Integrated Risk Mapping and Benchmarking for Designing Injection Well on the First CCUS Implementation in Indonesia

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Petroleum is one of the main energy source to meet the needs of an ever-growing energy demand along with the challenge of decarbonization. It's not the only solution to this dilemma exists: Carbon Capture, Utilize, and Storage (CCUS), a technology that keep CO_2 out of atmosphere. Indonesia has great potential to implement CCUS due to its large CO_2 storage capacity. However, no potential wells were constructed and abandoned properly, whereas laying down a respective well integrity standards are crucial. To know the feasibility of CCUS project, evaluating the risk factors and mitigation plans are mandatory.
In this study, risk assessment with quantitative approach that focuses on risks associated with well barrier element uncertainties will be established based on industry standards and practices. The established well integrity risk assessment is then carried out on Well Z-TW as the first CCUS project CO_2 injection well candidate in Indonesia. The risks are calculated according to the currently available information and study results, defined as combination of consequence and likelihood. After risks are identified and resulting risk categories for each well barrier elements, mitigation plans to reduce or prevent the risks are recommended. There are two low-risk categories (wellhead and Christmas tree), one medium-risk (cement), and four high-risk (casing, tubing, packer, and annuli pressure) mainly caused by improper material selection of downhole tools. In order to deal with the associated risks, several recommendations from other fields implementation around the world are proposed to create the injection well design. This concept is effective as quick risk assessment method.
Keywords: CCUS, risk assessment, well integrity

Introduction

1.1 Background

Global demand for energy is expected to be increasing by 48% in 2050 due to population, economic, and industrial growth (Moodley & Trois, 2021). Meanwhile all of human activities at the moment, collectively each year, put about 50 billion tons of carbon dioxide up into the atmosphere (Ritchie, Roser, & Rosado, 2020). The challenge is to meet future energy demand while reducing carbon footprint. However, lowering carbon emissions is no longer enough. To limit global warming to 1.5°C and avoid the worst effects of climate change, 100-1000 $GtCO_2$ need to be removed out of atmosphere over the 21st century (IPCC, 2018). Carbon Capture, Utilization, and Storage (CCUS) is one of the most industry highlighted solutions that currently available, especially industries that inherently produce pure stream of CO_2 like oil and gas.

The fact that Indonesia has 1.5 giga metric tons storage capacity of CO_2 in depleted oil and gas fields (MEMR, 2021) is a driver for the implementation of CCUS in Indonesia. While leak-free is a key part of the acceptance of CO_2 injection and storage, those high potential wells were not constructed and abandoned according to well integrity standards that can lead to well integrity failure. NORSOK D-010 (2013) describes well integrity as "Application of technical, operational and organizational solutions to reduce risk of uncontrolled release of formation fluids throughout the life cycle of a well." If the well integrity failure happens and the wellbore function loses, the risks of injection and more serious safety problems and consequences will occur (Zhang, et al., 2020).

In a feasibility study of CCS/CCUS project, well integrity assessment along with geological risk analysis needs to be done to evaluate risk and identify uncertainties. The establishment and application of well integrity risk assessment is crucial to determine the acceptability and reliability of each parameter as well as controls required to mitigate the risk to an acceptable level.

(Patil, et al., 2021) developed a well integrity risk assessment that was limited for P&A depleted gas fields in offshore. Yet, there is no published risk management

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that is applicable in any type of wells (both for onshore/offshore and oil/gas well). Therefore, this study intends to create an established well integrity risk management. The risk matrix referring to NORSOK, ISO, and API standard evaluates risk from several well barrier elements. Under the risk matrix method, the likelihood and consequences of injection well are evaluated by expert scoring, resulting risk value, risk level, and its mitigation for each barrier. This method can help user to decide the future of CCS/CCUS project of a well.

1.2 Objective

This study aims to assessing feasibility of Well Z-TW as CO_2 injection well candidate on CCS/CCUS project from well integrity point of view using quick risk assessment method.

2. Basic Theory

2.1 Well Integrity Definition

The most widely accepted definition of well integrity is given by NORSOK D-010 (2013) "Application of technical, operational and organizational solutions to reduce risk of uncontrolled release of formation fluids throughout the life cycle of a well."

