integration, increased liquid level in column sump	Pressure and temperature indicators along length of column, level control in the column sump	Consider pressure controller on the stripper, reboiler duty control, redundancy of pressure controllers

Table19: Hazop analysis

ID	Function	Important Parameter	Hazard	cause	Possible consequence	detection	Safeguard
Stripper	Removal of CO_2 from Selexol	Pressure	High Pressure	Increased temperature, condenser malfunction, reboiler malfunction, high solution loading, high rate of degradation, malfunction of solvent circulation pump leads to no liquid in absorber	Increased separation leads to too low lean loading, increased condenser duty leads to higher operating costs, leaks and rupture of vessel,	Pressure indicators along the length of the column Pressure indicators along the length of the column	Pressure controllers on the stripper, reboiler duty control, change process set points (liquid load), pressure safety valve
			Low pressure	Leakages, reboiler malfunction, pressure controller malfunction, circulation pump increases flow rate caused by controller malfunction, malfunction of the transfer pump from the absorber column	Decreased separation, cost increase, reduce the CO_2 capture rate, low temperature, decreased mass transfer rates, increased viscosity, increased flashing in the stripper, less opportunity for heat integration, increased liquid level in column sump	Pressure indicators along the length of the column	Pressure controllers on the stripper, reboiler duty control, change process set points (liquid load)

Table19: Hazop analysis

ID	Function	Important Parameter	Hazard	cause	Possible consequence	detection	Safeguard
Stripper	Removal of CO_2 from Selexol	Improper wetting of packing	Very low liquid flow rate, fouling on packing, distributor not working at scale, need perfectly horizontal distributor, perfectly vertical column, high gas flow rate, high viscosity, gas diffusers	Less efficient stripping due to less contact area	Less efficient operation of absorber		
H_2S Absorber	Remove CO_2 from SynGas	Temperature	High Temperature	Flow decrease, Malfunction of flash drums	Increased degradation of the solvent, Decreased the viscosity of the solvent, increased the corrosion	Decrease the efficiency of the absorber	Pressure controller on the condenser
			Low Temperature	Increase flow ,malfunction of condenser	Increased the viscosity of solvent		

Table19: Hazop analysis

ID	Function	Important Parameter	Hazard	cause	Possible consequence	detection	Safeguard
H_2S Absorber	Remove CO_2 from SynGas	Fluid flow	Maldistribution of liquid	Low liquid flow rate. high gas flow rate	Less efficient removal of CO_2,increase in pressure drop		Quality control during manufacturing and erection
H_2S Absorber	Remove CO_2 from SynGas	Fluid Flow	Improper wetting	Very low liquid flow rate, fouling of packing, distributor not working properly	Less efficient absorption due to less effective area		
H_2S Absorber	Remove CO_2 from SynGas	Pressure	High Pressure	Increased temperature, malfunctioning of condenser, high solution loading, malfunctioning of solvent recirculation pump	Reduction in performance of the absorber	Pressure indicators along the length of the column	Pressure controller on the absorber

Table19: **Hazop analysis**

ID	Function	Important Parameter	Hazard	cause	Possible consequence	detection	Safeguard
H_2S Absorber	Remove CO_2 from SynGas	Pressure	Low Pressure	Low temperature, malfunctioning of the recirculation of the pump	Reduction in performance of the absorber	Pressure controller on the absorber	
H_2S Absorber	Remove CO_2 from SynGas	Composition	Solvent Composition	Presence of the oxygen in the flue gas degrade the solvent,	Fouling can take place,	Corrosion inhibitors	
Gas Turbine	Provide Hot gas	High temperature Low Temperature	Improper cooling Insufficient Combustion	Non-optimal fuel to air ratio Non-optimal fuel to air ratio	Damage turbine blade, NOx emissions,GT material constraints Combustion related issues	Careful monitoring of turbine temperature Temperature Controller	Temperature controller Temperature Controller

Table19: Hazop analysis

ID	Function	Important Parameter	Hazard	cause	Possible consequence	detection	Safeguard
Gas Turbine	Provide Hot gas	Compressor Surge		Increased outlet pressure of compressor due to high flow rate	P_2/P_1 varies, no change in T2/T1,compressor efficiency drops	PA system data, and vibration data	
HRSG	Produce Steam	Temperature	High Temperature	High temperature of turbine exhaust	Excessive production of steam, Increase corrosion rate of HRSG	Temperature Controller	Temperature Controller
			Low Temperature	Low turbine exhaust temperature	Less production of steam		
HRSG	Steam Production	Contaminated Feed Water	Contaminated supply of steam to the Process	Malfunctioning of the deaeartor	Corrosion of heat exchanger, contaminated supply of steam to the gasifier, affect on gasification reaction	Loss of steam production,	

Table19: Hazop analysis

ID	Function	Important Parameter	Hazard	cause	Possible consequence	detection	Safeguard
HRSG	Steam Production	Temperature	High Temperature	High turbine exhaust temperature,	Increase the load on the HRSG ,Increases the rate of corrosion	Excessive steam production	
			Low Temperature	Low turbine exhaust temperature	Less supply of steam to rebolier of stripper. less supply of steam to gasifier, efficiency of stripper is affected	Production of power is affected,	
HRSG	Steam Production	Heat Transfer	Gassing	Non-condensable gases form an insulating film on tubes	Reduction in heat transfer rate	Malfunctioning of HRSG by low production of steam	Monitoring of water quality

Table19: Hazop analysis

ID	Function	Important Parameter	Hazard	cause	Possible consequence	detection	Safeguard
Heat exchanger	To Cool SynGas	Fluid Flow	High steam flow	Failure of valve,	More decrease in the syngas temperature, can cause tube vibration		Low temperature alarm
			Low Steam Flow	Less supply of steam from HRSG	High Temperature syngas supplied to the Gas Cleaning system, Can affect the cleaning of syngas, corrosion of heat exchanger		High Temperature alarm
Heat Exchanger	To cool Syngas	Temperature	High temperature	Less supply of steam	High Temperature syngas supplied to the Gas Cleaning system, Can affect the cleaning of syngas, corrosion of heat exchanger	High temperature of syngas	High temperature controller

