ASIA TURBOMACHINERY & PUMP SYMPOSIUM

TURBOMACHINERY FOR HIGH CO2 APPLICATION: CHALLENGES, OBSTACLES AND LESSON LEARNT

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ABSTRACT

Turbomachinery is the heart of any platform, which generates power and compresses gas. However, the current practices of turbomachinery are entangled with various challenges and obstacles, which eventually affect the overall performance of the platform. Hence, this paper aims at appraising the challenges and obstacles in turbomachinery application for high CO_2 application. This paper aims to achieve objectives: (1) reviewing the oil and gas industry in terms of its operation and project execution; (2) determining the basic attributes of turbomachinery as well as the challenges and obstacles entangling its execution; and (3) proposing the solutions to these challenges and obstacles. It is found that stabilized process requirement and constant flow; subsurface uncertainties; production decline; selection process; specification and standard variations; contractual delivery; human factor; after sales support and services; and expenditure are listed among the challenges and obstacles in executing turbomachinery project for oil and gas. The findings of this paper would technically contribute to the project management elements of turbomachinery project execution and assist the management team particularly on the client/consultant side in efficiently and effectively manage the turbomachinery project execution via the prediction of challenges and obstacles.

This case study presents the issues encountered, solutions implemented, results mitigation, lessons learnt, and technical replication based on two high CO_2 application projects.

INTRODUCTION: TURBOMACHINERY PROJECT EXECUTION

Turbomachinery is the heart of any platform and processing facilities, which generates power and compresses gas. It is by definition; a turbine driven package utilized for either mechanical drive or power generation application. It is by far the most critical equipment in any oil and gas facilities ranging from upstream unit to downstream refining and gas processing division. For upstream segment, it is used in exploration and production of the oil and gas or activities taking place prior to processing and refining of hydrocarbons such as Gas Injection, Gas Lift and pipeline export to onshore. As for the downstream segment, it is used in various applications in Petro-chemical plant, oil refineries, gas processing plant and gas transmission station. For the power generation application, in both segment upstream and downstream, turbomachinery is used as driver to drive electrical generator to generate electrical power for supporting life on platforms as well as utilities and process area.

The same level of criticality is applicable when any of these facilities are being built/develop, turbomachinery is the most critical equipment in any development projects. It covers both the Greenfield development and Brownfield rejuvenation projects. Due to the criticality and complexity of turbomachinery in project execution, it is marked under the critical path of majority of project. Adding complexity into this are turbomachinery in high CO_2 application, where the complexity of turbomachinery is combined with the challenges and obstacles of handling CO_2. As described by C.Wacker et al., (2012), CO_2 has a long tradition in modern industrial processes and furthermore plays an increasing role in the present discussion of the world wide climate change. Its application in oil and gas such as Carbon Capture and Storage (CCS) is vital for the industries to support effort in combating climate change. Therefore, this paper aims to address the challenges, obstacles and lesson learnt for turbomachinery in high CO_2 application.

Challenges and obstacles related to turbomachinery project execution have been a topic of discussion and study of past. Harris Abd. Rahman Sabri, Abd. Rahman Abdul Rahim, Wong Kuan Yew and Syuhaida Ismail (2016) stated that, stabilized process requirement and constant flow; subsurface uncertainties; production decline; selection process; specification and standard variations; contractual delivery; human factor; after sales support and services; and expenditure are listed as amongst the challenges and obstacles in executing turbomachinery project for oil and gas. For upstream greenfield project, the main challenges and obstacles are issues pertaining to managing subsurface uncertainties and the cost related to these uncertainties. These leads to challenges in arriving to final process parameters for the design and selection to take place. Related with it lies the challenges on cost and procurement where shaggy process parameters will always lead to difficulties in contract management and subsequently change orders which are major contributor to project cost overrun.

In brownfield project however, there is a different set of challenges such as declining production that requires greater flexibility in the design of turbomachinery packages specifically for mechanical drive unit besides accommodating footprint requirement in already congested offshore real estate. Another challenges common to either greenfield or brownfield projects is the differences between Technical Specification and Original Equipment Manufacturer Technical Deviations. As highlighted by W.G Hoppock (2002), when it comes to differences in technical requirements, most of the issues are not related the core machinery design, rather the issues linger around the auxiliaries of the turbomachinery package such as piping, instrumentations, electrical and control where normally compliance to these comes at a premium additional cost. As rightly stated, these premium additional costs will eventually impact the Total Cost of Ownership where these changes or premium request will add up to the CAPEX of the project and together with the package OPEX, it will bring about difference between OEM when comparing them throughout the commercial evaluation stage. In addition, C. M. Soares (2007) in his book "Gas Turbine, *A Handbook of Air, Land and Sea Applications*" indicates that there are three relevant factors that should also be considered such as equipment unavailability which leads to opportunity loss, and unscheduled downtime, fuel cost that depends on geographical location and driven by market factors, and finally the spare parts cost. For older turbomachinery, there is always a concern on obsolescence of spare parts that will greatly affect the performance of the turbomachinery package and OPEX related to it.

INTRODUCTION TO TURBOMACHINERY

Turbomachinery definition, according to Hasnan et al. (2004), is a turbine driven package utilized to drive either a compressor train or an electrical generator. These requirements can be differentiated between mechanical drive and generator drive. A typical turbomachinery, or sometimes known as a turbo-compressor package is shown in *Figure 1* and *Figure 2*.

