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Lesson learned from the assessment of planned converted CO_2 injection well integrity in Indonesia – CCUS project

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A R T I C L E I N F O

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A B S T R A C T

The risk of CO_2 leakage from carbon capture, utilization, and storage (CCUS) wells and geological storage sites must be properly assessed before the implementation of CO_2 injection. According to ISO 27914 and ISO/FDIS 27916, the design and construction of an injection well needs to guarantee safety and ability to contain the stored CO_2 over a long-term period. However, these standards alone were inadequate to evaluate the well integrity due to the need to specify criteria, duration of measurement, and range of measurement parameters of the available tools according to industries' best practices.

The methodology used in the study adapted applicable and readily-available international standards, field experiences, and lessons learned that could be used to support the construction of new and/or the conversion of existing oil and gas wells into CO_2 injection wells. This study focused on Jepon-1 in Gundih field, Indonesia, an abandoned oil and gas well. Its actual conditions, well integrity, capabilities of the equipment used in the workover and logging operations, and its limitations in checking the conditions of various crucial aspects of integrity, were evaluated. The results showed that the application of the international standards could not fulfill all the detailed requirements of integrity evaluation of the JPN-1 well due to its particular condition and situation. Other field experiences needed to be adapted, improved, and incorporated in the integrity evaluation of this well. Additionally, longer duration of measurement and more accurate and sensitive logging evaluation tools, combined with temperature logging tools, are required to detect leakage that could not be identified by the commercial tools used in this well.

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The result of this well integrity study will be used as a fundamental basis for constructing CCUS well regulations by the Government and stakeholders.

1. Introduction

One of the important parts in a carbon capture and storage (CCS)/carbon capture, utilization, and storage (CCUS) project is a well to inject the carbon dioxide (CO_2) from the surface into the subsurface formation. The well can be either a new drilled well or an existing oil and gas well converted into a CO_2 injection well. The study discusses the latter, specifically well Jepon-1 (JPN-1), an abandoned oil and gas well situated in Gundih Field, Indonesia. This well is planned for conversion into a CO_2 injection well through workover operation [1].

According to ISO 27914 [2] and ISO/FDIS 27916 [3], for either a new or a converted well from an existing oil and gas well, the design and construction of the injection well need to guarantee the safety and the ability to contain the stored CO_2 for a long-term period. The components (e.g. tubular, cement, elastomers, and surface and downhole equipment) of the injection well need to be tested and their performance shall be maintained to work properly and have the ability to withstand the operational loads and environment through the life cycle of the CCUS/CCS project. Aside from the quality of the geological storage and injected CO_2, the specific design parameter and construction basis for the CO_2 injection well affect significantly the successful of CCUS [4].

The oil and gas-converted-CCUS or any existing-converted-CCUS well possesses a higher risk of having leakage than new-constructed CCUS well during the life cycle of the well. The risk of CO_2 leakage from the CCUS well and geological storage sites must be properly assessed before the implementation of CO_2 injection [5,6]. The leakage may happen anywhere from within the geological storage, through permeable formations layers, along the existing wellbore, through failed wellbore barrier elements (WBE) or well integrity components [7], through the shallower permeable formation layers, until the surface facilities or surface leakages. According to Watson and Bachu (2009) [8], surface leakages and gas migration can be correlated with the economy, technology, geographic location, and applicable regulations. The study also showed the indication of a correlation between the surface leakage and gas migration with the top of the low-annular-cement, external corrosion, and casing/liner failure in the wellbore with consideration of factors, such as wellbore inclination, surface casing depth, and the number of wellbores in the area. This study can also be used as a reference for the CCUS well design, well conversion, and well integrity evaluation [6,9–12].

The hazard and catastrophic level of the CO_2 leakage will depend on the leakage rates and location, thus, any potential leakage pathways should be listed and assessed. The leakages are usually in the form of a certain geometry such as aperture, diameter, and

Table 1
International standards related to well integrity of a CO_2 injection well [17,18].

Standard	Title
CCUS	
ISO 27914 [2]	Carbon dioxide capture, transportation and geological storage - geological storage
ISO/FDIS 27916 [3]	Carbon dioxide capture, transportation and geological storage - Carbon dioxide storage using enhanced oil recovery (CO_2-EOR)
Well and operation management related documents	
ISO 16530-1 [7]	Well integrity — Part 1: Life cycle governance
ISO 16530-2 [19]	Well integrity - Part 2: Well integrity for the operational phase
API RP 49 [20]	Drilling and well servicing operations involving hydrogen sulfide
API RP 54 [21]	Occupational safety for oil and gas well drilling and servicing operations
Christmas tree, wellhead, casing/tubing hanger	
ISO 10423 [22]/API Spec 6A [23]	Wellhead and Christmas tree equipment
API RP 90 report (2006) [24]	Annular Casing Pressure Management for Offshore Wells
Casing/tubing and joint seals	
API Spec 5CT [25]	Casing and tubing
ISO 11960 [26]	Steel pipes for use as casing or tubing for wells
ISO 15156 [27]/NACE MR 0175 [28]	Materials for use in H_2S containing environments in oil and gas production
NORSOK M – 001 [29]	Materials selection
ISO 13680 [30]/API Spec 5CRA [31]	Corrosion-resistant alloy [CRA] seamless tubes for use as casing, tubing, and coupling stock
Cement and cement additives	
ISO 10426-1 [32]/API Spec 10A [33]	Cements and materials for well cementing
API TR 10TR1 [34]	Cement sheath evaluation
API Std 65-2 [35]	Isolating potential flow zones during well construction
Packers and related equipment	
ISO 14310 [36] API Spec 11D1 [37]	Packers and bridge plugs

Note: American Petroleum Institute (API), Final Draft International Standard (FDIS), Corrosion Resistant Alloy (CRA), International Organization for Standardization (ISO), Norsk Sokkels Konkuranseposisjon/Norwegian Standards Organization (NORSOK), Recommended Practice (RP), Specification (Spec), Standard (Std), Technical Report (TR).

Table 2
Lesson learned from several fields' experiences

Nu.	Field	Project brief description	Lesson learned regarding the critical and design criteria for well integrity
1.	Malaysian offshore mature field (carbonate formation) [38–42]*	• Gas producer wells were planned to be converted into CO_2 injector wells. • New wells were planned to be drilled as another option for CO_2 injector wells. • CO_2 injection is planned at the supercritical phase.	• Original 30-40-year-old gas producer wells were not designed for high CO_2 concentration flow. • Associated well integrity risks were acknowledged for planned conversion wells: leakage, corrosion (CO_2, H_2S, water), cement degradation (cracks, microannuli, channeling, fluid flow, and migration), unsuitable existing surface equipment and downhole completion (material strength degradation, material integrity), tubing and connection stress, and solid production (wellbore stability). CO_2 leakage scenarios due to chemical, thermal, and mechanical degradation of barriers reasons were identified and modeled. • Continuous monitoring and surveillance were recommended before, during, and after the CO_2 injection operation: seismic profile, micro-seismic, production and injection data, logging measurement (ultrasonic, cement bond log (CBL), acoustic, pressure, and temperature), CO_2 analyzer, and environmental parameter.
2.	Lacq pilot project (onshore France) [43]**	• CO_2 injection was conducted from 2010 until 2013 with more than 51,340 metric tonnes CO_2 injected through one well. The well was converted from a 43-year-old existing oil and gas well. • Post monitoring was performed from 2013 until 2016; several monitoring devices and sensors were installed in the well.	• Short and long-term well integrity aspects to be considered: leakage (including simulation and modeling of several leakage scenarios), zonal isolation, cement sheath mechanical-chemical integrity, surface and downhole material degradation, corrosion, and other impacts from potential issues (e.g. blow out, earthquake). • Seismic and logging measurements for cement and casing evaluation were conducted thoroughly. • Continuous monitoring and surveillance were performed before, during, and after the CO_2 injection program: injected CO_2, pressure and temperature (along injection well, annulus, downhole, and reservoir), micro-seismic, production and injection data, logging measurement (ultrasonic, CBL, acoustic, pressure, and temperature), CO_2 analyzer, and the environmental parameter (surface gas, soil, ground and surface water, and biodiversity).
3.	Tomokamai offshore area [44–48]**	• CO_2 injection was conducted from 2016 until 2019 with a cumulative CO_2 injection of 300,100 metric tonnes. • Post monitoring was performed until 2020. • Two new wells were utilized for injection operation. Several monitoring devices and sensors were installed in the wells. • Three wells were utilized for observation. Several monitoring devices, sensors, and seismometers were installed in the wells. • CO_2 was injected at the supercritical phase.	• Periodic and continuous monitoring and surveillance were performed before, during, and after the CO_2 injection program: injection and observation wells, injected CO_2, pressure and temperature (surface and downhole), 2D and 3D seismic survey, natural earthquake, micro-seismic, ocean bottom cable (OBC), onshore seismometers, ocean bottom seismometers (OBS), injection data, and marine environmental survey.
4.	Cortemaggiore, Palino-Ascoli-Candela-Satriano (PACS), and Giaurone-Armatella-Gela (Italy) [49] **	• In 2004, a project was launched to identify and select fields for CO_2 sequestration. • Existing wells and new wells were planned for the CO_2 injection at the supercritical phase.	• The integrity of the existing wells was assessed to identify and select suitable wells for CO_2 injection. The assessment consisted of gathering all historical data of the wells (drilling and completion method, well pressures, plug and abandonment, and operational data), evaluating the last integrity status of the well (annulus pressure, sustained casing pressure, and leakages), analyzing the risk and hazard, and selecting the suitable wells (classification of wells). • New wells were constructed based on criteria for CO_2 injection. The technical requirements, specific guidelines, and critical criteria for well integrity were established before the construction of the new wells. • A monitoring program was planned, consisting of surface and well microseismic, geochemical, wireline logging measurement, surface and annulus pressure measurement, and fluid measurement.

*CO_2 injection was not performed yet, **CO_2 injection was already performed.

cross-sectional area. To evaluate the leakage potential risk and rates, a physics-based leakage model based on specific fluid properties and transport phenomenon should be established [6]. The database of previous CCUS wells, including well construction and design, injection operation, until post well and sites monitoring can be used for initial preliminary analysis and evaluation because of some similarities between wells. In case of the absence of CCUS wells data, other existing oil and gas wells databases, including the well construction, production operation, well intervention, and plug and abandonment, can also be used as a reference.

It is mandatory to ensure the integrity throughout the lifecycle of the CCUS well. The well integrity assurance includes the following aspects [2,6,12–14]:

1. Preventing CO_2 and other fluid leakages to the surface,
2. Isolating CO_2 or other fluid movements between various strata of formations to prevent contamination,
3. Preventing pressure breakdown of formations, particularly weak formations,
4. And preventing contamination of water-bearing formations or any existing critical formation.