Table19: Hazop analysis

ID	Function	Important Parameter	Hazard	cause	Possible consequence	detection	Safeguard
Heat Exchanger	To Cool syngas	Temperature	Low temperature	Excessive supply of steam, less flow rate of syngas	Undesired temperature of syngas	Temperature detector	Temperature controller
Heat Exchanger	To Cool Syngas	Corrosion	Corrosion of syngas	Hardness of steam	Crack of heat exchanger tube		Proper maintaince and periodic check
Heat Exchanger	To cool syngas	contamination	Contamination of syngas	Leakage of tubes and steam enters into syngas	Contaminated supply of syngas to the gas cleaning system, load on syngas cleaning system increases		Proper maintaince and periodic check
Steam Turbine	Produce Power	Contamination	Erosion of solid particles	Impurities in raw water entering system	Leakage in overflow valve, loss of turbine efficiency	Steam temperature down stream the valve	Check the valve position

4.4 Development of qualification plan:

"The objective of this step is to select qualification methods that adequately address the identified failure modes of concern with respect to its risk and determination of sufficient performance margins" (DNV, 2010).

Failure modes of concern which are identified in the threat assessment step will be addressed here. The basic methodology for the selection of these qualifications is given under the following points.

- The selection of the Qualification method in order to address the failure mode of concern is based on the requirement set in the qualification basis. How each of the qualification method is carried out should be discussed in detail.

Qualification shall be achieved by providing the documented evidence that each of the requirements given in the qualification basis has been met.

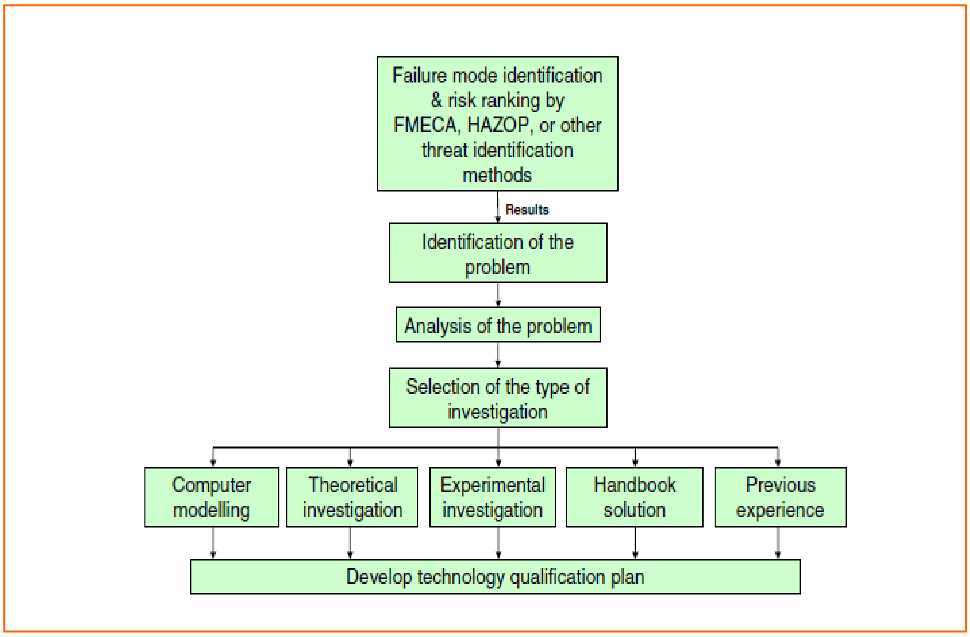

Figure 13: Schemetic description of selection of qualification activities (Myhrvold.T, et al., 2009)

Table 20: Qualification activities

NO	Activity Description	Equipment	Failure Mode	Failure Mechanism
1	Understanding of reaction kinetics of coal gasification	Gasifier	m_{15}<304 ton/hr T_{15}<900^{0}C	Conversion of fuel
2	Adjustment of fuel and air flow rate	Gas turbine	CO>60 vol% H_2<17 vol%	Combustor Related issues
	Adjustment of air flow	Gas turbine	Unstable operation of gas turbine	Compressor surge
3	Maintaining proper CO composition	Heat exchanger	Undesired temperature of syngas	High Temperature Corrosion
4	Maintaining proper steam to carbon ratio	Shift reactor	85%conversion of COS	Catalyst Deactivation
5	Packing development	Absorber	m_{37}<4743 ton/day	Maldistribution of solvent
6	Distributor design	Absorber	m_{37}<4743 ton/day	Maldistribution of solvent
7	Maintaining proper CO composition & avoid high Temperature of Syngas	Syngas cooler	Undesired temperature of syngas	Metal Dusting
8	Removal of solid particle from water	Steam turbine	m_{55}<23 ton/hr	Supply of steam
9	Treatment of water supply	HRSG	m_{62}<1 ton/hr	Supply of water

4.5 Execution of qualification plan:

The objective of this step is to carry out the qualification activities prescribed in the technology qualification plan developed in the previous step to document performance margins for the failure modes of concern (DNV, 2010).

The careful selection of the qualification activities has been done because to carry out each activity takes lot of time and money .Economic parameters should also be considered for the selection of these activities .For the case of this master economic parameters are not taken into consideration which is a limitation of this thesis work.

The basic methodology for the selection of activity for a particular failure mode is given below:

4.5.1 Qualification activity for CO_2 absorber:

Their design is of great importance because they serve to overcome the maldistribution of the solvent. So allowance must be made in design for difference in liquid load because it is obviously more difficult to distribute small than large amount of liquid. Distributor must be accurately finished and correctly installed to avoid the difference in liquid level. They should be fitted with drop edges, which prevent coalescence of the liquid on the underside and thus ensure trouble free operation. A crucial parameter in the design of a distributor is the liquid load required for the separation (Billet, R., 1995).