Other accepted definition is given by ISO TS 16530-2 "Containment and the prevention of the escape of fluids (i.e., liquids or gases) to subterranean formations or surface."

Or "Well Integrity is the design, construction, operation, maintenance, verification and abandonment of all well so as to ensure the flow of fluids through the design path to the surface, to isolate where required underground formations, and to reduce the risk of uncontrolled releases to as low as reasonably practicable (ALARP)."

2.2 The Importance of Well Integrity Management

Well Integrity is increasingly important to optimizing safety and operational efficiency in the oil and gas industry. It is no longer considered as an optional extra but a key element in ensuring a "license" to operate the well. It is also a vital element in the delivery of profit. Asset integrity has historically been unmanaged with a variety of different tools leading to overlaps and gaps. Therefore, effective well integrity management of its assets is essential to enable an operating company to achieve its business objectives, including production, financial, health, safety, environment, reputation, etc.

Neglecting well integrity could lead to serious accident or incident which may lead to human fatality, Company's asset, and environment. For example, BP's Macondo Accident in the Gulf of Mexico, USA (2010). This largest marine oil spill in history killed 11 workers and injured 17 others, nearly 5 million barrels of oil spilt into the Gulf of Mexico. Another example is Montara Accident in Timor Sea, Australia (2009) that occurred in total 74 days. More than 23 million litres of oil spewed uncontrollably into the ocean. These major accidents do not happen as a result of failure of one piece of equipment or one wrong action by an individual, instead, they are epitomized by a series of failures of plant, personnel functions and processes and procedures (Gouda & Aslam, 2018).

2.3 Well Integrity in CO_2 Injector Well

For CO_2 injection wells, the quality and robustness of well integrity need to be improved. CO_2-resistant design should be considered due to direct exposure of CO_2 to the well barriers including cement, casing/liner, tubing, packers, and other exposed downhole and surface equipment (i.e., wellhead and christmas tree). This is because an increase in the CO_2 content in the gas phase will lead to an increase in CO_2 in the aqueous phase and consequently a drop in pH. The carbon dioxide in water has the formula H_2CO_3 and is called carbonic acid and it is very corrosive to materials such as cement and steel. Over time, this situation can cause serious damage to downhole tubular and erode zonal-isolation integrity, necessitating costly remedial services or even abandonment of a well (Vignes, Enoksen, & Ovesen, 2010).

(Zhang, et al., 2020) summarized possible parts of well integrity failure of CO_2 injection well, as shown in (Fig. 1). Those failures caused by improper design, corrosion, and erosion can open up possible leakage pathways. They are (1) between cement and casing, (2) between cement and formation, (3) through the casing, (4) through the cement, and (5) annulus. Thus, it is necessary to evaluate long-term integrity of injector well (Vignes, Enoksen, & Ovesen, 2010).

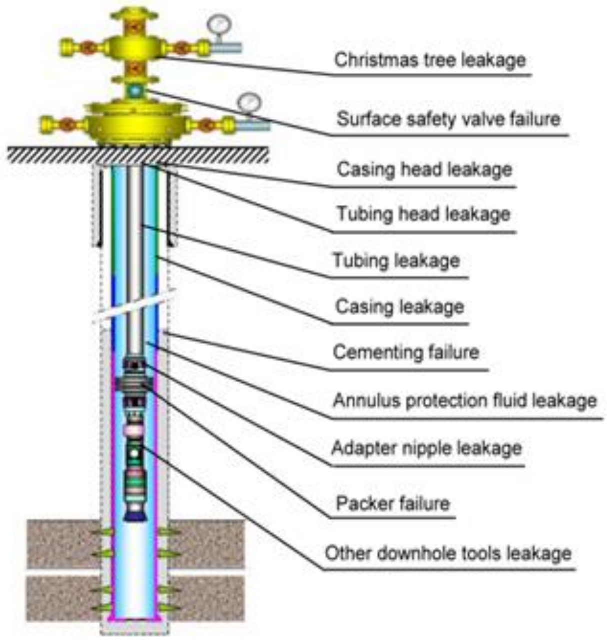

Fig. 1 Failure Risk Diagram of Injection Wells in CO_2 Flooding

2.4 Risk Assessment and Management

Risk Assessment is a procedure to determine the quantitative or qualitative value of a risk or threat to a specific situation. Risk can be defined as a combination of both the severity of the consequences of an event and the likelihood or probability that the event will occur. Risk increases with increasing severity and/or likelihood. Risk tolerance and risk rank category definitions can vary by company and location.