The establishment of specific regulations, standards and guidelines, enhancement in well design and construction, and improvements in knowledge and expertise of CCUS well integrity should be prioritized to prevent any undesirable failure [15].

However, there are not many specific standards governing CO_2-enhanced oil recovery (EOR), CCS, and CCUS well, especially in Indonesia [2,16]. Most design and construction processes of a CCUS/CCS well, including materials and equipment, are based on standards and guidelines developed in the oil and gas industry [2]. In particular, ISO 27914 [2] and ISO/FDIS 27916 [3] were used as the basis of well JPN-1 evaluation in this study; however, these standards alone were inadequate to evaluate the well integrity.

To support this inadequacy, international standards related to well integrity and barriers components which are readily available can be used to support both the construction of a new CO_2 injection well and the conversion of an existing oil and gas well into a CO_2 injection well.

Table 1 shows the international standards related to CCUS and well integrity of a CO_2 injection well that were published both by the International Association of Oil & Gas Producers (IOGP) and other international organizations [7,17]. These international standards were used in this study to evaluate the case study: well Jepon-1 (JPN-1).

In addition to the international standards, Table 2 shows the case studies and lesson learned regarding the critical and design criteria for well integrity of the CCS/CCUS well. Three projects shown in the table consist of the plan and actual case studies of new and converted CCS/CCUS wells that were used as additional references for JPN-1 well.

The comparison in Table 2 shows the list of critical integrity aspects to be considered both in the well design and in the CO_2 injection operation process, which needs to be monitored continuously before, during, and after the CO_2 injection operation.

The international standards in Table 1 and the list of critical integrity aspects in Table 2 were used in this study to evaluate the integrity of the planned conversion CO_2 injection well JPN-1. Workover and well intervention operations were conducted on this well and commercial tools were utilized to assess the well integrity; however, due to the limitation of the commercial tools, not all integrity aspects could be assessed properly. Besides, despite the successful CCS/CCUS case studies application shown in Table 2, the lesson learned could not be applied directly in well JPN-1 due to the difference in background and condition of the well. Therefore, Indonesia plans to build its database of lesson learned of the CCUS well design, conversion, and CO_2 injection.

The study presented here was a collaboration research between University, Oil and Gas Operator, and Service Company in CCUS research. The objective of this study is to develop a methodology to evaluate the integrity of JPN-1 which is planned to be converted into a CO_2 injection well based on the limitations of the commercial tools, focusing on the following three aspects:

1. A suitable assessment tool for a similar type of wells (planned conversion into CCUS well or new drilled CCUS well) in Indonesia,
2. Regulations related to CCUS wells application in Indonesia.

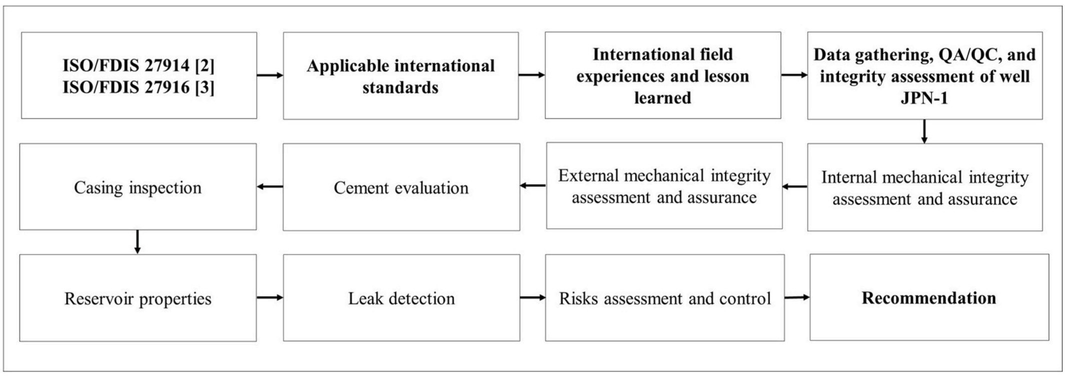


Fig. 1. Methodology of integrity evaluation of well JPN-1 [2,3,49,51–53].

3. The adaptation of international standards to be more detailed and used on a field/well basis.

The CO_2 injection project in this field is the first planned CCUS pilot project in Indonesia that was addressed for further research and development purposes [50]. The importance of the results of this study is threefold: (1) to evaluate and predict the leakage risk of the planned CO_2 injector well, (2) to be used as a reference for the CCUS well design and construction, conversion of an existing oil and gas well into a CO_2 injector well, and (3) to be used as a reference in the making of regulations related to CCUS well in Indonesia.

2. Methodology & overview of the well

2.1. Methodology

The CO_2 injection into geological storage must be nearly leak-free, both to the surface and subsurface, to achieve the safety requirements and to justify the high expenditure of the project [5]. Fig. 1 shows a flow path of design aspects for conversion well into a CO_2 injection well adapted from several applicable international standards and recommended practices from experiences of companies worldwide [2,3,49,51–53].

The methodology of well integrity measurement, assessment, and evaluation in ISO 27914 [2] and ISO/FDIS 27916 [3] were utilized as the basis in this study. However, methodology stated in these standards alone were inadequate to evaluate the well integrity in well JPN-1. Due to the lack of specific tools to measure CCUS well integrity, the integrity assessment of well JPN-1 was conducted using commercial tools that are widely used in oil and gas well. The commercial tools were acoustic log, caliper log, temperature, pressure, spinner log, production log, and porosity log. These commercial tools were not intended to measure the integrity parameter in CCUS well according to the ISO 27914 [2] and ISO/FDIS 27916 [3]. The specific criteria, duration of measurement, and range of measurement parameters of the tools in both ISO need to be specified in the operation according to the field and well basis. Therefore, other applicable international standards listed in Table 1 and experiences and documented lessons learned from industries worldwide in Table 2 were also used to support the integrity evaluation of the well in this study, particularly in defining the specific criteria and range of measurement parameter of the tools [54].

The following data were gathered and then quality assurance and quality control (QA/QC) of the data were performed based on ISO 27914 [2] and ISO/FDIS 27916 [3]:

1. Geological, reservoir, and subsurface data.
2. Reservoir and production fluid
3. Well schematic, tubulars, and downhole equipment.
4. Well drilling and intervention reports.
5. Wireline logging data, including caliper, cement, casing, temperature, pressure, production, reservoir, porosity, and saturation.

The data were shown in chapter 2.2 Overview of the well.

Experiences from industries worldwide in Table 2 shows that wellbores (e.g. active and inactive or abandoned) are prone to leakage of injected CO_2 into the well [38–49,52,54]. According to lesson learned from Malaysia (offshore mature field), France (Lacq), and Italy (Cortemaggiore, Palino-Ascoli-Candela-Satriano (PACS), and Giaurone-Armatella-Gela), the existing oil and gas wells, particularly old wells, possess high integrity risks that should be carefully considered before converting them into CO_2 injector wells. The integrity of each well surface and downhole components need to be investigated and evaluated.

Based on the statistics and lesson learned, most failures of internal well integrity can be found in the following components: casing, liner, tubing, packer, and downhole completion (including valve) [55]. This internal mechanical integrity also includes the connection of tubular. Besides, there should not be any upward migration flow from behind the designed downhole tubular due to problems, e.g. un-isolated formation zones, bad cement quality, micro-annulus, and channeling, except the CO_2 flows from the designed injection interval. Other integrity elements that should be also evaluated are the Christmas tree and wellhead which should be designed to withstand the planned working pressures and not exceed the maximum permissible loads. All the components of this two-surface equipment, including valves, should be regularly maintained, particularly from leaking.

Therefore, both the internal and external mechanical well integrity assessment and assurance, especially for long-term well integrity, are important during the operation [49,51,52], particularly cement and casing inspection.

In this study, the reservoir properties were evaluated. The porosity and permeability affect the CO_2 injection into the storage. Then, leak detection was carried out according to the available data. Leakage occurrence can be analyzed by identifying the following elements: the source of the leak, the pathway of the leak, and the force causing the leak to flow from the source along the pathway [5,12,56]. The force could be the buoyancy effect of the CO_2 or the differential pressure. Further, the risk assessment and control were established, and these will be used as a basis for the guideline and recommendation.

2.2. Overview of the well

From 2013 to 2019, the amount of natural gas produced from Gundih Field reached approximately 60 Million Standard Cubic Feet per Day (MMSCFD) [57], containing up to 23% CO_2 or equivalent to production of 800 metric tonnes per day of CO_2 [53,58]. The high CO_2 production in this field is considered to be a major issue and therefore CCUS project is planned to inject approximately 20,000 tonnes of CO_2 in two years (the amount of CO_2 to be injected is planned to be increased) [50,53].