4.5.2 Qualification activity for shift reactor catalyst:

Water-gas shift is an equilibrium-limited reaction, the CO slip – CO concentration in the exit gas – depends on the reaction temperature and the syngas composition. The composition of the syngas is given by the gasifier. The steam concentration before shift can be adjusted. A low CO slip can be achieved by increasing the steam to CO ratio or by decreasing the exit equilibrium temperature by cooling between two or more sour shift reactors. (H. Topsoe, 2011).

4.5.3 Qualification of tube vibration of heat exchanger:

The frequency of the flow excited forces will decline if the cross flow flux or rate on the shell side is reduced. In this way failure caused by flow induced vibration can be avoided. However the productivity of the heat exchangers will decrease at the same time.

A heat exchanger vibration analysis consists of the these steps: (i) flow distribution calculations, (ii) dynamic parameter evaluation (i.e., damping, effective tube mass and dynamic stiffness), (iii) formulation of vibration excitation mechanisms, (iv) vibration response prediction, and (v) resulting damage assessment (i.e., comparison against allowable) (Gelbe.H.,et al 1995).

4.5.4 Qualification of heat exchanger for metal dusting:

The potential for metal dusting is highest in the carbon monoxide rich gases at temperature 400-800C i.e., at conditions which are very likely to prevail for equipment during cooling. This situation can be avoided by controlling the composition of the syngas in the gasifier in order to avoid the excessive amount of CO (John R Brightling, et al, 2006).

4.5.5 Qualification of heat exchanger for fouling:

Fouling and plugging problems in the syngas cooling systems have been a major cause of unplanned downtime and a significant contributor to unreliability in IGCC plants. Development of high reliability of syngas cooling systems will require an improvement in the fundamental understanding of the condensation phenomena and the role that particulate matter plays in the process. In addition to research into the basic phenomena, the recommended multi-task program would:

- Develop computer models that simulate the flows, temperatures, and condensation phenomena experienced in syngas cooling systems.
- Use the computer models as the basis for the design of test rigs that could be installed in slipstream units at existing IGCC plants.
- Use the test installations to validate the models or provide data that could lead to better models.

When the models become capable of accurately predicting the conditions under which deposition would occur, and the locations of those deposits, they could be provided to syngas cooler designers for use in developing coolers that would not adversely affect unit reliability.

4.5.6 Qualification activity for steam turbine:

These impurities are transported from the boiler to the superheated steam by three different mechanisms: Mechanical carry-over, vaporous carry-over and temperatures (i.e. spray in a superheater). The degree of fouling and depositing is dependent on the boiler drum pressure level, the separation efficiency, spraying in superheaters, and other factors. Fouling in the turbine steam path causes degradation of turbine performance. Compounds deposit on different turbine parts, depending on the temperature in the steam path. Fault Fouling and deposits can be reduced by generally improving the quality of the processed water and by reducing spray in the superheaters (Karlsson C et al ,2008) .

Erosion of solid particles in the steam path is due to exfoliation of iron oxide and magnetite particles from the high temperature section of the boiler .The impact of the particles on the first turbine stage causes damage to the blades, which increases the swallowing capacity of the turbine, and decreases the efficiency of the turbine stage. Solid particle erosion can to some extent be avoided by using a bypass valve that leads the steam to the condenser during start-up. Other measures to mitigate the effects of solid particles erosion include the chemical treatment of the steam system to reduce exfoliation of the particle removal system and turbine with erosion-resistant coatings. Recently the use of fewer and larger blades in the first stage has been identified as the most important factor in eliminating solid particle erosion. Fouling originates from impurities in the raw water entering the steam system and from additives used in water processing.

4.5.7 Qualification activity for gas turbine:

A higher mass flow rate through the turbine may increase the pressure at the compressor outlet (back pressure) too much, so that the compressor runs into surge and the air flow no longer can be maintained. The amount of pressure increase the compressor can tolerate before this occurs is referred to as the compressor surge margin which is a characteristic of the design of a given compressor. If surge becomes a problem therefore depends on the type of gas turbine, but it seems that this is an issue for the majority of available large gas turbines.

The pressure increase at the turbine inlet (and thus also at the compressor outlet) can be explained by the theory for flow through a choked nozzle which states that in order to get a higher mass flow through a nozzle of fixed geometry, the inlet pressure must either increase or the inlet temperature must be reduced. As mentioned above the turbine inlet temperature should, however, be kept as high as possible, consistent with material limitations to ensure a high combined cycle efficiency. There are several other possible strategies to resolve the surge limitation problem (Ola Maurstad, 2005).

- Modify the turbine of the GT
- Modify the compressor of GT

- Integration with the air separation unit

4.5.8 Air integration between GT and ASU:

It involves bleeding off some of the air at the outlet of the GT compressor, and utilizing this air in the ASU. Also, a certain amount of nitrogen product from the ASU may be brought back the GT. This concept makes it possible to reduce the total mass flow through the turbine by bleeding off more air mass flow than the mass flow of nitrogen brought back. The two European plants at Buggenum and Puertollano apply this principle which enables the use of standard Siemens gas turbines with respect to the compressor and turbine. Air integration may therefore represent a solution to apply gas turbines which would otherwise need redesign to work on syngas. (Maurstad.O, 2005).

4.5.9 Qualification activity for gasifier:

A significant challenge for IGCC development has been predicting the actual conversion performance for new gasification projects. Even when a prior, proven technology has been used, gasifiers have experienced unexpected differences in performance compared to earlier gasifiers of the same technology. This caused higher sulfur levels in the clean syngas than had been anticipated during design, which required a retrofit installation of a COS hydrolysis system. (J.Phillips, 2007).

A better understanding of the fundamentals of high-pressure coal gasification reactions would help improve performance prediction for new coal gasifiers. Although gasification technology suppliers are using advanced computational fluid dynamics (CFD) software and other tools to improve gasifier modeling capabilities, there is still much to be gained through both independent and joint efforts to improve understanding of reaction fundamentals and modeling. In particular, there is a need to translate basic reaction rate data into a reactor model that can predict carbon conversion and sulfur speciation under typical conditions in a commercial gasifier. One possible path to success is to incorporate reaction rate data into a CFD model of the gasifier. Predicting the chemical reactions and products of the IGCC gasifier will require a thermochemical model similar to the tools used for process design in the petrochemical industry.