The effectiveness of the risk control measures should be monitored and periodically reviewed. There should be documented periodic reviews to identify opportunities for the elimination or reduction of risks and to ensure the wells remain fit for purpose.

There are three approaches for performing risk assessment: quantitative and qualitative approaches, and the combination of quantitative and qualitative called Hybrid approach. The comparison of these three approaches discussed by (Johnson, 2010); (Alhajri, Alsunaidi, Zagrouba, Almuhaideb, & Alqahtani, 2019); and (Svensson, 2017) is shown on Table 1.

Table 1
Comparison of Risk Assessment Approaches

	Quantitative Risk Assessment (QRA)	Qualitative Risk Assessment	QRA/ Qualitati-ve (Hybrid)
Defi-nition	Based on numerical probability using historical data and reliability models	Based on experience and the application of good engineering judgment	Based on known failure data, rules, procedures, and risk matrices rather than using straight qualitative or QRA analyses
Pro	Gives more accurate value	Easier to execute	Gives more credible result
Con	Limited by availability and applicability of well failure and reliability data for use in a risk model	Limited by the experience and knowledge of the people completing the assessment	May take longer to complete

3. Result and Discussion

3.1 Case Study

Considered to be one of the first CCS/CCUS injection well candidates, the established well integrity risk assessment will be carried out on Well Z-TW as part of feasibility study of the project. Well Z-TW is a twin-well with 26% of CO_2 and 1000 ppm of H_2S content, aims to produce gas of 90.44 BSCF and condensate of 0.77 MMBBL until end of contract in 2035. Drilled to a total depth of 2903 m MD, the well was spud in November 2018 and completed in January 2019 with well design consists of 30" conductor, 20" surface casing, 13-3/8" intermediate casing, 9-5/8" production casing and 2-7/8" tubing as shown in (Fig. 2).