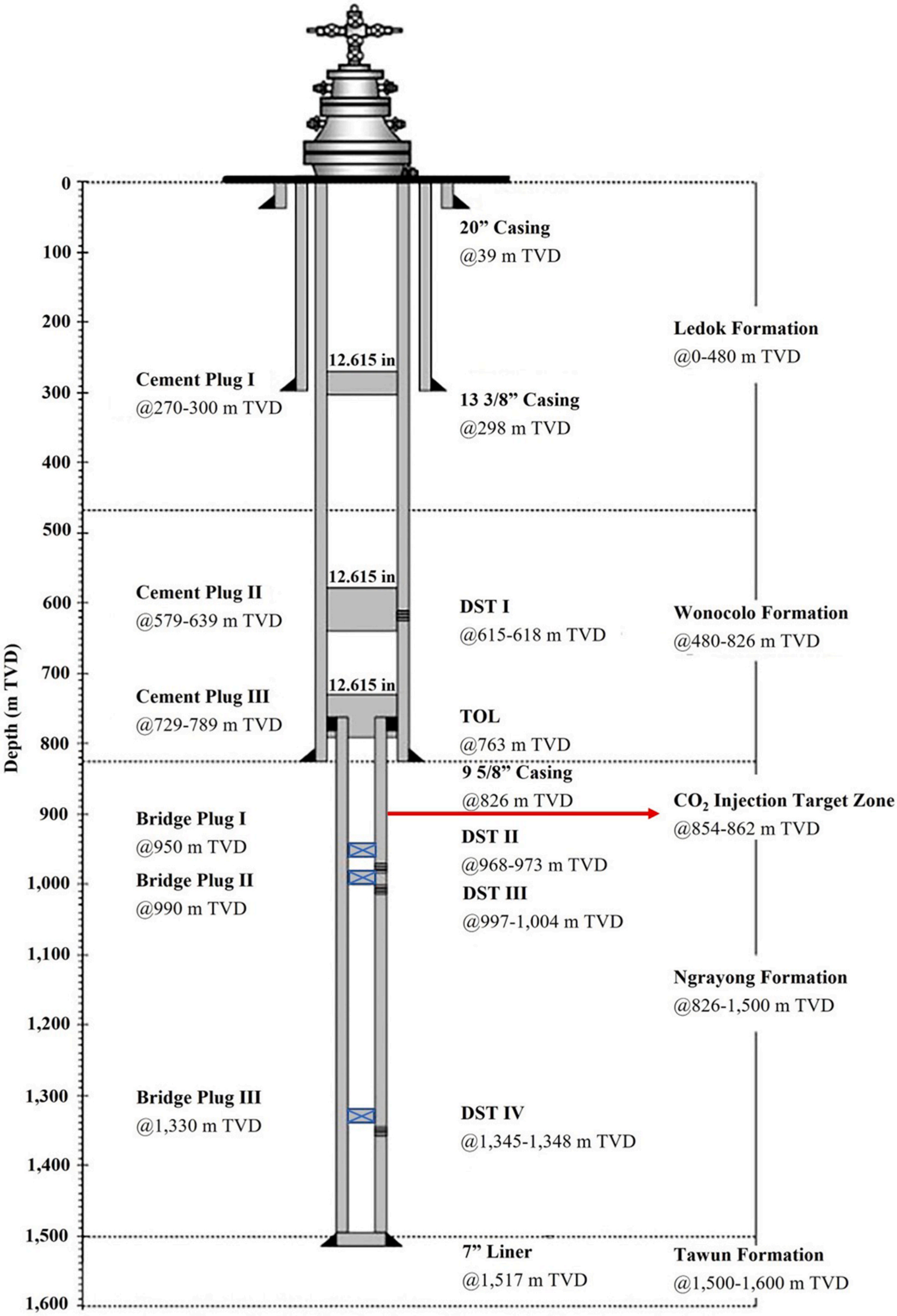


Fig. 2. Schematic of well JPN-1 [57,63].

Well JPN-1 in this field was a vertical exploration gas well drilled in 2007 [1]. This well was abandoned in 2008 and is planned for conversion into a CO_2 injection well through a workover operation. The selection of this well was based on the following consideration [1,50,53,57–61]:

1. The CO_2 injection near the production wells and Central Processing Unit (CPP) in this field (less than 3.2 km) is considered an effective method to reduce CO_2.
2. The objective plan is to inject CO_2 of approximately 30 tons per day or 0.57 MMSCFD in 2 years into Ngrayong formation at approximately 854–862 m. This formation consisted of claystone interbedded with sandstone and limestone. According to studies performed by Tsuji et al. (2014) and Kelly et al. (2019), at this depth, the CO_2 can be injected effectively at the supercritical phase or state [62]. The CO_2 pressure and temperature in the surface and pipeline will be regulated so that the single-phase supercritical liquid will flow into the well and reservoir. This is considered the most efficient condition for CO_2 injection.
3. The Ngrayong formation is considered not too deep formation, therefore the well cost could be less expensive and optimized. The available pumps are still able to be used to pump the injected CO_2 into this formation. Above Ngrayong formation, there is an impermeable formation (Wonocolo formation) that is considered as seal formation.
4. Based on offset wells, the pore pressure regime in the Ngrayong formation was considered to be almost hydrostatic which is favorable for CO_2 injection.
5. As much as 30 metric tonnes/day of CO_2 (0.58 MMSCFD) is planned to be captured, transported, and injected into well JPN-1. The surface facilities and required infrastructure already existed in this field to support production. These facilities are planned to be used in the CO_2 injection project.
6. The CO_2 injection plan in this well is the first planned CCUS pilot project in Indonesia that was addressed for further research and development purposes [50]. The well design and construction basis of this well is similar to other existing wells in other fields operated by the same operator company. This pilot project will be used as a reference for future CCUS conversion of an existing wells into CO_2 injector wells and injector well design and construction.

Fig. 2 shows the schematic of well JPN-1.

After the workover operation was done, well intervention and investigation were carried out to measure and evaluate the integrity of the well using commercial tools that are widely used in oil and gas well. Table 3 shows the aspect criteria and objectives of intervention and investigation at well JPN-1. Based on the aspect criteria, the type of well logging investigation was determined: acoustic log, caliper log, temperature, pressure, spinner log, production log, and porosity log.

Fig. 3 shows the acoustic test time data acquisition diagram.

A high fidelity (100 ms) data was used in the processing, providing a high sample data rate to detect high-resolution noise activity related to the source of the leak investigation.

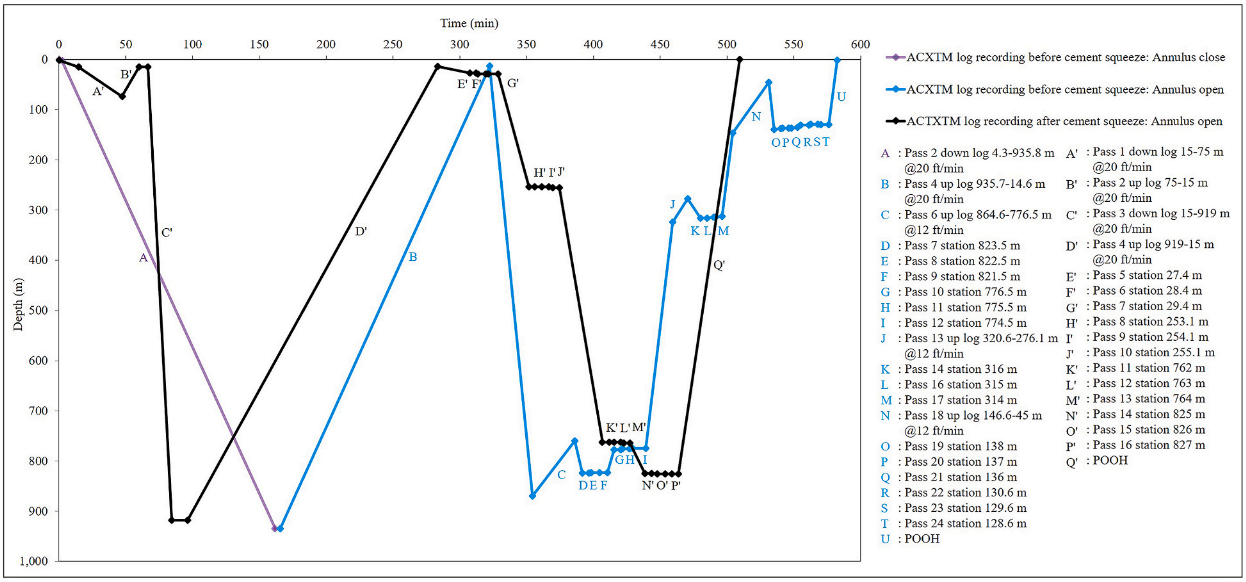
Road noise is noise related to tool motion and observed to be occurring at a low frequency in every dynamic pass [1,57]. In this study, dynamic and station passes processing were conducted to investigate the acoustic activity related to the leakages. Radial location around the suspected area were further assessed to investigate the noise source. The acoustic test results from the second logging run were largely similar in conclusion to the first run. Acoustic events heard by the tool were calculated to occur close to the tool body. Acoustic events identified on the up and down passes did not repeat with each other. Stations recorded at the casing shoes did not indicate any detectable leaks.

Table 4 shows CBL measurement in well JPN-1.

Fig. 4 shows the advanced cement evaluation at 420–460 m in 9 5/8" casing interval.

Table 3
Objectives of intervention and investigation at well JPN-1 [1].

Criteria	Expected outcome	Parameter
Acoustic visualization profile of the borehole in 2-D and 3-D format.	- Good cement height (minimum 10 ft).	- Cycle skip travel time. - Cement acoustic impedance (Z > 3.8). - Cement distributed evenly 360°.
Acoustic leak detection (See Fig. 3).	- No indication of fluid migration inside the borehole and behind the casing.	- Acoustic analysis tool post-processing result that uses hydrophone array technology to identify leaks and flow around the wellbore and behind pipe in real-time.
Temperature, pressure, and spinner log.	- No indication of fluid movement.	- Temperature profile close to geothermal gradient profile. - Zero relative spinner rotation - Pressure reading matching the hydrostatic pressure.
Reservoir monitor log for fluid saturation.	- No water movement behind the casing. - Good porosity on the target CO_2 injection zone based on cased hole (CH) porosity analysis.	- Small value of oxygen activation curve. This provides the ability to solve complex saturation profiles in the reservoir while eliminating phase-saturation interdependency. This information can be used to monitor the reservoir. - Saturation analysis, water saturation, porosity, and a qualitative measurement of permeability in the target zone. - Impermeable shale zone as a barrier above and below the injection zone.
Annulus pressure.	- Annulus pressure 0 psig.	- Stable Annulus pressure gauge (0 psig).
Compressive cement strength.	- The estimated compressive cement strength of the surface cement sample must be above the CO_2 injection pressure at 100 Bar (~1400 psi)".	



ACXTM: Acoustic conformance xaminer trademark

Fig. 3. Acoustic test time-depth data acquisition diagram [1].

Table 4
CBL measurement [1,57].

Depth (m)	Measurement			Evaluation
	First	Second	Third	
300–350	8	16	14	Moderate
350–400	10	21	21	Poor
400–450	8	13	13	Moderate
450–500	5	13	14	Moderate
500–550	5	13	12	Moderate
550–600	10	17	18	Moderate
600–650	7	11	11	Moderate
650–700	5	12	14	Moderate
700–750	2	16	7	Good
750–763	2	0	5	Good
763–800	32	51	52	Poor
800–850	31	41	36	Poor
850–900	30	21	19	Moderate
900–950	30	19	16	Moderate

The first CBL measurement was conducted in 2007 during drilling operation. The second and third CBM measurement were conducted in 2017, before and after squeezed cementing operation, respectively.

Fig. 5 shows the advanced cement evaluation at 850–900 m in 7” casing interval.

Fig. 6 shows the inspection log of the 7” liner in this well.

According to Fig. 6, the following observations were identified:

a. Thicker casing was observed at 770–780.2 m intervals showing the possibility of heavier casing weight.
b. Internal damage was observed at 780.2–794 m. However, the thickness analysis did not show any obvious metal loss of the casing. These scars were due to plug setting operations.
c. Internal damage was observed at 847.8–858.4 m. The casing evaluation and inspection results showed approximately 41% damage on the casing.
d. Larger radius anomalies were observed at 900–940 m. However, thickness analysis did not show any obvious metal loss of casing. The casing evaluation and inspection results showed approximately 20% damage.