4.5.10 Traceability of data:

In the following discussion a link is established from qualification basis to the to failure mode identification to the qualification activities In other words: someone outside the project should be able to follow what failure modes have been identified, how they have been addressed what evidence has been developed and how conclusive they are.

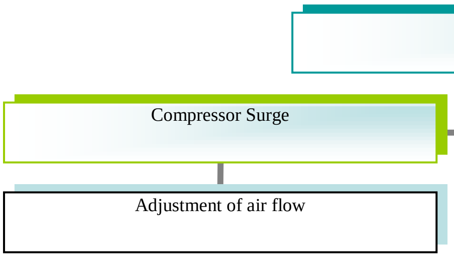

Figure 15: Audit trail for gas turbine

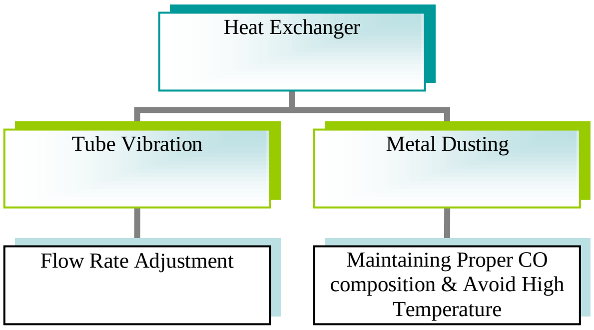

Figure 14: Audit trail for heat exchanger

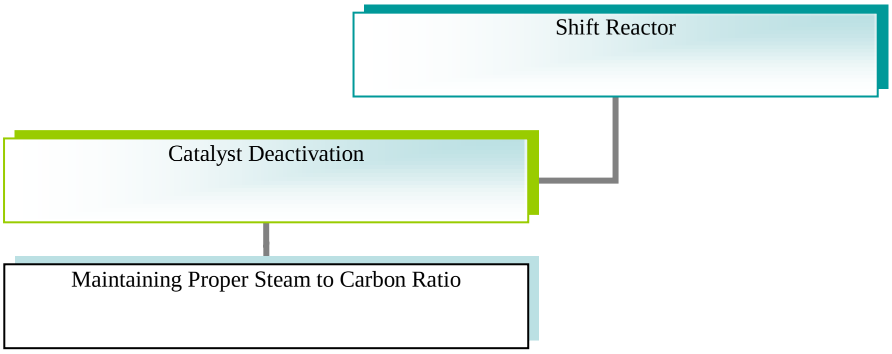

Figure 16: Audit trail for shift reactor

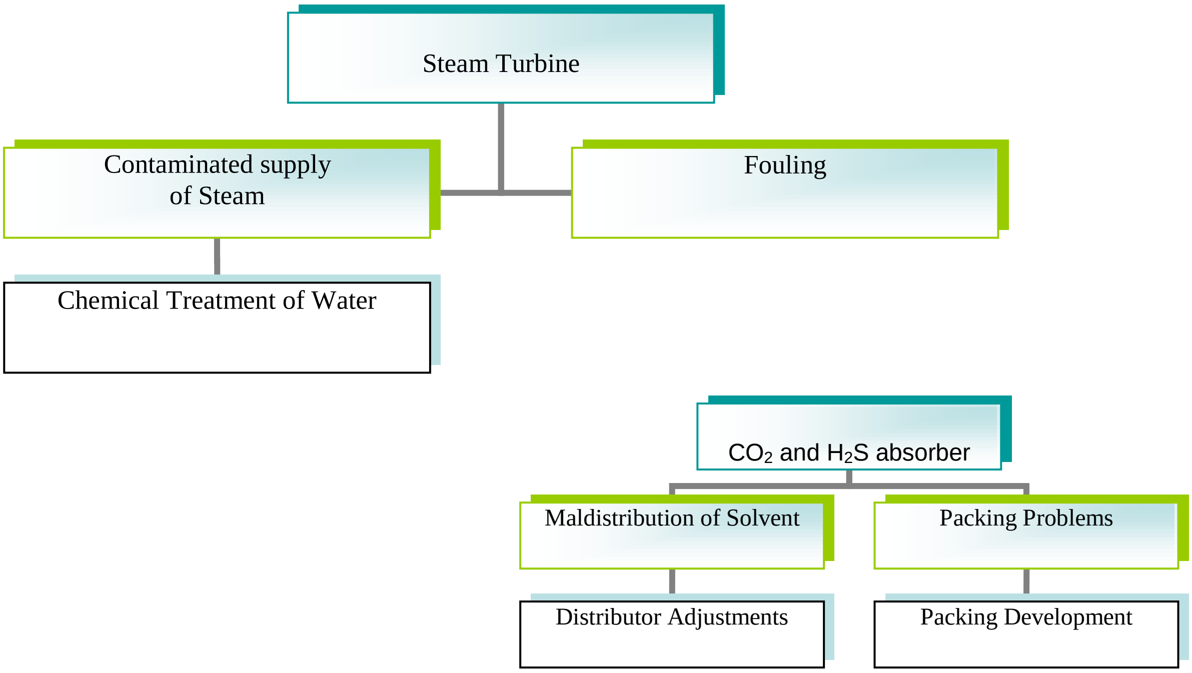

Figure 17: Audit trail for steam turbine and absorbers

4.6 Performance assessment:

The objective of this phase is to confirm that the performance, functional requirements, or target reliability as stated in the qualification basis are met (DNV, 2010).The performance assessment is carried out to quantify the overall performance of the technology, and to compare it against the defined margins stated in the qualification basis. If the final acceptance of the technology qualification process has not been achieved, recommendations for design improvements or further qualification activities can be made. Alternatively, the operating envelope for the technology can be reduced to ensure adequate performance margin based on the gathered evidence. As an extreme case, the technology cannot be qualified against the qualification basis.

4.6.1 Basic methodology:

Key steps of the performance assessment are to:

- Confirmation that the qualification activities have been carried out, and that the acceptance criteria have been met. The prominent feature of this confirmation is to carry out a gap analysis to ensure that all the identified failure modes have been adequately addressed.
- Assessment of the performance margin related to each identified failure mode of concern.