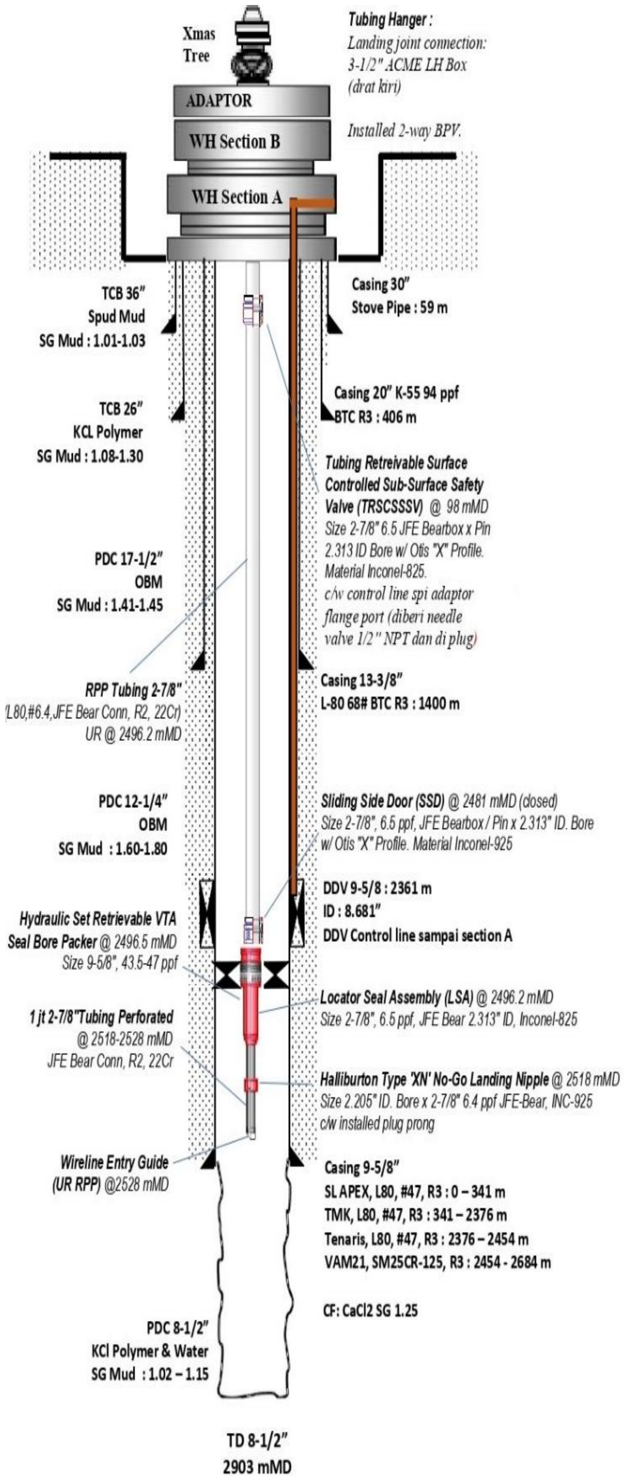

Fig. 2 Schematic of Well Z-TW

The first step in risk assessment is to get a clear picture of the Well Z-TW condition. In this case study, all required information was gathered from the given data: Well Executive Summary, Well Profile, Final Well Report (FWR), and Cement Bond Logs (CBL) result. The assumption used in this study is, the content of CO_2 injected will be 99.9%. After going through such mechanism, the well integrity risk assessment result for Well Z-TW CCS/CCUS project can be summarized in Table 2 and mapped in (Fig. 3). The most widely accepted.

Table 2

Risk Assessment Result of Well Z-TW

Failure Code No.	WBE	Risk Identification		Risk Analysis						Risk Treatment	
		Causes	Consequences	Likelihood	Consequen-ces Sqore	Likelihood Score	Risk Score	Risk Category		Risk Response	Mitigation
1	Wellhead	Cavity test seal wellhead good	Integrity of WH, valves, and seals assured by leak test	Remote	1	1	1	Low		Accept	No mitigation required
2	Christmas Tree	Leak test Christmas Tree good	Integrity of Christmas Tree, valves, and seals assured by leak test	Remote	1	1	1	Low		Accept	No mitigation required
3	Cement	Poor cemented at 2487-2638 m MD (at 9-5/8" casing) based on CBL interpretation Standard cement class	Poor cement barrier Cements not CO_2-resistant	Remote	3	1	3	Medium		Avoid or Mitigate	Perform squeeze cementing Re-evaluate material selection
4	Casing/Liner	Casing 30" Stove Pipe, Casing 20" K-55, Casing 13-3/8" L80, Casing 9-5/8" L80	Casing not CO_2-resistant	Possible	3	2	6	High		Avoid or Mitigate	Re-evaluate material selection
5	Tubing	Tubing 2-7/8" 22Cr	Tubing not CO_2-resistant	Possible	3	2	6	High		Avoid or Mitigate	Re-evaluate material selection
6	Packer	JFE Bear VTA Sealbore Packer	Packer not CO_2-resistant	Possible	3	2	6	High		Avoid or Mitigate	Re-evaluate material selection
7	Annuli Pressure	No annulus pressure data available	MAASP data unavailable**	Possible	3	2	6	High		Avoid or Mitigate	Perform MAASP calculation

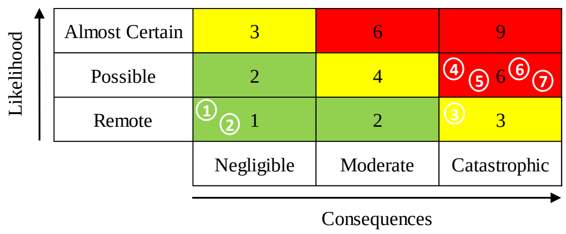

Fig. 3 Risk Map of Well Z-T

As shown in (Fig. 3), there are two well barrier elements categorized as low-risk; wellhead and Christmas tree, one category of medium-risk; cement, and the rest of them; casing/liner, tubing, packer, and annulus pressure are classified as high-risk. Risk treatment for each well barrier failure mode will be discussed further below.