Fig. 7 shows the production logging acquisition 4.

Fig. 8 shows the temperature plot for all intervals.

The temperature data were recorded using production logging tool (PLT). PLT was aimed to measure the fluid movement in the

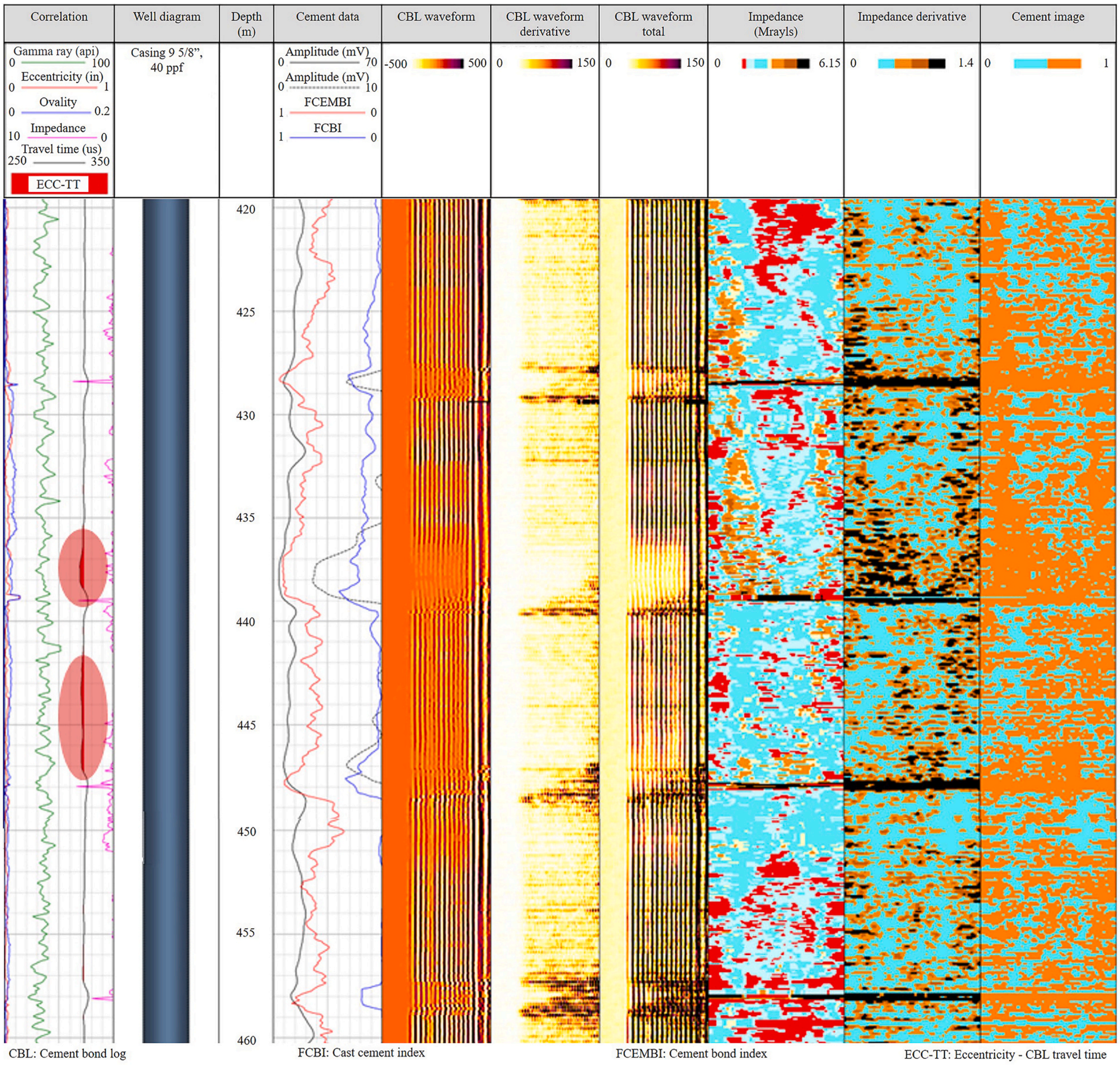


Fig. 4. The advanced cement evaluation of 9 5/8″ casing intervals 420–460 m [1].

wellbore, including the flow rates, properties, pressure and temperature [49]. The PLT measurement was performed in JPN-1 to evaluate and quantify the downhole leakages. The PLT measurement were taken at four different times. According to Figs. 7 and 8, the following observations were identified in Table 5.

Fig. 9 shows the saturation analysis at 830–920 m.

3. Results and discussion

A holistic evaluation of well integrity was required on JPN-1 well, prior to converting it into a CO_2 injection well. The first and the most critical step was data collection, particularly related to information regarding the status of the wells. These data include the design and equipment of the wells to identify the well integrity and to evaluate whether they are suitable for CO_2 injection wells.

Table 6 shows the summary of the well integrity evaluation of well JPN-1 [1,57] according to the International standards [17]. Besides, the case studies and lesson learned in Table 2 were also used as additional basis for integrity evaluation of well JPN-1 in Table 6.

The well JPN-1 was formerly designed as an exploration oil and gas well with minimum requirements following the standards and guidelines stated in the oil and gas industry.

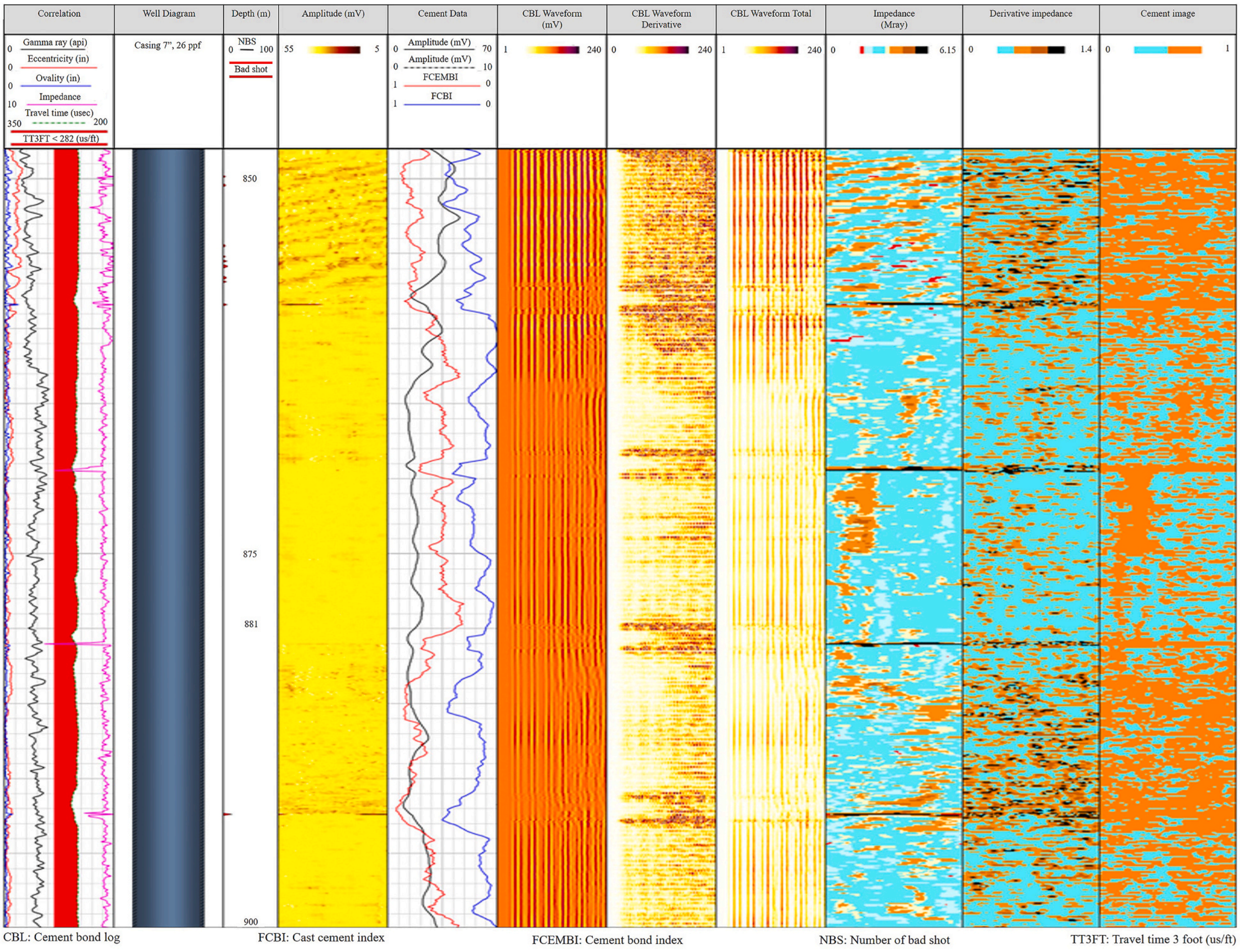


Fig. 5. The advanced cement evaluation of 7″ casing intervals 850–900 m [1].