Improvements would normally imply that the previous steps in the qualification process need to be updated. The updates may range from limited update of parameters or risk data to major rework of all documents. Regardless of the scope of the updates, traceability of the process is important to reflect the qualification process

4.6.2 Performance assessment of heat exchanger:

Some of the performance assessment approaches of heat exchanger are adhoc where as some involve meticulous calculation. The following key practices have been seen to be most prevalent and include monitoring of:

- Outlet temperature of the hot stream profile
- Approach Temperature profile
- Log Mean temperature Difference
- Heat load Profile
- Time series of overall heat transfer coefficient

The first four methods are extensively used but they are ineffective in terms of isolating the net impact of fouling from the process upsets. On the other hand overall heat transfer coefficient method requires detailed calculations and knowledge of the geometry of heat exchanger; operators calculate these parameters once or twice in a week based on either instantaneous temperature and flow measurements or daily average sample of the measurement. (Vijaysai, 2006).

4.6.3 Performance assessment of gasifier:

A better understanding of the ground rules of high-pressure coal gasification reactions would help improve performance forecast for new coal gasifiers. Although gasification technology suppliers are using advanced computational fluid dynamics (CFD) software and other tools to improve gasifier modeling capabilities, there is still much to be gained through both independent and joint efforts to improve understanding of reaction fundamentals and modeling. In particular, there is a need to translate basic reaction rate data into a reactor model that can predict carbon conversion and sulfur speciation under typical conditions in a commercial gasifier. One possible path to success is to incorporate reaction rate data into a CFD model of the gasifier (J.Phillips, 2007).

- On-line monitoring of refractory wear
- Reliable optical access to the gasifier
- On-line coal quality analysis
- Rapid, on-line measurement of syngas composition using laser absorption spectroscopy
- Trustworthy gasifier temperature measurement
- On-line slag composition analysis or slag viscosity measurement or slag thickness measurement

4.6.4 Performance assessment of steam turbine:

A thermal performance program should include the following essential factors (Paul Albert,?):

- Obtain baseline performance data on individual turbines and cycle components during initial operation and after a maintenance outage to establish a base for identifying specific areas of performance losses
- Periodic acquisition of repeatable performance data
- Proper evaluation and assessment of performance data so that deterioration can be detected, located, trended, and corrected in a cost effective manner
- Detailed inspection of and quantification of the expected performance recovery from restoration of turbine steam path.

4.7.5 Performance assessment of HRSG:

The performance of the HRSG can be predicted by analyzing the variation in the following elements:

- The gas and water flow rates, temperatures, pressures and gas compositions which vary with fuel type;
- Water and air temperature changes due to diurnal and seasonal temperature changes;
- Fouling of the heat-transfer surfaces which vary with time and lead to significant changes in

- Heat-transfer rate and pressure loss
- The geometry of the HRSG
- Variable conditions at the gas turbine exhaust, e.g. gas velocity and temperature.

Prediction of heat exchanger performance can be based on the assumption about flow patterns. Departure from these assumptions can be accommodated using empirically derived degradation formulae (F.J.G. Carazas, 2011).

4.7 Concept improvement:

The objective of the concept improvement step is to implement improvements that have been found necessary or beneficial during the failure mode identification and risk ranking or in the performance assessment. All concept improvements have to be analyzed for cost benefit (DNV, 2010). When making modifications to the concept, care should be taken to ensure that the modification either:

- Removes a failure mode
- Reduces the probability or consequence of failure mode to an acceptable level,
- Reduces the total concept cost without introducing new failure modes.

Concept improvement for gas turbine:

- Integrate the gas turbine to the air separation unit by extracting air from the compressor of the GT in order to avoid surge of the compressor.

Concept improvement of heat exchanger:

- Maintain proper composition of CO and try to avoid high temperature so that metal dusting can be avoided.
- Try to maintain the proper flow of steam so that tube vibration on the shell side of the heat exchanger can be avoided.

Concept improvement of steam turbine:

- Proper treatment of the water supply in order to avoid the contamination problem.

Concept improvement of water gas shift reactor:

- Maintain proper steam to CO ratio to avoid catalyst deactivation.

Concept improvement of CO_2 and H_2S absorber:

- Check the loading of solvents in these two absorbers after reviewing distributor design and proper packing development.

Concept improvement of heat recovery steam generator:

- Proper treatment of the water supply in order to avoid the contamination problem.

Concept improvement of gasifier:

- Proper understanding of coal gasification reaction.

Chapter 5:Conclusion and future work:

5.1 Conclusion:

From the above discussion it can be concluded that the coal and other fossil energy resources are likely to remain the key fuel for electricity generation. At the same time, the need to reduce anthropogenic emissions of CO_2 to avoid the substantial negative impacts of climate change is pressing. This combination of circumstances strongly promotes the business case for large scale IGCC power plant with carbon dioxide capture. Large-scale capture of CO_2 by means of physical absorption in power plants is however not a commercially available concept. While the concept is likely to have a large potential, it remains to be proven that it in application will work within acceptable ranges of quality, reliability and cost. In other words, the technology must be qualified.

In the technology classification it was seen that the pre-combustion capture of CO_2 in the power plant has been given the highest ranking because of the fact that this technology is commercially not available.

Hazop and FMECA are important steps in the IGCC with CO_2 capture reliability analysis, as they can serve as a platform and basis for further analysis. Also, the results from the FMECA and Hazop can be interesting for determining how the failures propagate through the system and their failure effects on the operation of the process. From the FMECA performed in this work, it can be seen that the gas turbine is the most critical equipment in an IGCC plant. One of the reasons for this is the process integration between the power island and the pre- combustion process. For example, the gas turbine feeds air to the enriched air blown gasifier and receives fuel from the pre-combustion process. This integration has an effect on the overall reliability of the system. In addition to integration issues, the gas turbine technology is less mature for syngas than for natural gas.