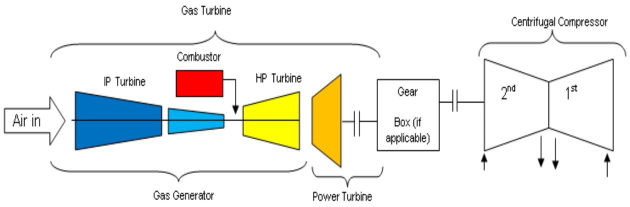

Figure 1. *Schematic of turbomachinery package*

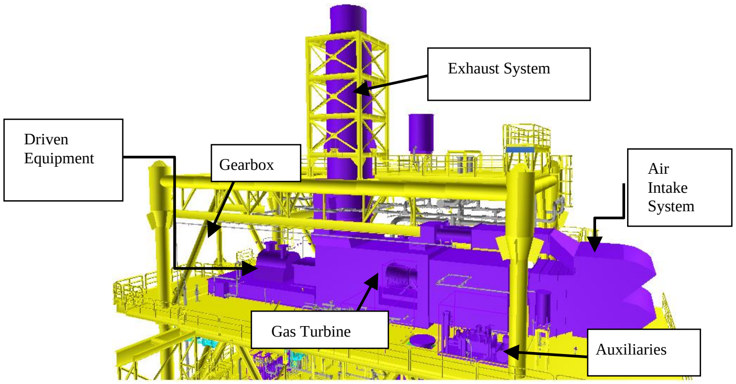

Figure 2. *Graphical representation of turbomachinery package*

As far as the oil and gas industry is concerned, there are two main functions of turbomachinery. The first function of turbomachinery is as the mechanical drive to process and compress the gas by boosting up the pressure to allow for transmission or to comply with a specific process requirement.

Generator drive on the other hand is the second function of the turbomachinery. Through this function, an electric generator is driven to generate electrical power for the specific platform/plant.

TYPICAL PROJECT EXECUTION IN OIL AND GAS INDUSTRY

Project execution in the oil and gas industry involves five different phases as summarized in *Figure 3*, namely (1) conceptual phase, (2) feasibility study phase, (3) detailed design phase, (4) material procurement phase and finally, (5) construction or start-up phase. In accordance with Will et al. (1991), these phases are varying between organizations and projects, yet the actual processes are quite similar in nature.

Figure 3. *Phases in oil and gas project execution*

In the conceptual phase, the project execution is initiated by determining the concept for the field development. Various development scenarios will be tabled out and the most optimum solution will be selected for further deliberation during the next phase. With reference to Project Management Institute (2013), the product life cycle cost should be considered as part of the selection.

The engineering is carried out during the detailed design phase, where the engineering is being detailed out based on the specification and requirement of the clients. The main deliverables also include the Approved for Construction (AFC) drawings.

Once the details of the material and equipment requisitions are developed, the next important milestone would be the procurement phase, which also includes material and sourcing activities. Depends on the nature of each project, some of the procurement processes might start earlier and hence overlap with the engineering stage, which is also known as Front End Engineering Design (FEED) or detailed design. This is due to the fact that this paper observes that turbomachinery is quite well known as one of the long lead items in the oil and gas project development.

The next phase is the construction or fabrication of the offshore platform or plant. This involves a lot of physical activities including fabrication of structures, pipings, electrical and instrumentation works; installation of equipment into its location; pre-commissioning and also proper preservation. If the facilities are located onshore, the start-up/commissioning phase will also be part of the construction works.

For offshore oil and gas projects, additional phase involved prior to the start-up/commissioning phase would be the installation of the platform, where the platform will be towed away from the fabrication yard to its designated location. Once properly installed, the work will be continued with hook-up and commissioning activities in order to obtain the final deliverables of the project. It is noteworthy to underpin that the turbomachinery involves in each of the aforementioned phases, hence is deliberately discussed in the following section.

Common challenges faced during project execution has been highlighted in various research and papers. As defined by Ajay Vyas (2019), CO_2 compressor train configuration were selected accordingly based on few factors:

- Capital Expenditure (CAPEX)
- CO_2 carbon capture production efficiency
- Overall availability of the rotating equipment and impact on total production
- Other factors include operating references (historical installation for similar application) a.k.a proven reference
- Single point responsibility and interfacing issues

ADVANCED COMPRESSION SOLUTIONS FOR CCS, EOR AND OFFSHORE CO_2

CO_2 in any industrial process application is not something new in the modern industrial process, ranging from metal industries to food industries. As per Habel (2011), it is playing an even more vital role now to address the climate change and went on further to say that nowadays, numerous industrial procedures require CO_2 not in gaseous but in a compressed state at specific pressure and temperature which means, more and more CO_2 compression project is required to address these industrial thirsts. In his same paper, he addressed the change in compression system and technology in delivering compressed CO_2 be it in industrial use or oil and gas use such as Carbon Capture & Storage (CCS) or Enhanced Oil Recovery (EOR). Traditionally these services were dominated by reciprocating machines, but due to the limitation of these reciprocating machine design, the industry is moving towards big centrifugal machines to handle higher flow and pressures. For offshore application, higher flow, and pressure for CCS and EOR means higher driving power is required where then the turbines are used as driver making these packages as one of the mechanical drive applications in turbomachinery packages. It was also recognized that in recent years, the tendency towards exploration and development of fields with more complexity as highlighted by R.T. Hill et.al (2011) which also includes high temperature, high pressure, deep water and high CO_2 fields, which may result in bigger challenges in managing the capital expenditure (CAPEX) as well as the operating expenditure (OPEX). Both considerations are vital towards the life cycle cost of each fields, and in general it is expected that high CO_2 fields would be translated into a higher life cycle cost compared to normal conventional fields.