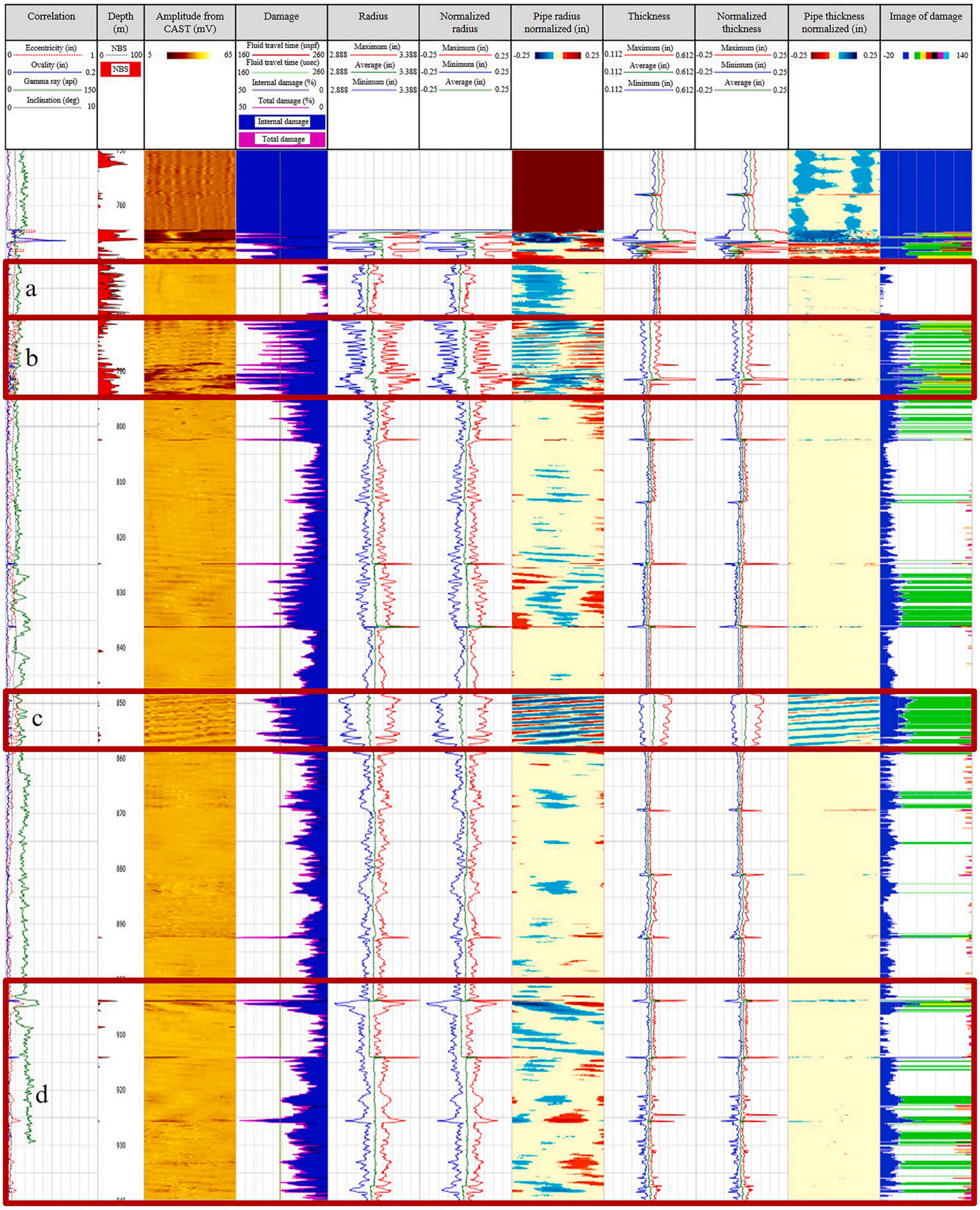
According to ISO 27914 [2], wellbore condition shall be verified for any defect by logging tools. The logging should be capable to inspect the actual internal-external condition of tubular (liner, casing) for any defect (wear, corrosion, erosion, thickness reduction, etc.), cement (casing-cement and formation-cement bond, microannuli, fracture, etc.), reservoir and fluid saturation, and leakage. Most of the commercial logging tools used to measure and evaluate the integrity of well JPN-1 were unable to detect and measure the leakages sources in the wellbore. The indication of leakages was observed through the temperature anomaly measurements.

Therefore, more accurate and sensitive measurement and logging evaluation tools combined with other tools, such as temperature logging tool, and/or longer time duration of measurement, are required to detect this type of leakages in CCUS well, particularly abandoned oil and gas well which is planned to be converted into a CO_2 injector well.

The result summary and analysis from Table 6 show that the outcomes were not in line with the plan shown in Table 3, even though the workover operation had been carried out. After the workover operation, leakages were still observed and the integrity of the well did not reach the minimum target according to the international standards and guidelines shown in Table 1.

In line with ISO 27914 [2] and ISO/FDIS 27916 [3], re-construction or re-completion is mandatory before performing the CCUS project in this well. The age and current condition of this well, tubular, surface and downhole equipment, and WBE should be considered as it will affect the well performance, whether it can meet the minimum requirements of a CCUS well after the re-construction/re-completion. Particular attention should be addressed to leakages (e.g. leakage from the casing, cement, downhole and surface equipment), since this can lead to a serious issue in a CCUS project; therefore, the integrity of WBE shall be re-established.

The injected CO_2 into the reservoir dissolves in the formation fluid (brine) and reacts to form carbonic acid (H_2CO_3) [42,53]. The carbonic acid attacks the wellbore, particularly at the injection area. CO_2-resistant cement is mandatory to be placed in the wellbore, especially in the reservoir section, injection area, and up to the safety zones and seal formations above the reservoir formation. In case normal cement or non–CO_2–resistant cement is used, this type of cement can be placed above the CO_2-resistant cement, since this cement is vulnerable to CO_2 attack. The cement should be able to sustain the permeability as low as possible and provide long-term protection against the supercritical CO_2 attack (>31 °C at 1059 psi) and formation fluid at elevated pressure and temperature and low pH condition.



NBS: Number of bad shot

Fig. 6. 7″ liner inspection log [1].

Aside from the requirements listed in Tables 3 and 6, Table 7 shows the additional requirements for a CO2 injection well based on ISO 16530-1 [7], ISO 16530-2 [19], and ISO 27914 [2] related to WBE and critical well integrity elements.

The gas leakage in JPN-1 might occur through the various pathways from natural existing spaces (e.g. geological pathway, pores, fractures, and faults) to barriers failures (e.g. bulk cement, cement deterioration, microannuli, poorly cemented casing/liner, casing/liner failure, cracks, and corrosion) [5,8,12,56]. Gas migration might occur outside of the cemented casing/liner and flow upwards to the surface. Various factors contribute to this migration, including poor cement quality behind the casing/liner or cement/formation rock fracturing/channeling at the shoe and behind the casing/liner. The following are factors that should be considered in wellbore leakage investigation of this well:

1. Well status, age, and depth.

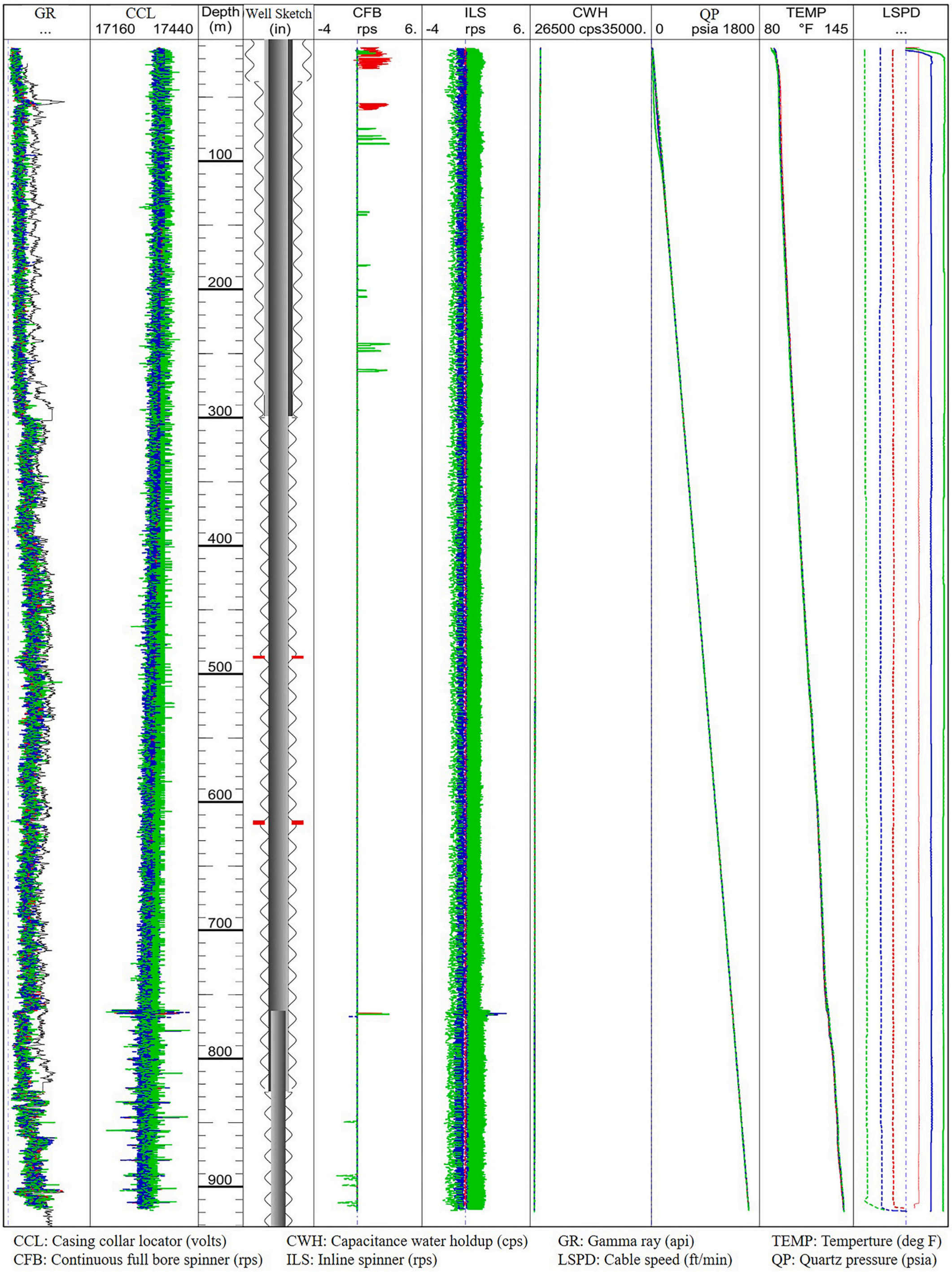


Fig. 7. Result of production logging acquisition 4 [1].

This includes the status of the new or converted well, and producing or abandoned well. The depth of the reservoir and the number of wells that penetrate the reservoir also affect the risk of CO_2 leakage and migration potential as cross-flow between close existing wells and different formation strata might occur.