It is an industry-accepted practice to require prevention or mitigation plan for well barrier with integrity anomalies. In this Well Z-TW case, workover and material reselection should be put in place to reduce the risk to the tolerance level. The use of appropriate corrosion resistant metallurgy due to unique CO_2 phase behavior is mainly highlighted here.

The wellhead and Christmas tree are categorized as low-risk since cavity test FS seal wellhead section A and B and leak test Christmas tree come with good results. CO_2-unfriendly material consequence of wellhead and Christmas tree is not considered in the established risk assessment because these surface equipment(s) do not have direct exposure to CO_2 as the subsurface(s) do. Moreover, (Smith, Billingham, Lee, Milanovic, & Lunt, 2010) claimed that standard low alloy carbon steel (AISI 4130) wellhead and Christmas tree equipment would be completely safe for a CO_2 injection well for the injection fluid is completely dry at wellhead conditions. AISI 316 stainless steel trim is recommended to ensure long-term sealing capacity. In addition, (Duncan & Hartford, 1998) recommended for those components not directly exposed like wellhead and Christmas tree can be coated with materials like Teflon. Due to Well Z-TW's high temperature, there is another possible consequence of wellhead uplift: where the wellhead would move up, becoming serious threat to wellbore integrity if the axial force as a result of excessive temperature change is higher than bearing capacity of the shear pin at the wellhead. This accident happened in the South China Sea: the Christmas tree flange was pulled off, inducing natural gas leak and other accident in the consequence of temperature effects. Therefore, wellhead equipment uplift must be studied further in cementing design to prevent damage to well integrity and surface facilities.

Well Z-TW has poor quality of the cement bond behind 9-5/8" casing above the reservoir indicated by the CBL evaluation. The cement material is also still the standard one. Well Z-TW's cement barrier is categorized as medium risk since the completion type of this well is open hole completion so any possible leakage will not probably go to the formation directly. However, further mitigation plan is needed. Squeeze cementing is the most common remediation practice in oil and gas industry used for various well leakage scenarios, it is generally performed by perforating the casing and squeezing a sealant behind the casing (Todorovic, Raphaug, Lindeberg, Vrålstad, & Buddensiek, 2016). The remedial design for 9-5/8" casing can be referred from gas well in Kurdistan region, North Iraq done by (Abdulqader & Khoshnaw, 2017). In their case, squeeze top job was done through annulus to isolate gas formation and un-squeeze top job was done through annulus with to fill the annulus between casings up to 100 m TOC. These two scenarios for minimizing risk of leakage apparently did not enough, the gas formation did not seal and the cement column penetrated by gas channeling. Further actions were taken. CBL and ultrasonic log were done to evaluate the cement behind casing and detect the gas gap in cement. Next, perforation puncher of the 9 5/8" casing below bad cement intervals was run and anti-gas chemical (Latex) was utilized to make a cover around cement slurry to prevent gas channeling. For Well Z-TW case, the squeeze cement job in the beginning is sufficient to be performed unless it has further problems. Moreover, the new cement slurry selected has to be resistant to carbon dioxide than the conventional cement (i.e., Portland cement) which is inherently alkaline and thus reactive towards acidic CO_2-saturated brine according to (Iyer, et al., 2022). API Spec 10A defines eight classes (A, B, C, D, E, F, G, and H) and three grades (O, MSR, and HSR) of standard cement system that has different temperature and pressure ranges. To increase cement matrix's capability of preventing or slowing the reaction with CO_2, the Portland cement system can be modified by adding fly ash, silica fume, or other non-reactive material e.g., Calcium Phosphate Cement (CPC) as stated by (Iyer, et al., 2022). Other recommendation of special types of CO_2-resistant cement materials analyzed by (Bai, Sun, Song, Li, & Qiao, 2015) is listed in Table 3.