Among factors driving the usage of turbomachinery in CO_2 applications are that reciprocating compressors are maintenance intensive; the capacity of most CO_2 recovery schemes today exceeds the range of reciprocating compressors (12kg/s). The high density of CO_2 may cause problems with high velocity valves and lastly, reciprocating machine requires massive foundation works to minimize impact from imbalance forces as compared to turbomachinery packages. For offshore application, the remedial works to counter the vibration and acoustic resonance issues related to reciprocating machines are more expensive to resolve as compared to foundation works for turbomachinery packages. Among challenges in dealing with CO_2 for upstream segments are request of very high-pressure levels to accommodate CCS and EOR.

High pressure in CO_2 application has to be carefully addressed as above the critical point, the compression will be in “supercritical region”, and as such knowledge of real gas behavior in this region is extremely important to select a turbomachinery package that will work well for its intended design. Another challenges in dealing with CO_2 compression is the gas higher molecular weight as compared to methane. While higher molecular weight enables higher compression ratio with fewer compression stages and power consumption, the impact on rotordynamic and thus a stable operation is greatly affected by the molecular weight and this needs to be address profoundly as to avoid issues throughout the design life of the machines. For CO_2 compression, as per Dekker et.al (2012), material selection is another important selection criterion which is affected by the fluid and gas exposure conditions e.g temperature, pressure, flow velocity, sand production, pH and contents of water, chlorides, potentially CO_2 and H_2S. Functional assessment such as erosion influences, corrosions, and natural strength and stiffness are required in order to qualify the material for CO_2 application.

CASE STUDY A – PLATFORM A, MALAYSIAN WATERS

Platform A is located approximately 188 kilometers offshore of East Coast Peninsular Malaysia. It consists of few gas fields. The gas from these fields contains relatively high level of CO_2 (between 30% up to 48%) with a chloride content of 50g/l as compared to the other developed gas fields in the area. Treatment and partial extraction of the CO_2 component is necessary to meet the export gas quality specifications of less than 8 mole percent CO_2 content. The processing facilities located offshore was designed to accommodate Acid Gas Removal Unit (AGRU) Facilities, Gas Compression, Main Power Generation, Utilities and Living Quarters for daily operations. These facilities are designed to handle 400 MMscfd of Full Well Stream (FWS) fluids and 3,500 bbls/day of condensate.