The selection of the qualification activities for the identified failure modes of concern obtained from FMECA, Hazop analysis and novel elements of the technology was done. For the case of gas turbine it was suggested that the adjustment of air flow of compressor of the gas turbine should be done in order to avoid the surge problem of the compressor. Maintaining proper steam to carbon ratio was recommended as a qualification activity for the deactivation of shift reactor catalyst.

For the steam turbine, removal of the solid particle from water was chosen as a qualification activity. Recommendation of maintaining proper CO composition and temperature has been done so that metal dusting in heat exchanger can be avoided. For CO_2 absorber it can be seen that the maldistribution of the solvent can be avoided by the maintaining proper distribution of the solvent with the help of distributor and packing development.

Confirmation of the fact that the qualification activities have been performed and the acceptance criteria have been met was done by performing the performance assessment step in the technology qualification procedure. The main purpose of this step was to quantify the overall performance of the each equipment.

Performance assessment of the heat exchanger was done by analyzing outlet temperature of hot stream profile, approach temperature profile, log mean temperature difference, heat load profile and time series of overall heat transfer coefficient. Performance assessment of the HRSG was done by analyzing the variations in gas and water flow rates, pressure and gas composition, fouling of heat transfer surfaces, heat transfer rate and pressure losses, geometry of heat exchanger. For the case of enriched air blown gasifier it was suggested that the performance assessment can be done by online coal quality analysis, reliable optical access to the gasifier, trustworthy gasifier temperature measurement. Performance of the steam turbine can be assessed by the periodic acquisition of repeatable performance data. Proper evaluation and assessment of performance should be done for steam turbine so that deterioration can be detected, in a cost effective manner.

At the last but not the least concept improvement step was performed in order to improve the failure modes of concern by implementing qualification plan.

5.2 Future work:

A more in depth study and analysis of Risk assessment of IGCC with CO_2 capture with the involvement of the relevant experts should be done. It will be quite interesting if activates like FMECA and Hazop analysis are carried out in a systematic way like conducting workshops with relevant experts. It is of crucial importance that the qualifications of these experts include the disciplines necessary to understand the potential failure mode of the technology. More attention should be paid while selecting and identifying the activities for the qualification for the failure modes of concern as it is very time consuming and capital intensive. Experts of air separation unit, gasifier, heat exchanger, CO_2 absorber, H_2S absorber, Steam turbine, Gas turbine, Heat recovery steam generator, compressors should be involved while identifying failure modes of concern and purposing a qualification plan for these failure modes.

Economic parameters should also be taken into consideration while selecting the qualification activities and checking the performance of specific equipment. It should also be taken into account that there is no unnecessary overlap between the qualification activities as it is extremely capital intensive.

Last part of the technology qualification (performance assessment) should be carried out in full detail by applying different system reliability assessment techniques or by carrying out Quantitative Risk assessment. Investigation of future technologies and technology advancements, such as membrane reforming reactor, sorption enhanced reforming, membrane water-gas shift reactor, and sorption enhanced water-gas shift could be of interest.

This thesis work is a beginning of a “Start” for the technology qualification of IGCC power plant with CO_2 capture.

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.

Appendix A

Table 21: Fuel and transport gas specification for fuel preparation shell gasifier case

Fuel		
Temperature (^{0}C)	25	
Mass Flow (ton/hr)	92.9	
Mass Flow(ton/day)		
(Composition,wet,ash free)		
Carbon	46.47	atomic %
Hydrogen	46.71	atomic %
Oxygen	5.4	atomic %
Nitrogen	.6973	atomic %
Sulfur	.7253	atomic %
Ash in	9.94	weight %
Fuel Transport Gas (Nitrogen)		
Compressor inlet Temperature (^{0}C)	15	
Compressor inlet Pressure (Bar)	2.5	
Compressor exit Pressure (Bar)	35.79	
Compressor exit Temperature (^{0}C)	113.5	
Uncompressed stream mass Flow (ton/hr)	2.36	
Compressed stream mass flow (ton/hr)	7.09	

Table 22: Material balance of IGCC with CO_2 capture shell gasifier case

Stream#	T(^{0}C)	P(bar)	Mass flow Rate (ton/hr)	MW	O_2 (Vol%)	CO_2 (Vol%)	H_2O (Vol %)	N_2 (Vol%)	Ar (Vol%)	SO_2 (Vol%)	COS (Vol%)	CH_4 (Vol%)	H_2 (Vol%)	H_2S (Vol%)	CO (Vol%)
3	15	1.0321	363.4		20.74	.03	1.011	77.29	.93	0	0	0	0	0	0
4	20	5.175	363.4		20.74	.03	1.011	77.29	.93	0	0	0	0	0	0
5	15	2.53	2.36		0	0	0	100	0	0	0	0	0	0	0
6	15	2.53	2.36		0	0	0	100	0	0	0	0	0	0	0
7	113.5	35.79	7.079		0	0	0	100	0	0	0	0	0	0	0
8	15	2.53	87.91		95	0	0	3.5	1.5	0	0	0	0	0	0
9	118.7	41.6	87.91		95	0	0	3.5	1.5	0	0	0	0	0	0
10	15	5.175	266		0	.0379	1.339	97.82	.79	0	0	0	0	0	0
11	900	33.32	362.1	19.39	0	1.7	54.2	2.5	.0028	0	.029	.0051	13.63	.42	27.2
12	350	33.32	439.7	20.81	0	3.5	7.034	5.1	.44	0	.064	.0032	27.66	.86	55.21
13	350	33.32	439.7	20.81	0	3.5	7.034	5.1	.44	0	.064	.0032	27.66	.86	55.21
14	353.8	34	248.4		0	3.5	7.034	5.1	.44	0	.064	.0032	27.66	.86	55.21
15	350	33.32	191.3	20.81	0	3.5	7.034	5.1	.44	0	.064	.0032	27.66	.867	55.21
17	260	33.32	359	19.91	0	39.14	.2148	3.5	.30	0	.0008	.0022	54.46	.62	.74
18	174.5	32.84	358.7		0	39.14	.2148	3.5	.30	0	.0008	.0022	54.46	.62	.74
19	146.6	31.75	308		0	39.14	.2148	3.5	.30	0	.0008	.0022	54.46	.62	.74
20	37.87	30.47	269.9			39.14	.2148	3.5	.30	0	.0008	.0022	54.46	.62	.74
22	35	30.47	52.68	6.136	0	5.19	.0339	5.5	.48	0	.0013	.0035	87.56	.0099	1.182
23	255	29.99	52.68	6.136		5.198	.0339	5.5	.48	0	.0013	.0035	87.56	.0099	1.182