Table 3

CO_2 Resistant Cements

Name	Description
Pozzolanic Portland cements	Pozzolanic materials blended with Portland cements to produce light weight slurries. The addition of Pozzolanic can reduce permeability and

	minimizes chemical attack from corrosive formation water
Micro-fine cements	Cements composed of very finely ground cements of either sulfate-resisting Portland cements, Portland cement blends with ground granulated blast furnace slag, or alkali-activated ground granulated blast furnace slag. Average and maximum particle size is 4-6 and 15 pm, respectively. These cements penetrate small fractures and harden fast
Expanding cements	Expanding or swelling cements are available primarily for improving the interface between cement and casing or between cement and formation
Latex cements	Latex cements are blends of API Class A, G or H cements with the polymer latex added. The additive may protect the cement from chemical attacks, such as formation water containing carbonic acid. Latex improves the hardened cements' bonding strength, elasticity, as well as filtration control of the cement slurry

WBE of Z-TW is categorized high-risk largely due to its improper material selection of downhole tools (i.e., casing, tubing, and packer) for implementing CO_2 storage whereas those components have higher exposure to corrosive CO_2. Based on literature study, the selected material specification requires limit of acceptance of general corrosion at ≤ 45 mm/y and 0.5 mm/y for spend acids phase (Cheldi, Piccolo, & Scoppio, 2004). Sumitomo Metals suggestion for the best material to utilize is 25% Cr since it gives the lowest corrosion rate (Fig. 4). With reservoir temperature of 300°F, the original casing grade application of casing 20" K-55, casing 13-3/8" L80, and casing 9-5/8" L80 for Well Z-TW is acceptable for all temperatures according to NACE MR0175/ISO 15156. On the other hand, that is not in line when considering the two primary corrosion mechanisms: partial pressure of carbon dioxide and hydrogen sulphide at reservoir pressure of 1500 psi and reservoir temperature of 300°F (148.9°C) as calculated in Table 4. Based on the Sumitomo Metals (Fig. 5), the best material to comply with Well Z-TW condition is SM22CR-110, 125 meanwhile Nippon Steel (Fig. 6) recommends Nickel Alloy SM2535 or SM2542 (3% Mo) to be utilized. Still, 2-7/8" Tubing 22Cr is an appropriate choice in accordance with Sumitomo standard. Note that higher CO_2 content will require higher standard in selecting corrosion resistant material for CCS/CCUS project. On Well Z-TW, with 99.9% content of CO_2 injected, 25Cr for casing and tubing material selection is preferable. The proposed packer design is, the inner mandrels and packer bodies below packer sealing element were made of Incoloy as implemented in Jedney Field in Canada for disposal of acid gas (Fig. 7). Another recommendation came up from the most widely used materials in various CO_2 injection projects in the USA (in most cases) and North Sea is summarized by (Smith, Billingham, Lee, Milanovic, & Lunt, 2010) in Table 5. After all, the decision of material selection can be different due to different standards used as reference and/or different policy and regulation owned.