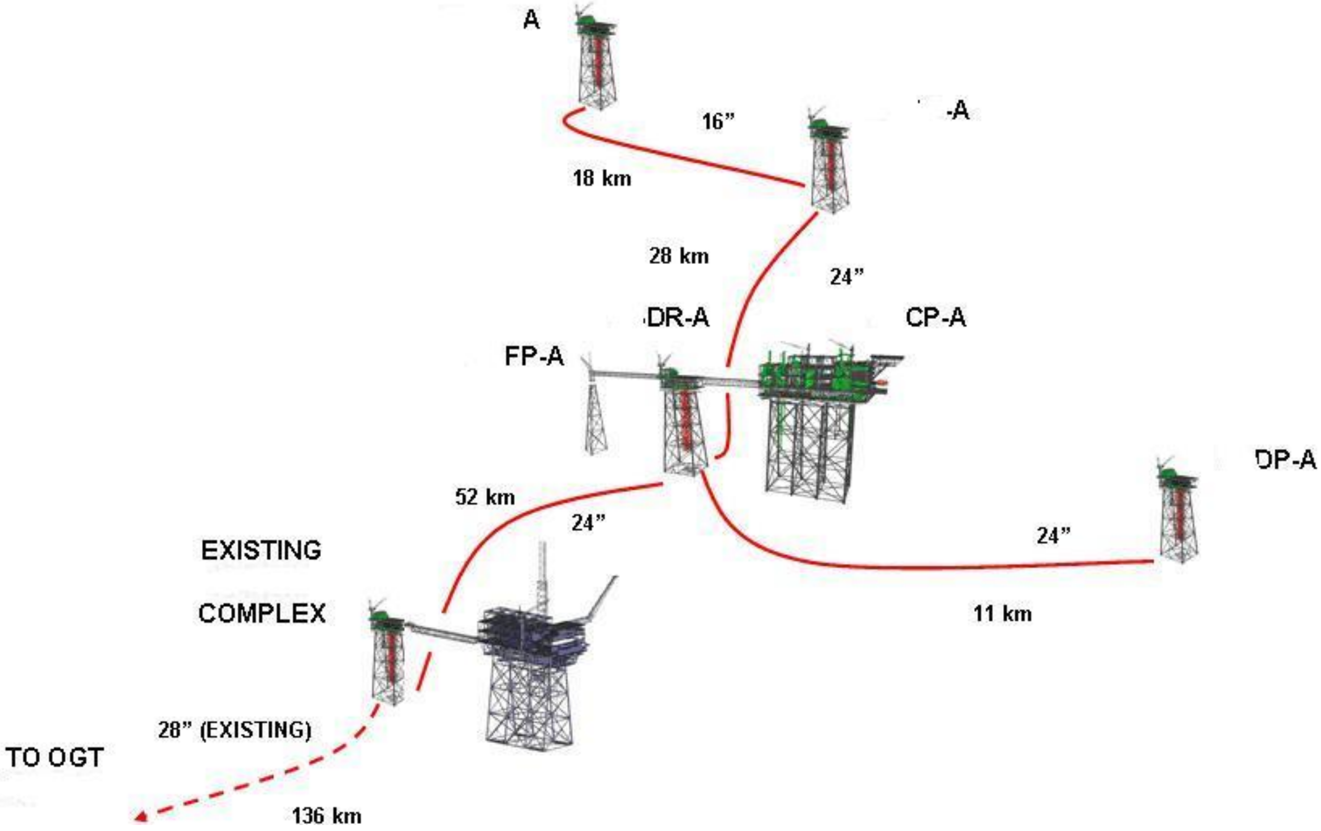

Figure 4. *Platform A Configuration*

Platform A initial study consists of options to either utilize 2x100% or 3x50% compression trains serving the purpose of Booster Compressor. These compressors are utilized to overcome pressure drop across the Acid Gas Removal Unit (AGRU) which adopted membrane technology. Figures 5 and 6 below indicate the typical schematic for both the options of the compression trains while the subsequent Figure 7 indicates the summary of required process performance throughout the design life of the field.

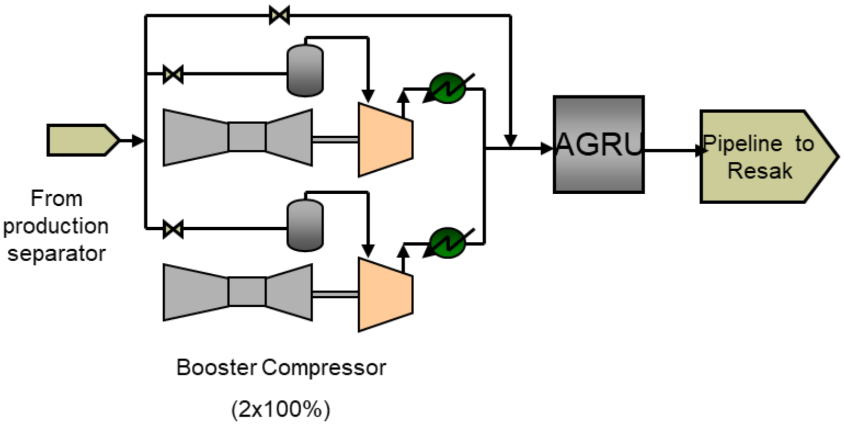

Figure 5. *Process Schematics for Platform A Booster Compression Option 2x100%*

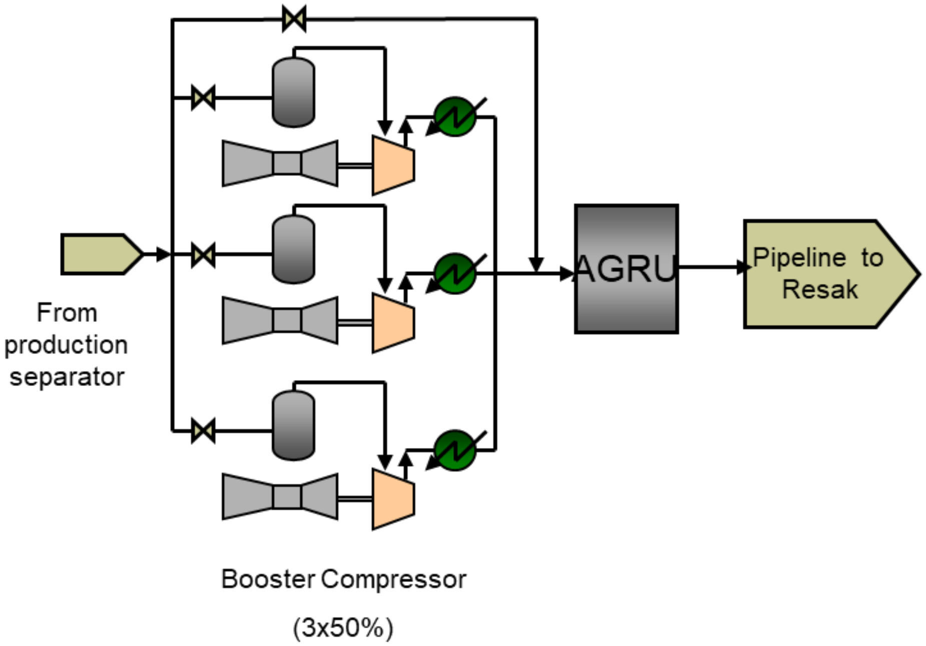

Figure 6. *Process Schematics for Platform A Booster Compression Option 3x50%*

YEAR	**Suction Pressure (psia)**	**Gas Flowrate (mmscfd)**	**Discharge Pressure (psia)**	**Compression Power For 2 x 100% (MW)**	**Compression Power for 3 x 50% (MW)**
Jan-June 2013	410	400	750	10.87	5.45
June-Dec 2013	310	400	750	16.89	8.45
2014	245	400	750	22.34	11.20
2017	245	324	750	17.5	8.75
2019	245	215	750	12.1	6.1

Figure 7. *Booster Compressor Process Requirement*

TBCP-A was the first of its kind to deploy a CO_2 separation membrane on an offshore platform. In such a scenario, this adds up to typical challenges when executing a turbomachinery projects where uncertainties of subsurface data was further coupled with requirement of membrane separation system, making it difficult to establish the sizing of the compressors and its turbine driver.