2. Well construction, structure, schematic, and completion.

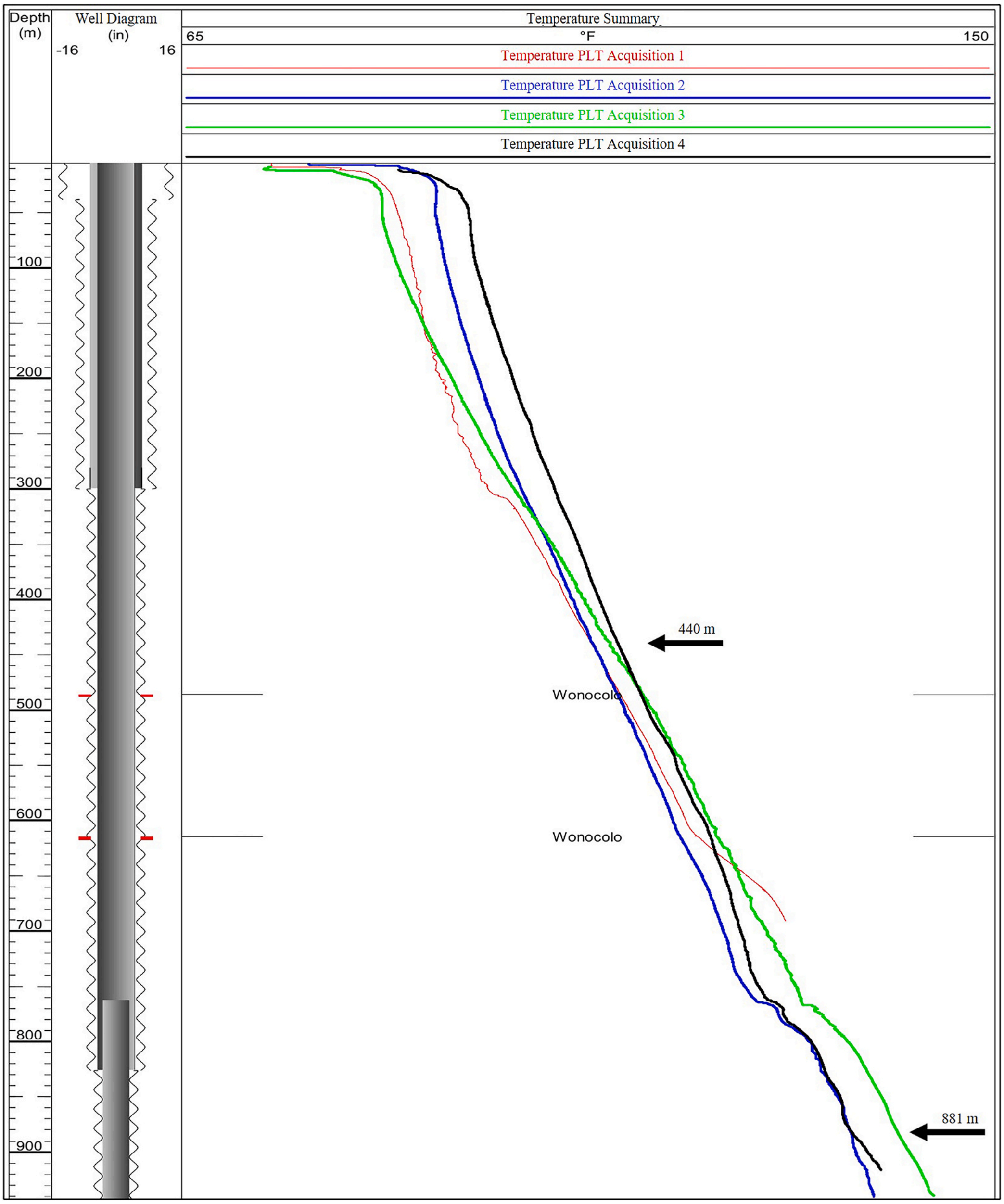


Fig. 8. Temperature plot for all intervals [1].

3. The number of wellbores in the area as this may affect the cross-flow between near existing wellbores and cause leakage through other wellbores.
4. Installed downhole equipment, since their performance and integrity capability are time-dependent. These will affect the wellbore integrity and reduce the maximum allowable load that the wellbore can withstand.
5. The historical purpose of the well (e.g. oil/gas producing well, injection well, and abandoned well)
6 Presence of corrosive substances or other substances enhancing the corrosion, such as H_2S, CO_2, and water.

Additionally, a model of fluid characteristics and flow throughout the leakage pathway is required to estimate and calculate CO_2 flow along a leaking wellbore [2,6]. The range of effective permeability of either formation or cement microannuli is also required to estimate the risk of CO_2 leakage [66]. The input parameters for the model should at least consist of the wellbore dimension (e.g. outside and inside diameter, length, height, inclination, and depth), fluid and CO_2 properties (composition, saturation, density, viscosity, and injection flow rate), formation properties (e.g. pressure, temperature, permeability, porosity, compressibility, and thermal effect), and potential pathway properties (e.g. dimension, permeability, and porosity of cracks, microannuli, cement, and fracture.) [9–11,67–72].

Table 5
PLT acquisition and temperature analysis [1,57].

Aspect analysis	PLT acquisition			
	1st	2nd	3rd	4th
Spinner log	No flow	No flow	No flow	No flow
Pressure	Stable	Stable	Stable	Stable
Capacitance	Well was filled with liquid	Well was filled with liquid	Well was filled with liquid	Well was filled with liquid
Temperature	At approximately 305 m (below casing shoe), a temperature anomaly was observed that might indicate an activity.	There was no indication of temperature anomaly at 305 m with respect to observation on PLT acquisition 1.	Slight increase in temperature compared to previous PLT acquisitions.	At 881 m, a temperature gradient change was observed, indicating a leakage. Another leakage potential was observed at approximately 440 m.
Reservoir pressure at upper Wonocolo perforation	765 psi	820 psi	813 psi	866 psi
Reservoir pressure at lower Wonocolo perforation	970 psi	1035 psi	1027 psi	1094 psi
Reservoir temperature at upper Wonocolo perforation	111 deg F	110 deg F	113 deg F	113 deg F
Reservoir temperature at lower Wonocolo perforation	120 deg F	118 deg F	121 deg F	120 deg F

In addition, CO_2 physical properties might change over time and along the flow pathway including the leakage pathway. This dynamic condition, together with existing uncertainties in the geological storage and wellbores, should also be addressed in the model calculation [73]. In recent years, various research and development have been done related to wellbore leakages through various barriers systems resulting in different models. However, these models are specific to each case, which might not always applicable to JPN-1 conditions. For the specific case in well JPN-1, considering this well was formerly an abandoned exploration oil and gas well that is planned for conversion into a CCS/CCUS well with its well integrity potential issues, particular precautions and consideration should be taken in the leakage modeling.

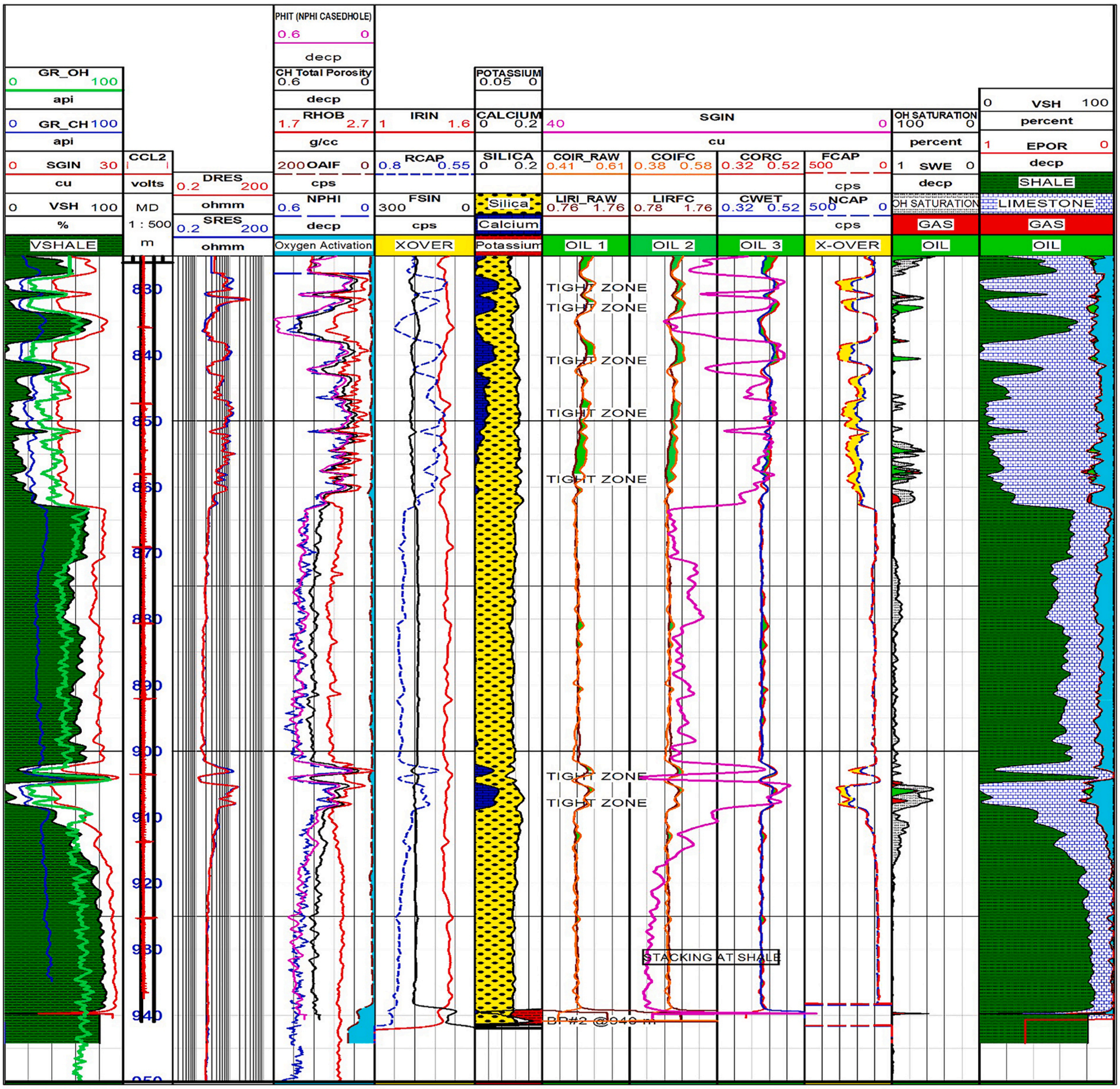
If the CO_2 injection at JPN-1 were to be performed, the leakages could occur and cause worse impact due to this integrity issue. The amount of injected CO_2 into the formation and loss of CO_2 (leakage, surface operation, etc.) must be quantified. Well integrity assurance is mandatory to minimize the loss of CO_2 as much as possible, particularly from the surface and downhole leakage. There are still more unknown required data; therefore, it is difficult to perform a holistic integrity evaluation of well JPN-1 and to estimate the leakages. Due to this lack of data, it is also difficult to apply the international guideline and application in workover and investigation operations in this well.

Regulations and specific guidelines and standards should be determined as the basis for the CCUS project in JPN-1. Further, firm criteria should be established to ensure well integrity, e.g. acceptable condition of downhole equipment, and cement and casing/liner condition. Then, an investigation should be performed on this well to check against these predetermined criteria. If leakages are identified, well intervention and repairmen should be carried out directly before proceeding with the CO_2 injection operation.