Table 23: Energy balance of IGCC with CO_2 capture shell gasifier case

Power Block Energy In	
Ambient Air Sensible(KW)	6695
Ambient Air Latent(KW)	6652
Process Return and make up(KW)	2731
Gasifer Energy In	
Gasifer Fuel Enthalpy(KW)	762386
Syngas Recirculation Compressor Power	443.9
Gas clean up system energy In	
Scrubber Water(KW)	2664.8
Air Separation Unit Energy In	
Ambient Air Sensible and latent heat(KW)	3126

Power Block Energy Out	
Energy Out (KW)	784455
Net Power Out put(KW)	273867
Stack Gas Sensible(KW)	54303
Stack Gas Latent(KW)	101123
GT Cycle Losses	5603
Condenser	189837
Steam Cycle losses	5612
Non.Heat Balance Auxiliaries	6227
Transformer Losses	1684.1
Gasifer energy Out	
Heat losses(KW)	338.8
Slag(KW)	9597
Syngas Recirculation Compressor Mech./Elec.Losses	44.39
Gas Clean up system Energy Out	
H2S Removal(KW)	13462
Water Condensed from syngas(KW)	10447
CO2 capture and Acid gas heat Rejection(KW)	39705
CO2 Capture and Acid Gas Heat losses(KW)	8152
Cooler heat Rejection to external Sink(KW)	41368
Air Separation Unit Energy Out	
Discharge Gas(KW)	2685.8
Heat Rejection from Compressor (KW)	24677
Compressor Mechanical and electrical losses(KW)	1450.8
ASU Heat Rejection to External Sink(KW)	544.3

Table 24: Plant summary of IGCC power plant oxygen blown gasifier case

IGCC Summary	
Plant total power out @generator terminal (KW)	336813
Total Auxiliaries losses (KW)	62946
Plant net power out put (KW)	276869
Plant LHV heat rate @generator terminal (KJ/kWh)	7773
Plant HHV heat rate @generator terminal (KJ/kWh)	8132
Plant Efficiency	
PURPA Efficiency, LHV (%)	37.6
PURPA Efficiency, HHV (%)	36
Plant Net LHV heat rate (KJ/kWh)	9560
Plant Net HHV heat rate (KJ/kWh)	10001
Plant LHV electrical efficiency@ generator terminal (%)	46.31
Plant HHV electrical efficiency@ generator terminal (%)	44.27
Plant net LHV electrical efficiency (%)	37.6
Plant net HHV electrical efficiency (%)	36
Gas Turbine Performance	
Gross Power Out Put (KW)	200653
Gross LHV efficiency (%)	39
Gross LHV efficiency (%)	33
Gross LHV heat rate (KJ/KWh)	9217
Gross HHV heat rate (KJ/KWh)	10866
Exhaust Mass Flow (ton/hr)	1638
Exhaust Temperature (^{0}C)	636.7
Fuel Chemical LHV input (25 ^{0}C)	513703
Fuel Chemical LHV input (25 ^{0}C)	605649
Steam Cycle Performance (LHV)	
HRSG (efficiency) (%)	85
Steam Turbine Gross Power (KW)	136160
Internal Gross Efficiency (%)	49.5
Overall Efficiency (%)	42
Gasifer	
Name	Shell(Oxygen Blown)
Pressure(Bar)	34
Gasifier Temperature (^{0}C)	1550
Gasifier Efficiency (Cold Gas Efficiency)(%)	80
Fuel mass flow (ton/hr)	94.5

Appendix B

Table 25: Fuel and transport gas specification for fuel preparation Mitshusbhi gasifier case

Fuel		
Temperature (^{0}C)	25	
Mass Flow (ton/hr)	89	
Mass Flow(ton/day)		
(Composition,wet,ash free)		
Carbon	46.47	atomic %
Hydrogen	46.71	atomic %
Oxygen	5.4	atomic %
Nitrogen	.6973	atomic %
Sulfur	.7253	atomic %
Ash in	9.94	weight %
Fuel Transport Gas (Nitrogen)		
Compressor inlet Temperature (^{0}C)	15	
Compressor inlet Pressure (Bar)	2.5	
Compressor exit Pressure (Bar)	34.88	
Compressor exit Temperature (^{0}C)	112.4	
Uncompressed stream mass Flow (ton/hr)	2.2	
Compressed stream mass flow (ton/hr)	6.6	
Total mass flow (ton/hr)	8.9	