When evaluating options for turbocompressor trains in CO_2 application, the following criteria was used to assist the team in landing to optimum configuration with the best Life Cycle Cost:

i. Compression Power Requirement meeting the available turbine ranges in the market
ii. Sparing philosophy for maximum availability throughout the field life
iii. Flexibility to operation
iv. CAPEX and OPEX
v. Material selection suitable for CO2 application

Compression Power

As can be seen in Figure 7 above, for either the option, the maximum power requirement is in the year 2014; 22.34 MW per train for Option 2x100% and 11.2 MW per train for Option 3x50%. In this particular year, the gas production remains high, but the suction pressure drops significantly to 245 psia compared to initial suction pressure of 410 psia resulting in the high-power requirement. This was the first challenge in selecting the right size of turbine, balancing the requirement of early years operation, mid-years and the late life of the field power requirement. Available drivers in the market are as per Figure 8:

Gas Turbine Model	ISO Power Rating
Model A	15.7MW
Model B	18.1MW
Model C	23.2MW
Model D	26.0MW
Model E	29.0MW

Figure 8. *Available GT Range in the Market*

This specific challenge was overcome by having a selection criterion for the compressor power requirement as well as the gas turbine driver power margin as per the requirement in Petronas Technical Standard. The Figure 9 criterion was established to assist in comparison between offered Model from different OEM:

• API 617 power margin for compressor	4 %
• Unrecoverable GT losses	
i. Air compressor fouling	2%
ii. Ageing	3%
• Inlet system losses	2%
• WHRU in exhaust	2%
• Main gearbox	2%
Total	**15%**

Figure 9. *Gas Turbine Power Margin*

i. Sparing philosophy for maximum availability throughout the field life

The turbomachinery gas compression train configurations should be able to meet the CO_2 removal package inlet pressure requirement as well as the export requirement and fuel gas user pressure requirement. From the market survey conducted, there are GT drivers which can support power requirement for 2x100% train configuration as well as 3x50% train configuration. The challenges in getting the sparing philosophy right, goes back to the overall configuration study including the CAPEX and OPEX. The configuration is then supported by RAM study conducted to verify whether the proposed configuration can meet targeted reliability and availability.

Figure 10 indicates the criterion used to compare between the two options of sparing philosophy in assisting the project to achieve the optimum spare trains. These criteria are an excerpt of the overall CAPEX and OPEX which will be deliberated in later part of the paper. Figure 10 indicates the impact of different sparing philosophy to the footprint of an offshore platform and its subsequent impact to the structural cost. It's worth noting that, even though the option of 3x50% have a smaller skid size per unit, but when it is compared to overall footprint, the resulting cost is always higher for higher number of units. Having said that, 3x50% sparing philosophy have a higher availability as compared to 2x100% option but with a negligible impact of 0.04%. This low difference between the two options makes the selection are purely pivoted on the CAPEX from larger footprint.

Sparing Philosophy	2 x 100%	3 x 50%
Total Overall Footprint for Entire System, m^2	329.2	349.5
Total Dry Weight for Entire System, MT	866	831
Structural Cost (Million USD)	9.73	10.10
Availability (%)	99.94	99.98

Figure 10. *Comparison between Option 2x100% and 3 x 50% Compression Configuration*

ii. Flexibility to operation

Another challenge in selecting turbomachinery package for high CO_2 application is to have a unit which is flexible to operate. This covers broad ranges of items such as familiarity of operators to the units being procured or in other words, installation base of the units within the operation fleet, the flexibility to operate with certain amount of CO_2 in the fuel gas, sparing of the trains which have been elaborated in earlier section of the paper, familiarity in handling high CO_2 gas, availability of spare parts to support the machine for its intended design life and requirement for re-wheeling during the design life of the compressor. The main challenge for the project was related to familiarity with CO_2 in the process stream while other considerations such as spare parts and familiarities of the proposed OEM model were well within the operation knowledge.

Fuel gas system for the project was designed to utilize gas stream downstream of the CO_2 separation membrane and hence was having max 8% CO_2 in the fuel gas as part of the sales gas specification. These was well within all the OEM models available in the market hence no modification was required on the Gas Turbine section, giving flexibility to operation team. The compressors on the other hand do have to utilize special material to handle CO_2 and this will be discussed separately in a later part of the paper.