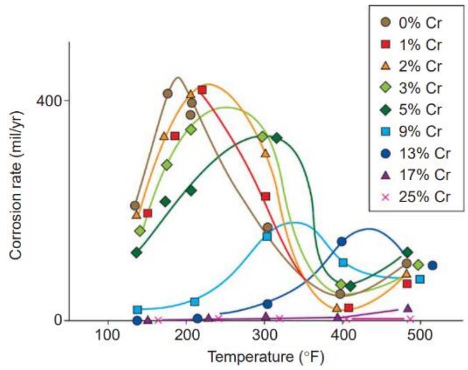

Fig. 4 Corrosion Rate as a Function of Chromium Content

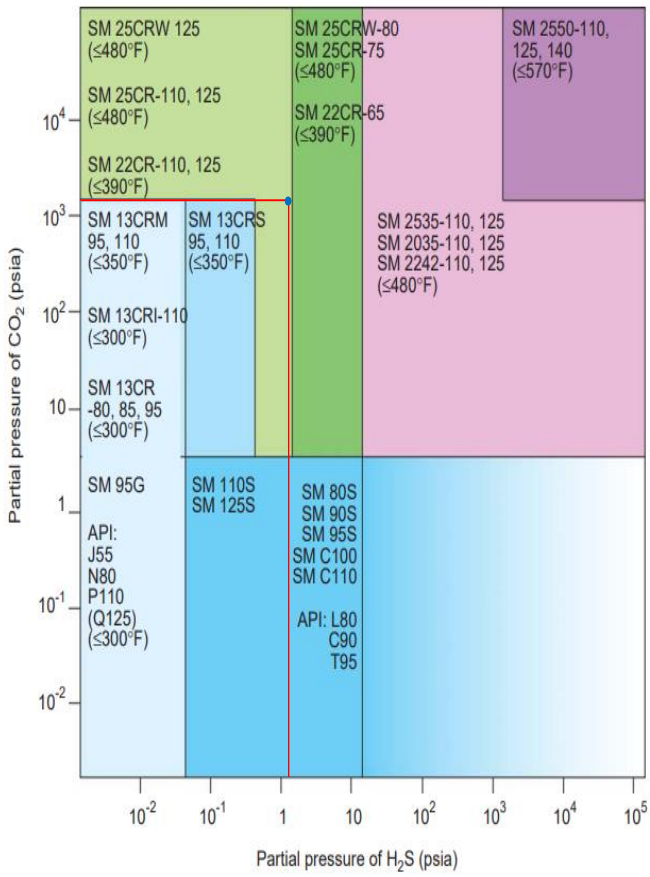

Fig. 5 Sumitomo Metals Chart for Well Z-TW Material Selection

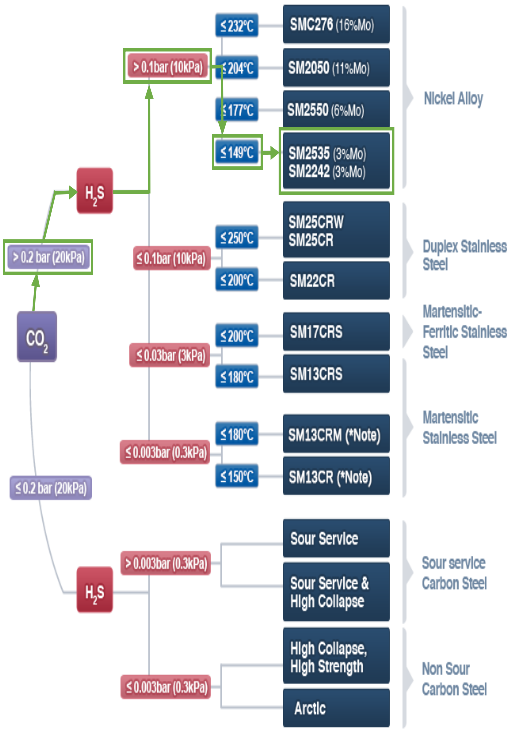

Fig. 6 Nippon Steel Chart for Well Z-TW Material Selection

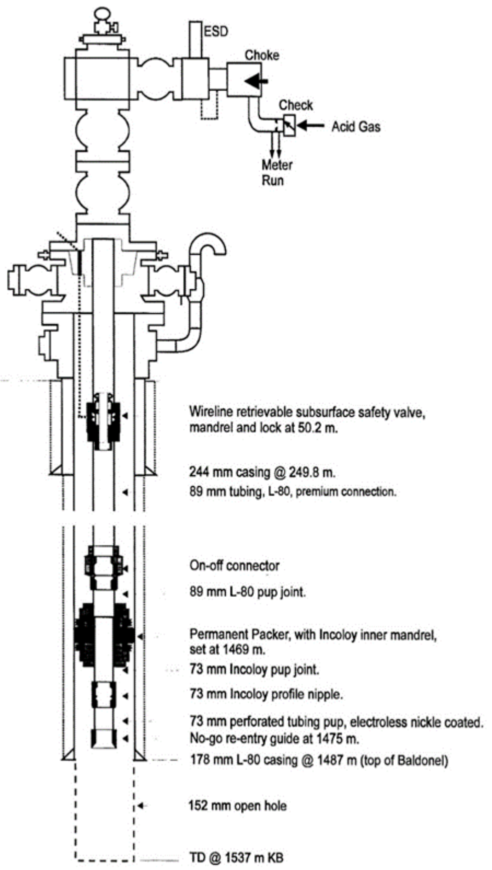

Fig. 7 Jedney a-79-J Acid Gas Injector

Table 4
Calculated Partial Pressures of CO_2 and H_2S of Well Z-TW

Gas	Content	Partial Pressure (psi)	Partial Pressure (bar)
CO_2	99.9%	1,498.5	103.3
H_2S	0.1%	1.5	0.1