Table 26: Material balance of IGCC with CO_2 capture enriched air blown gasifier

Stream#	T(^{0}C)	P(Bar)	Mass flow Rate	MW	O_2 (Vol%)	CO_2 (Vol%)	H_2O (Vol%)	N_2 (Vol%)	Ar (Vol%)	SO_2 (Vol%)	COS (Vol%)	CH_4 (Vol%)	H_2 (Vol%)	H_2S (Vol%)	CO (Vol%)
4	15	1.0131	121.2		20.74	.03	1.011	77.29	.93	0	0	0	0	0	0
5	20	5.171	121.2		20.74	.03	1.011	77.29	.93	0	0	0	0	0	0
6	15	2.585	7		0	0	0	100	0	0	0	0	0	0	0
7	112.4	34.88	7		0	0	0	100	0	0	0	0	0	0	0
8	15	2.585	2.36		0	0	0	100	0	0	0	0	0	0	0
9	15	2.585	29.3		95	0	0	3.5	1.5	0	0	0	0	0	0
10	120.5	43.6	29.3		95	0	0	3.5	1.5	0	0	0	0	0	0
11	15	1.013	1585.3	28.856	20.74	.03	1	77.29	.93	0	0	0	0	0	0
12	402.8	17.78	219.9		20.74	.03	1	77.29	.93	0	0	0	0	0	0
13	402.8	17.78	219.9		20.74	.03	1	77.29	.93	0	0	0	0	0	0
14	612	43.6	219.9		20.74	.03	1	77.29	.93	0	0	0	0	0	0
15	1100	34.88	348.7	23.51	0	1.689	1.83	42.46	.57	0	.03	.33	17.94	.54	34.59
16	350	34.18	348.7		0	1.689	1.83	42.46	.57	0	.03	.33	17.94	.54	34.59
18	284.7	34.18	525.1		0	26.91	.20	32.08	.43	0	.0005	.24	39.16	.20	.52
19	161.3	33.46	522.7		0	26.91	.20	32.08	.43	0	.0005	.24	39.16	.20	.52
20	137.1	32.6	474.6		0	26.91	.20	32.08	.43	0	.0005	.24	39.16	.20	.52
21	37.78	31.48	435.2		0	26.91	.20	32.08	.43	0	.0005	.24	39.16	.20	.52
23	35	31.48	218.7	14.9	0	3.026	.027	42.92	.57	0	.0007	.34	52.4	.0058	.69
44	279.7	30.76	218.7		0	3.026	.027	42.92	.57	0	.0007	.34	52.4	.0058	.69
45	642.5	1.043	1584.2		10.52	0	13.53	73.98	.90	.0016	.99	0	0	0	0

Table 27: Energy balance of IGCC with CO_2 capture enriched air blown gasifier

Power Block Energy In	
Energy In (KW)	**740885**
Ambient Air Sensible(KW)	6695
Ambient Air Latent(KW)	6652
Process Return and make up(KW)	2542.7
Gasifer Energy In	
Gasifer Fuel Enthalpy(KW)	762266
Syngas Recirculation Compressor Power	
Gas clean up system energy In	
Scrubber Water(KW)	4207
Air Separation Unit Energy In	
Ambient Air Sensible and latent heat(KW)	985.3

Power Block Energy Out	
Energy Out (KW)	**740777**
Net Power Out put(KW)	262695
Stack Gas Sensible(KW)	54601
Stack Gas Latent(KW)	98135
GT Cycle Losses	5460
Condenser	183116
Steam Cycle losses	5483
Non.Heat Balance Auxiliaries	6760
Transformer Losses	1607.7
Gasifer energy Out	
Heat losses(KW)	308.2
Slag(KW)	6241
Air Booster compressor Mech/Elec.losses	1506.8
Gas Clean up system Energy Out	
H2S Removal(KW)	12709
Water Condensed from syngas(KW)	9447
CO2 capture and Acid gas heat Rejection(KW)	39246
CO2 Capture and Acid Gas Heat losses(KW)	7755
Cooler heat Rejection to external Sink(KW)	42072
Air Separation Unit Energy Out	
Discharge Gas(KW)	822.1
Heat Rejection from Compressor (KW)	8058
Compressor Mechanical and electrical losses(KW)	478.8
ASU Heat Rejection to External Sink(KW)	170.6

Table 28: Plant summary of IGCC enriched air blown gasifier

IGCC Summary	
Plant total power out @generator terminal (KW)	321543
Total Auxiliaries losses (KW)	58848
Plant net power out put (KW)	262695
Plant LHV heat rate @generator terminal (KJ/kWh)	7686
Plant HHV heat rate @generator terminal (KJ/kWh)	8040
Plant Efficiency	
PURPA Efficiency, LHV (%)	38
PURPA Efficiency, HHV (%)	36.5
Plant Net LHV heat rate (KJ/kWh)	8040
Plant Net HHV heat rate (KJ/kWh)	9407
Plant LHV electrical efficiency@ generator terminal (%)	46.8
Plant HHV electrical efficiency@ generator terminal (%)	44.7
Plant net LHV electrical efficiency (%)	38
Plant net HHV electrical efficiency (%)	36.5
Gas Turbine Performance	
Gross Power Out Put (KW)	190546
Gross LHV efficiency (%)	37.6
Gross LHV efficiency (%)	31.9
Gross LHV heat rate (KJ/KWh)	9564
Gross HHV heat rate (KJ/KWh)	11263
Exhaust Mass Flow (ton/hr)	1584
Exhaust Temperature (^{0}C)	642.5
Fuel Chemical LHV input (25 ^{0}C)	506237
Fuel Chemical LHV input (25 ^{0}C)	596156
Steam Cycle Performance (LHV)	
HRSG (efficiency) (%)	84.4
Steam Turbine Gross Power (KW)	130996
Internal Gross Efficiency (%)	48.8
Overall Efficiency (%)	41
Gasifer	
Name	Enriched air blown
Pressure(Bar)	34.88
First Stage Gasifier Temperature (^{0}C)	1815
Second Stage Gasifier Temperature (^{0}C)	1100
Gasifier Efficiency (Cold Gas Efficiency)(%)	83
Fuel mass flow (ton/hr)	89.2

Appendix C

Table 29: Technology classification

Subsystem	Equipment	Function	Application			Technology			Classification
			Known	L.knowledge	New	Known	L.knowledge	New	
ASU System	ASU	Separate O_2 & N_2 from air	x			x			1
Gasification	Gasifier	Produce syngas	x			x			1
Gas Clean up System	Scrubber	Remove Contaminant	x			x			2
Gas Clean up System	Shift Reactor	Convert CO to CO_2	x			x			2
Raw Syngas Cooler	Heat exchanger	Cool syngas	x			x			1
Gas Cleaning System	Heat Exchanger (2)	Cool Syngas	x			x			1
Gas Cleaning System	Heat Exchanger (3)	Cool Syngas	x			x			1
Gas Cleaning System	Heat Exchange (4)	Cool Syngas	x			x			
Absorption	CO_2 Absorber	Remove CO_2			x			x	3
Absorption	H_2S absorber	Remove H_2S			x			x	3
Absorption	Stripper	Remove CO_2 from solvent			x			x	3
Power Block	Gas Turbine	Produce Power		x			x		2
Power Block	Steam Turbine	Produce Power		x			x		2