Another important factor to consider when considering flexibility of operating turbocompressor packages for upstream is requirement of re-wheeling during the mid-life operation of the compressor. For the 2x100% configuration, the proposed compressor model by OEM had a wider range of operating envelop covering entire field life operating requirement. However, the 3x50% configuration does not have such flexibility thus requires a mid-life bundle change out which have an impact to production and reduce flexibility of operation.

iii. CAPEX and OPEX

The main challenge in any turbomachinery project execution is to ensure the CAPEX and OPEX are adequately captured and that it is well within the project economics. For high CO_2 application, this became extremely important as projects with high CO_2 in its process stream have to deal with costly special material to ensure reliability of the equipment. A holistic CAPEX and OPEX study will avoid any variation orders during project execution related to the machine design as well as changes related to operation of the equipment. The challenge is overcome by having criteria that detailed out CAPEX and OPEX from all angles and shown in Figure 11 were the criteria used to conclude Total Life Cycle cost for the project:

Item	**Description**
A	**CAPEX**
A1	Engineering – Includes Material Selection Study for High CO_2 application
A2	Procurement Piping Structural Major Equipment - Turbocompressor ■ Control system ■ Switchgear/transformer/MCC ■ UPS/Batteries ■ Field Instrument ■ E&I Cables ■ Fire & Safety Equipment ■ Critical Spares i.e Rotor Bundle

Item	**Description**
B	**OPEX**
B1	Operation ■ Fuel gas (mmsfcd/unit) at USD/Mmbtu Maintenance ■ Compressor Re-Wheeling ■ Manhours/Manpower
B2	Maintenance ■ Operating spares ■ Annual maintenance, inspection, Engine Changeout, LTSA ■ Periodic Overhaul/refurbishment ■ Training

A3	Fabrication Module Piping Structural Equipment inclusive installation, pre-commissioning		**TOTAL OPEX**
A4	Installation and hook-up (modules) Load out, seafasteining and transportation Installation (including mob/demob) HUC		
	Total (A1+A2+A3+A4)		
	Project Management Import Duties Insurance & Certification		
	TOTAL CAPEX		
GRAND TOTAL = CAPEX + OPEX			

Figure 11. *Total Life Cycle Cost elements*

iv. Material selection suitable for CO_2 application

Turbomachinery project execution for high CO_2 have an additional challenge on material selection which are normally absence in other upstream projects. Special care shall be taken to ensure material specification for parts in contact with high CO_2 gas is suitable for prolonged exposure or contact with the gas. These parts are the compressors internals, dry gas seals system and fuel gas system for the gas turbine package.

The first step to ensure material suitability is to specify the requirements clearly in the project technical specifications. The material shall be suitable for sour wet gas service as per NACE MR 0175. Typically, for a 25% - 48% saturated CO_2, with a 50g/l chloride content, the material shall contain as minimum 13% Chromium and 4% Nickle. Among other challenge is to ensure accuracy in gas composition to which gas analysis shall be performed to make sure there are no other elements presents such as water, chloride and H_2S. Having these additional elements will greatly impact the material selection and subsequently having impact on the lead time and CAPEX. On the other hand, ignoring these elements will have a much severe impact as then the material selected will not be able to withstand the design life of the compressor package. Figure 12 indicates options available for main components of the compressor in high CO_2 application.

Components		Option 1	Option 2	Option 3
Casing	Nozzle	ASTM A 216 (WCC Quenched & Tempered)	ASTM A 216 with Internally clad of SST309	ASTM A 352 CA-6NM (Reduced Hardness)
	Casing & Cover	ASTM A 765 Gr. II Forging		ASTM A 352 F-6NM (Reduced Hardness)
Shaft		ASTM A 688 STL	AISI 403 SST (12%Cr) Forging	ASTM 705 (17-4 ph) SST
Impellers		1st & 2nd Stage Impellers: AISI 403 SST Other stages: USS T-1 (ASTM A514)	AISI 403 SST (12%Cr) for all stages	ASTM 705 (17-4 ph) SST
Diaphragms & Guide Vanes		ASTM A514	ASTM 176 SST (12.5% Cr)	ASTM 705 (17-4 ph) SST
Fasteners		ASTM A193 Gr. B7 CST	ASTM A193 Gr. B6 410 SST	
Dry Gas Seals Metallic Components		ASTM 410 SST Plate	ASTM 705 (17-4 ph) SST Plate	

Figure 12. *High CO_2 compressor material selection*

CASE STUDY B – PLATFORM B BOOSTER COMPRESSION PLATFORM

The development of a new Platform B Booster Compression has been identified within Location X to support the existing facilities to be ready for operation within certain number of years. The Booster Compression Facilities will enable the Location X landing pressure to be reduced to approximately 150 psia, hence lowering the wellhead abandonment pressure and allowing for increased gas reserves recovery. The new platform will be bridge-connected at North East of existing central processing platform. The feed gas will then be routed existing platform to the new Platform B Booster Compression, where the gas will be compressed to approximately 770 psia. The higher pressure gas will then be routed back for normal gas processing. The simplified process flow diagram for the Platform B Booster Compression Facilities is shown (red) in Figure 13.