Table 5
Provide the caption of your legend The Commonly Used Materials in CO_2 Injection Well Design and Construction - USA Projects

Component	Materials
Christmas Tree (Trim)	316 SS, Electroless Nickel plate, Monel
Valve Packing and Seals	Teflon, Nylon
Wellhead (Trim)	316 SS, Electroless Nickel plate, Monel
Tubing	Glass Reinforced Epoxy (GRE) — lined carbon steel: internally plastic-coated carbon steel, Corrosion Resistant Alloys (CRA)
Tubing Joint Seals	Seal ring (GRE), Coated threads and collars
ON/OFF Tool, Profile Nipple	Nickel plated wetted parts
Packers	Internally coated hardened rubber, etc. Nickel plated wetted parts: corrosion resistant alloys particularly in old wells to improve sealing to worn casings.
Cements and Cement Additives	API cements and/or acid resistant cements

Source: Reproduced from Smith, Billingham, Lee, Milanovic, & Lunt, (2010)

MAASP is defined as the maximum allowed annulus surface pressure measured at the wellhead for a specified annulus. This is a limit given for pressure on an annulus applicable for short periods (weeks). To eliminate the cause of MAASP data unavailability risk in Well Z-TW, MAASP calculation must be performed. The purpose of the MAASP calculation is to safeguard the weakest element in the pressure envelop, maintain well safety while also ensuring timely and efficient handling of well integrity issues and thereby reduce production loss. The MAASP shall be determined for each annulus of the well which is explained further in ISO 16530-1:2017(E). Besides, possible consequence regarding annulus pressure owing to Well Z-TW's high temperature that must also be investigated further is Annular Pressure Buildup (APB), where casing would be burst or collapsed on the account of high-temperature tubing fluid heating the trapped annular fluid and formation would fracture (Ma, Tang, Chen, & He, 2019).

Sets of recommendation for CCUS injection well design is illustrated in (Fig. 8).

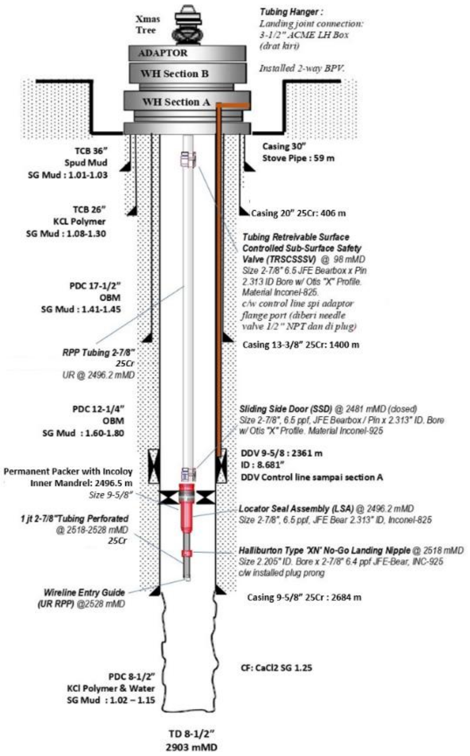

Fig. 8 Sumitomo Metals Chart for Well Z-TW Material Selection

4. Conclusion

In conclusion, feasibility of implementing CCS/CCUS on Well Z-TW as CO_2 injection well candidate has been evaluated from well integrity point of view using quick risk assessment method. The quantitative well integrity risk assessment used is accordance with recognized standards and good practice including API, ISO, NACE, and NORSOK standards. With likelihood of failure and consequence of loss of well integrity, the risk categories of each well barriers are defined, resulting two low-risk categories (i.e., wellhead and Christmas tree) and five high-risk categories (i.e., cement, casing, tubing, packer, and annuli pressure). Overall, although most likely the risk analysis result indicated that the project is not feasible, several remedial actions and well design have been recommended to reduce or prevent associated risks.

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