> Well observation and proper testing and investigation are required by regulations to ensure that there is no leakage or CO_2 migration occurrence during the CO_2 injection operation. CO_2 migration and leakage may occur later after some period of the CCUS operation. The well integrity degradation can occur slowly causing unawareness of the CO_2 leakages risk potential. Therefore, close monitoring for a longer time is required to ensure no leakages occur from geological storage and wellbores for a very long time [73]. The storage and well must be monitored and the results must be reported on a regular basis according to the applicable regulations. Wireline logging measurements are recommended to be run to measure the injection profile and injected CO_2 and possible properties changes over time and homogeneity [49]. In addition, the offset and historical data of the wells and fields should be reviewed and used as the basis for establishing the regulations [5]. Further, a decision tree can be established based on the offset and historical data analysis of the well and the field, the current condition of the well, and the investigation results. This decision tree will simplify the analysis and decision-making of whether the conversion of the well can be performed.

4. Conclusion

1. This paper reviewed the well integrity of well JPN-1 in Gundih Field. After the workover and well intervention operations that were conducted on this well, not all integrity aspects could be assessed properly due to the limitation of the commercial tools. Besides,



CH: Cased hole
CCL: Casing collar locator (volts)
COIFC: Carbon/Oxygen inelastic ratio far detector
COIR: Ratio of inelastic Carbon/Oxygen
CORC: Carbon/Oxygen inelastic ratio far detector
CWET: C/O wet formation
DRES: Deep resistivity (ohmm)
EPOR: Effective porosity from sigmasat (decp)
FCAP: Far capture count rate (cps)
FSIN: Far inelastic count rate (cps)
GR: Gamma ray (api)
IRIN: Ratio of total inelastic count rates
LIRFC: Calcium/Silicon inelastic ratio far detector
LIRI: Ratio of inelastic Calcium/Silicon
MD: Measured depth (m)
NCAP: Near capture count rate (cps)
NPHI: Neutron porosity (decp)
OAIF: Oxygen activation far (cps)
OH: Open hole
PHIT: Cased hole NPHI (decp)
RCAP: C/O ratio near/far capture
RHOB: Density (g/cc)
SGIN: Sigma intrinsic (cu)
SRES: Flushed zone resistivity (ohmm)
SWE: Effective water saturation (decp)
VSH: Volume of shale (%)
X-OVER: Crossover

Fig. 9. Saturation analysis for interval 830–920 m [1].

the well integrity aspects did not meet the minimum requirements according to international standards and guidelines reviewed in this study. Among the well integrity data and parameters measured in this well, regardless of the tools' limitations, temperature measurement was the most reliable to show the preliminary indication of leakages in the well.

2. A holistic evaluation of the well integrity is required on this well, prior to converting it into a CO_2 injection well. The first and most critical step is to complete data collection. These data include the design and equipment of the wells to identify the well integrity and to evaluate whether they are suitable for CO_2 injection well. The risk of CO_2 leakage is the main concern of the well integrity that should be fully taken into consideration throughout the life of the well.
3. Based on the literature study performed in this research, the well integrity aspects of the CCUS well need to be managed, monitored, and maintained throughout the life of the well. The wellbore condition shall be verified for any defect by suitable measurement

Table 6
Summary of the well integrity review and check of well JPN-1 [57] according to international standards [17].

International standards	Recommended practices	Well JPN-1
Internal mechanical integrity		
- API Spec 5CT [25] - ISO 11960 [26] - ISO 27914 [2]	Tubular evaluation: - Casing thickness - Casing deformity - Casing internal diameter	Tubular evaluation (Fig. 6): - There was a thickness reduction. - An internal damage was detected, especially at 7″ liner reaching 41%. - There was an increase in the casing internal diameter radius. - The casing might have experienced elongation and compression that exceeded the yield stress rating and lead to plastic deformation [64].
- ISO 13679/API RP 5C5 - ISO 27914 [2]	Casing pressure testing	The 9-5/8″ casing and 7″ liner could withstand the pressure testing.
- ISO 13680/API Spec 5CRA [31] - NORSOK M – 001 [29] - ISO 27914 [2]	Corrosion monitoring: - Corrosion rate calculation <2 mm/year - Material selection	Corrosion monitoring [57]: - Simulation result >2 mm/year - Existing casing was not suitable for CO_2
External mechanical integrity		
- ISO/FDIS 27916:2018 (E) [3] - ISO 27914 [2]	- Reservoir monitor log for fluid saturation	- Based on the cased hole logging analysis, the total porosity at interval 854–862 m for CO_2 injection target was around 20%, which was categorized as good porosity. - The impermeable shale zones at upper interval 834–838 m and lower interval 865–900 m could be used as barriers. - The saturation analysis in Fig. 9 showed that there was no potential hydrocarbon at the planned CO_2 injection interval.
- ISO 10426-1 [32]/API Spec 10A [33] - API TR 10TR1 [34] - API Std 65-2 [35] - ISO 27914 [2]	Cement evaluation: - CBL amplitude below 10 mV - No micro-annulus and channeling - Distribution of cement Compressive cement strength	Cement evaluation (Table 4, Fig. 4, and Fig. 5): - The range of amplitude was 0–52 mV. - Indication of micro-annulus, especially cement sheath behind the 7″ liner. - The cement was evenly distributed in all squeeze cementing zones. Compressive strength was not defined precisely.
- ISO 16530-1 [7] - ISO 16530-2 [19] - ISO 14310 [36] - API Spec 11D1 [37] - ISO 27914 [2]	Log and monitoring program: - Downhole leakage investigation - Pressure, temperature, and spinner with production logging tool (PLT) acquisition	Log and monitoring program: - According to Fig. 3, the acoustic log acquisition could not detect leakage. The sensitivity of the leakages was below the tools' sensitivity and capability. - According to Fig. 7 and Table 5, the PLT acquisition could not detect leakage. The spinner, capacitance, reservoir pressure, and reservoir temperature measurement show no significant difference or leakage indication. However, the temperature measurements (Fig. 8) showed indications of two leakages at approximately 440 m and 881 m.
Christmas tree and wellhead integrity		
- ISO 10423 [22]/API Spec 6A [23] - API RP 90 report (2006) [24]	Surface	- According to the well intervention and investigation result, gas bubble was found at the surface of well JPN-1; however, the leak rate and pressure build-up rate were unable to be identified. - There was no identifiable pressure inside the casing, which inferred that there was no communication between the gas bubbling at the surface to the inner casing. - The gas measurement showed methane content in the gas.
	Leakage investigation	The average flow rate of the gas leak at the casing head spool surpassed the maximum leakage rate allowed.
	Annulus and well pressure	No firm information.
API RP 54 [21]	Lower explosive limit (LEL)	The gas leaking from the casing head spool reached 100% LEL in 18–22 s, meaning the accumulated methane had already reached its minimum potential of combustion.

tools (e.g. logging) that are capable to identify the performance of all WBE, and if defects are found, further remedial actions are mandatory to be conducted to ensure the integrity of the well prior to converting it into a CCUS well.

4. According to the review summary in this study, most of the essential and critical data of this well were not available. In addition, some available data showed that this well had well integrity issues, particularly related to the leakages and some critical WBE performance, e.g. casing, liner, cement, and wellhead. Therefore, based on these well integrity issues, the conversion of this well into a CO_2 injection well cannot be performed yet.

5. Recommendations

1. Longer duration of measurement and more accurate and sensitive logging evaluation tools combined with other tools, such as temperature logging tools, are required to detect leakage that could not be identified by these commercial tools in CCUS well, particularly in the abandoned oil and gas well which is planned to be converted into a CO_2 injector well.
2. Future CCUS applications in other wells in Indonesia, both for planned conversion into CCUS wells and for new drilled CCUS wells need to guarantee the integrity throughout the life cycle of the well. The methodology established in this study can be used as a reference and basis for this purpose. In addition, this study can also be used as a basis for constructing regulations related to CCUS wells application in Indonesia.

Table 7
Additional requirements for a CO_2 injection well [2,7,19].

Nu.	Aspects	Additional requirements
1.	WBE [7,19]	• The standard of performance for all WBE should be defined and specified according to the well type, particularly casing/liner and cement sheath. Each WBE should have the ability to function for a determined period when there is an external load that can have major effects. Each WBE should be monitored, maintained, inspected, tested, and verified throughout the operation to verify its standard of performance. • An acceptable leakage rate may be defined accordingly for each WBE. This acceptable leakage rate may be different for each WBE and well type and an acceptable matrix can be specified as part of the standard of performance. • The determination of MAASP for all annuli in the well should be performed. The re-calculation of MAASP for all annuli should be performed if there is a standard change of WBE performance, service type change of the well, annulus fluid density change, tubing and/or casing wall thickness loss, or reservoir pressures change. All critical points should be identified. ISO/TR 10400 is used as the basis for burst and collapse pressure calculation. Required adjustment due to degradation, e.g. wear, corrosion, and erosion, should be accounted for. • The review and investigation of the annulus, including annulus pressure, should be defined, particularly when there is an indication of sustained pressure or leakages.
2.	Material selection (e.g. tubular, surface and downhole equipment, elastomers) and corrosion treatment [2]	• Corrosion prediction and evaluation need to be considered: CO_2 composition, pressure, temperature, project lifetime, in-situ condition, exposure to CO_2, other substances presence (e.g. water, O_2, H_2S), and other possible corrosion attacks (H_2S, galvanic, etc.) • CRA and elastomer for CO_2 condition might be required, particularly if the material contact with corrosion substances directly. • Corrosion handling method and chemical treatment should be well-prepared. • Laboratory testing may be performed to determine the corrosion risk and rates [65].
3.	Tubular and other downhole equipment (e.g. packer) [2]	• Withstand the maximum in-situ condition (pressure, temperature) and operating condition (CO_2 injection) • Same principles of tubing and casing design to be applied according to the material and other requirements
4.	Cement [2]	• Not shrinking • Resistance to CO_2 and other possible corrosion substances
5.	Annulus pressure (e.g. annulus tubing-casing, casing-casing) [2]	• Periodic monitoring and measurement of annulus pressure and temperature • No leakage of injected CO_2 into wellbore annulus

3. Detailed international standards on a field/well basis for CCUS well integrity in Indonesia needs to be developed, and this can follow the methodology and case in this study. Further study related to continuous monitoring and surveillance during and after the CO_2 injection operation, will be carried out in the near future.