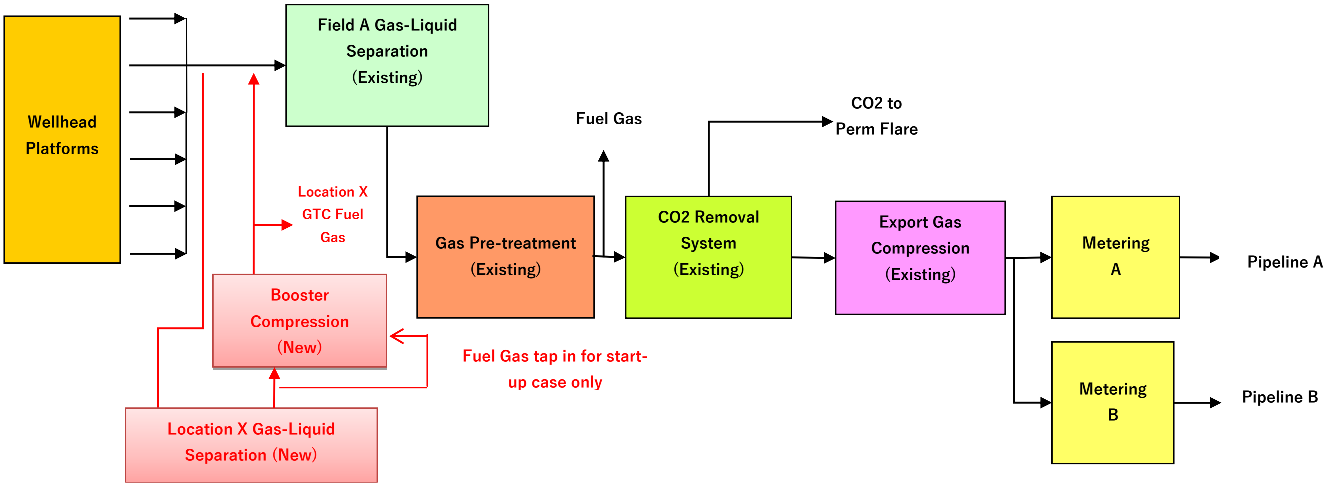

Figure 13. *The simplified process flow diagram for the overall Booster Compression Facilities*

The key considerations in the Platform B Booster Compression Feasibility Study are divided into 5 main categories as shown in Figure 14: -

ELEMENTS	CRITERIA FOR CONSIDERATION
1. PROCESS CONDITION	Meets Process Requirement for Booster Compressor and Gas Turbine, with a minimum of 10% power margin and capability to start up using 37% CO_2 fuel gas. Chloride content for design case was in the range of 100mg/litre to maximum 1000mg/litre.
2. HISTORICAL INSTALLATION	Proven equipment with at least two units successfully operating for a minimum of 24,000 operating hours in similar offshore operations
3. EQUIPMENT DELIVERY SCHEDULE	Able to meet Required on Site (ROS) date at the nominated fabrication yard
4. OPERABILITY& MAINTAINABILITY	Production Opportunity Loss and Spare Parts interchangeability
5. TOTAL COST OF OWNERSHIP (TCoO)	Lowest CAPEX and OPEX for long term production period

Figure 14. *Key Considerations in Platform B Booster Compression Feasibility Study*

PROCESS CONDITION OF GAS TURBINE COMPRESSOR

The Gas Turbine Compressor must meet the process conditions shown in Figure 15, which is within the envelope of a typical booster compression system except for the presence of H2S and high CO2 in the process stream. The presence of H2S and CO2 not only lead to metallurgy challenges, but also prove to be challenging when it comes to gas turbine selection. For a start-up fuel gas design case, the gas turbine should be able to start with as high as 37% CO2.

PARAMETERS	DESCRIPTION		
Compressor Performance, year	*2015 – 2018*	*2018 – 2022 (Design Case)*	*2022 onwards*
P inlet, PSIA	250	170	150
P discharge, PSIA	770	770	770
Feed flowrate, mmscfd	1340	1340	1340
CO2 content, %	22 – 37 %	22 – 37 %	22 – 37 %
H2S, ppmv	25	25	25
Chloride, mg/l	Min: 100 Max: 1000		
Operating Philosophy, unit	3 + 1	4 + 0	4 + 0
Flow Per unit, mmscfd	447	337	337* & 403**

Note:- * flow for 4 units running **flow for 3 units running

Gas Turbine Performance condition	*Normal Fuel Gas*	*Start Up Fuel Gas*	*Low CO2 Fuel Gas*
Site Ambient Temperature, °C	35	35	35
LHV, BTU/SCF	703	634	778
Fuel Composition:-			
• CO2	31%	37%	22%
• Methane	60.6%	54.5%	69.8%
• Nitrogen	1.4%	1.2%	1.6%
Minimum power margin requirement	Minimum 10% for operating cases from 2015 - 2022		

Figure 15. *Platform B Process Conditions requirements*

Compressor Metallurgy

With the combination of H2S, mercury, chloride, sulphide, CO2 and wet gas in the gas stream, special care needs to be taken into account for the compressor metallurgy for various critical components to ensure resistance to various form of corrosion is understood and addressed. One of the prime importance when selecting material is to evaluate each impeller margin on water condensation curves during normal condition. If there are possibility to operate at boundary of the curves without ample margin which tends to make the gas more corrosive and erosive, then special material is required to tolerate wet condition operation. The compressor metallurgy comparison chart by OEM is shown in Figure 16.

Component	**Standard Material for non-High CO_2 compressor**	**OEM A Selected Material**		**OEM B Selected Material**		**Reason for Selected Material**
	Material type	Material	Type	Material	Type	
Casing/Head Flanges	Carbon Steel	ASTM A350 LF2, with Inconel cladded	Carbon Steel	ASTM A216 Grade WCC or ASTM A-765 Gr.II Forging (with SS cladded)	Carbon Steel	Inconel or SS Cladding for gas path
Intake Wall	Carbon Steel	ASTM A182 F6NM, with ENP coating	Stainless Steel	ASTM-176 SST (12.5% Cr Martensitic)	Stainless Steel	Standard material not suitable for wet CO2, H2S and Chloride
Diaphragm	Carbon Steel	ASTM A182 F6NM	Stainless Steel	ASTM A 516 or ASTM A 514	Carbon Steel	
Shaft	Carbon Steel	AISI 4340	Stainless Steel	ASTM A-668 Class M	Carbon Steel	Standard material for shaft. No direct contact with gas
Labyrinth Seal	Aluminium	Arlon 1260 PEEK	PEEK	Arlon 1260 PEEK	PEEK	Aluminium is prone to mercury attack, thus PEEK is the suitable material
1st Impeller of 1st and 2nd Section	Carbon Steel	Virgo 38, with IP88 coating	Stainless Steel	AISI 403 SST (12% Cr Martensitic)	Stainless Steel	Standard material not suitable for wet CO2, H2S and Chloride.
All other impellers	Carbon Steel	Virgo 38	Stainless Steel	USS Carrilloy T-1	Carbon Steel	

Figure 16. *Compressor Metallurgy*

CONCLUSION AND WAY FORWARD

Based on both case studies, the selection criteria for turbomachinery will be more less the same regardless type of projects, whether it is meant for clean gas or for high CO2 application. However, the focus will be given more towards two critical points. The first one would be on the driver side ie Gas Turbine, where the capability to start the unit using high CO2 fuel gas is vital, as well as to be able to continue to operate with the same fuel gas quality. There are ways to mitigate this such as gas blending, using alternate fuel resource for start up ie diesel, however this may add up into the overall cost of implementation due to the requirement of additional equipment and auxiliaries. As a baseline, the gas turbine should be designed to be able to handle high CO2 fuel gas as per specified according to the site requirement.

Next critical point would be the Centrifugal Compressor Metallurgy, where the selection of material to which has the right resistance towards various form of corrosion is vital. At the same time, the challenge would be to ensure that the metallurgy selection is not gold-plated, which may lead to high CAPEX. The selection will also have to strike the balance for the OPEX, where in a situation if less superior material is selected, thus it may lead towards few replacement or increase of overhaul interval during the operational lifetime of the compressor and leads to the incremental of OPEX. Thus, TCOO would play a big role in determining the metallurgy selection.

This paper has successfully achieved its objectives of (1) reviewing the oil and gas industry in terms of its operation and project execution; (2) determining the basic attributes of turbomachinery as well as the challenges and obstacles entangling its execution; and (3) proposing the solutions to these challenges and obstacles, which is beneficial as the practical reference to professionals involved directly and indirectly in the execution of turbomachinery projects for high CO_2 gas field. It is expected that for future studies, the important variables in successfully managing the turbomachinery projects obtained from those turbomachinery professionals based on specific case studies could be ranked in adding relevant information to the current turbomachinery body of knowledge.

REFERENCES

Campos M. M., Teixeira A., Von Meien O., Neto S., (2013), Advanced Control System for Offshore Production Platform, Offshore Technology Conference

Campos M. M., Grizante R., Junior L. et al, (2015), Critical Equipment Monitoring in Production Platforms, Offshore Technology Conference, OTC-26246-MS

Harris A. R. Sabri, Abdul Rahman A Rahim, Haris A Majid, 2013, Concepts of Turbomachinery Selection For Upstream Oil and Gas Facilities Project, 2nd International Conference on Mechanical, Automotive and Aerospace Engineering (ICMAAE) 2

International Standard (2016), ISO14224, Petroleum, petrochemical and natural gas industries – Collection and Exchange of Reliability and Maintenance Data for Equipment. Third Edition.

M.R. Will and D.C. Steward, “Project Management for Small Projects: A Case Study”. Society of Petroleum Engineers, SPE21701, 1991.

Project Management Institute, “A Guide to The Project Management Body of Knowledge (PMBOK Guide)” Fifth Edition, 2013.

Hasnan, N., Nazim, S. and Yusof, Y. "Challenges to Improve *Turbomachinery* Availability". SPE Asia Pacific Oil and Gas Conference and Exhibition. 18-20 October. Australia: Perth, 2004.

Habel, R. (2011). Advanced Compression Solutions for CCS, EOR and offshore CO2. *All Days*. https://doi.org/10.4043/22659-ms

Dekker, G. J., Keim, B., & Mathijssen, G. (2012). Compression solutions for CO2 Enhanced Oil Recovery. *All Days*. https://doi.org/10.2118/161163-ms

Wacker, C., & Kisor, K. (2012). Integrally geared centrifugal compressors for high-pressure CO2. *Carbon Management Technology Conference*. https://doi.org/10.7122/150951-ms

R.T Hill, F.A. Ramirez, B. Monty, G. Palanivel (2011). Material Selection Assessment for Topside Process Equipment for Production Fluids with High CO2 Content. Retrieved from http://onepetro.org/NACECORR/proceedings-pdf/CORR11/All-CORR11/1684033/nace-11118.pdf

Vyas, A. (2019). Monetization opportunity in gas processing facilities by CO2 Recovery. *Day 1 Mon, November 11, 2019*. https://doi.org/10.2118/197502-ms

Hoppock, W. G. (2002) “Evolution toward Effective Project Management in Turbomachinery Projects,” *PMI Seminars & Symposium 2002*. Pennsylvania: Newtown Square.

Soares, C.M. (2007) “Gas Turbine; A Handbook of Air, Land and Sea Application”, United States; Butterworth-Heinemann.