Author statement

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Data availability statement

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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List of Abbreviations and Nomenclature

API	American Petroleum Institute
ANSI	American National Standards Institute
ASTM	American Standard Testing and Material
BP	Bridge plug
BTC	Buttress thread casing
CBL	Cement bond log (mV)
CCL	Casing collar locator (volts)
CCS	Carbon capture and storage
CCUS	Carbon capture, utilization, and storage
CFB	Continuous full bore spinner (rps)
CH	Cased Hole
COIFC	Carbon/Oxygen inelastic ratio far detector
COIR	Ratio of inelastic Carbon/Oxygen
CORC	Carbon/Oxygen inelastic ratio far detector
CO_2	Carbon dioxide
CPP	Central Processing Unit
CSG	Casing
CWET	C/O wet formation
CWH	Capacitance water holdup (cps)
CRA	Corrosion Resistant Alloy
DRES	Deep resistivity (ohmm)
DST	Drill stem test
EOR	Enhanced oil recovery
ECC	Eccentricity (in)
EPA	Environmental Protection Agency
EPOR	Effective porosity from sigmasat (decp)
FCAP	Far capture count rate (cps)
FCBI	Cast cement index
FCEMBI	Cement bond index
FDIS	Final Draft international standard
FSIN	Far inelastic count rate (cps)
GR	Gamma ray (api)
GS	Geologic Sequestration
H_2CO_3	Carbonic Acid
ID	Inside diameter (in)
ILS	Inline spinner (rps)
IOGP	International Association of Oil & Gas Producers
IRAD	Inside radius (in)
IRIN	Ratio of total inelastic count rates
ISO	International Organization for Standardization
JPN	Jepon
LIRFC	Calcium/Silicon inelastic ratio far detector
LIRI	Ratio of inelastic Calcium/Silicon
MAASP	Maximum allowable annulus surface pressure (psi)
MD	Measured depth (m)
MMSCFD	Million standard cubic feet per day
MSG	Micro seismogram
NBS	Number of bad shots
NCAP	Near capture count rate (cps)

NPHI Neutron porosity (decp)
NORSOK Norsk Sokkels Konkuranseposisjon/Norwegian Standards Organization
OAIF Oxygen activation far (cps)
OBC Ocean bottom cable
OBS Ocean bottom seismometers
OD Outside diameter (in)
OH Open hole
ORAD Outside radius (in)
PHIT Cased hole NPHI (decp)
PLT Production logging tool
QA/QC Quality assurance and quality control
QP Quartz pressure (psia)
RCAP C/O ratio near/far capture
RHOB Density (g/cc)
RP Recommended Practice
SCP Sustained casing pressure
SGIN Sigma intrinsic (cu)
SOP Standard operating procedure
Spec Specification
SQZ Squeeze
SRES Flushed zone resistivity (ohmm)
SWE Effective water saturation (decp)
Std Standard
TEMP Temperture (deg F)
TR Technical Report
TT Travel time (us)
TT3FT Travel time 3 foot (us/ft)
TVD True vertical depth (m)
U.S. The United States
VDL Variable density log (μs)
VSH Volume of shale (%)
WBE Well barrier elements
WH Water Holdup
WP Wellhead pressure
X-OVER Crossover
Z Acoustic impedance (Mrayls)

References

[1] E.P. Pertamina, Jepon-1 (JPN-1) Well Data - Unpublished, Pertamina EP, Jakarta, 2008.
[2] International Organization for Standardization (ISO), ISO 27914: Carbon Dioxide Capture, Transportation and Geological Storage - Geological Storage, first ed., ISO, Geneva, 2017.
[3] International Organization for Standardization (ISO), *ISO 27916: Carbon Dioxide Capture, Transportation and Geological Storage — Carbon Dioxide Storage Using Enhanced Oil Recovery (CO_2-EOR)*, ISO, Geneva, 2018.
[4] L. Smith, M. Billingham, C. Lee, D. Milanovic, G. Lunt, CO_2 sequestration wells - the lifetime integrity challenge, in: Abu Dhabi International Petroleum Exhibition and Conference, Abu Dhabi, 2010.
[5] T. Watson, S. Bachu, Evaluation of the potential for gas and CO_2 leakage along wellbores, SPE Drill. Complet. 24 (1) (March 2009) 115–126.
[6] Q. Tao, D. Checkai, N. Huerta, S. Bryant, Estimating CO_2 fluxes along leaky, SPE J. 19 (2) (April 2014) 227–238.
[7] International Organization for Standardization (ISO), Petroleum and Natural Gas Industries - Well Integrity – Part 1: Life Cycle Governance, first ed., ISO, Geneva, 2017. *ISO 16530-1*.
[8] T. Watson, S. Bachu, Identification of wells with high CO_2-leakage potential in mature oil fields developed for CO_2-enhanced oil recovery, in: SPE Symposium on Improved Oil Recovery, Tulsa, 2008.
[9] L. Boukhelifa, N. Moroni, S. James, S. Le Roy-Delage, M. Thiercelin, G. Lemaire, Evaluation of cement systems for oil and gas well zonal isolation in a full-scale annular geometry, 01, SPE Drill. Complet. 20 (March 2005).
[10] R. Xu, Analysis of Diagnostic Testing of Sustained Casing Pressure in Wells, 2002.
[11] R. Bird, W. Stewart, E. Lightfoot, Transport Phenomena, revised second ed., John Wiley and Sons, New York, 2007.
[12] F. Moeinikia, E. Ford, H. Lohne, Ø. Arild, M. Majoumerd, K. Fjelde, Leakage calculator for plugged-and-abandoned wells, SPE Prod. Oper. 33 (4) (November 2018) 790–801.
[13] D. Liversidge, S. Taoutaou, S. Agarwal, Permanent plug and abandonment solution for the north sea, in: SPE Asia Pacific Oil & Gas Conference and Exhibition, Adelaide, 2006.
[14] C. Oldenburg, S. Bryant, J. Nicot, Certification framework based on effective trapping for geologic carbon sequestration, Int. J. Greenh. Gas Control 3 (4) (July 2009) 444–457.
[15] G. King, R. Valencia, Environmental risk and well integrity of plugged and abandoned wells, in: SPE Annual Technical Conference and Exhibition, Amsterdam, 2014.

[16] B. Marbun, D. Santoso, W. Kadir, A. Wibowo, P. Suardana, H. Prabowo, D. Susilo, D. Sasongko, S. Sinaga, B. Purbantanu, J. Palilu, R. Sule, Improvement of borehole and casing assessment of CO_2-EOR/CCUS injection and production well candidates in sukowati field, Indonesia in a well-based scale, Energy Rep. 7 (November 2021) 1598–1615.
[17] International Association of, Oil & Gas Producers, "Standards and Guidelines for Well Construction and Well Operations, International Association of Oil & Gas Producers, Brussels, 2015.
[18] Norwegian Technology Centre, Materials Selection, Norwegian Technology Centre, Oslo, 2002.
[19] International Organization for Standardization (ISO), Well Integrity for the Operational Phase, first ed., ISO, Geneva, 2014. *ISO/TS 16530-2: Well integrity - Part 2*.
[20] American Petroleum Institute (API), API RP 49: Recommended Practice for Drilling and Well Servicing Operations Involving Hydrogen Sulfide, third ed., API, Washington, DC, 2001, p. 42.
[21] American Petroleum Institute (API), API RP 54: Occupational Safety and Health for Oil and Gas Well Drilling and Servicing Operations, fourth ed., API, Washington, DC, 2019.
[22] International Organization for Standardization (ISO), ISO 10423: Petroleum and Natural Gas Industries - Drilling and Production Equipment - Wellhead and Christmas Tree Equipment, fourth ed., ISO, Geneva, 2009, p. 430.
[23] American Petroleum Institute (API), API Spec 6A: Wellhead and Tree Equipment, twenty-first ed., API, Washington, DC, 2019.
[24] American Petroleum Institute (API), API RP 90: Annular Casing Pressure Management for Offshore Wells, first ed. ed., American Petroleum Institute (API), Washington, DC, 2006.
[25] American Petroleum Institute (API), API Spec 5CT: Casing and Tubing, tenth ed., API, Washington, DC, 2019.
[26] International Organization for Standardization (ISO), ISO 11960: Petroleum and Natural Gas Industries - Steel Pipes for Use as Casing or Tubing for Wells, sixth ed., ISO, Geneva, 2020, p. 267.
[27] International Organization for Standardization (ISO), *ISO 15156-1: Petroleum and Natural Gas Industries - Materials for Use in H_2S-Containing Environments in Oil and Gas Production - Part 1: General Principles for Selection of Cracking-Resistant Materials*, fourth ed., ISO, Geneva, 2020, p. 11.
[28] National Association of Corrosion Engineers (NACE) International, *-1: Petroleum and Natural Gas Industries - Materials for Use in H_2S-Containing - Environments in Oil and Gas Production*, first ed., NACE, Houston, TX, 2001, p. 149. *NACE MR0175/ISO 15156*.
[29] The Norwegian oil and gas association and the federation of Norwegian industries, NORSOK standard M-001, Materials selection, 5th ed., Lysaker: Standards Norway (2014).
[30] International Organization for Standardization (ISO), ISO 13680: Petroleum and Natural Gas Industries - Corrosion-Resistant Alloy Seamless Tubular Products for Use as Casing, Tubing, Coupling Stock and Accessory Material - Technical Delivery Conditions, fourth ed., ISO, Geneva, 2020, p. 125.
[31] American Petroleum Institute (API), 5CRA Api Spec, Corrosion Resistant Alloy Seamless Tubes for Use as Casing, Tubing and Coupling Stock, first ed., API, Washington, DC, 2010, p. 97.
[32] International Organization for Standardization (ISO), ISO 10426-1: Petroleum and Natural Gas Industries - Cements and Materials for Well Cementing - Part 1: Specification, third ed., ISO, Geneva, 2009, p. 38.
[33] American Petroleum Institute (API), API Spec 10A: Cements and Materials for Well Cementing, 25th ed., API, Washington, DC, 2019, p. 76.
[34] American Petroleum Institute (API), API TR 10TR1: Cement Sheath Evaluation, second ed., API, Washington, DC, 2008.
[35] American Petroleum Institute (API), API Std 65-2: Isolating Potential Flow Zones during Well Construction, second ed., API, Washington, DC, 2010, p. 96.
[36] International Organization for Standardization (ISO), ISO 14310: Petroleum and Natural Gas Industries - Downhole Equipment - Packers and Bridge Plugs, second ed., ISO, Geneva, 2008, p. 27.
[37] American Petroleum Institute (API), API Spec 11D1: Packers and Bridge Plugs, fourth ed., API, Washington, DC, 2021, p. 82.
[38] M. Picha, M. Abu Bakar, P. Patil, F. Abu Bakar, D. Das, P. Tiwari, Overcoming CO_2 injector well design and completion challenges in a carbonate reservoir for world's first offshore carbon capture storage CCS SE asia project, in: Abu Dhabi International Petroleum Exhibition & Conference, Abu Dhabi, 2021.
[39] P. Patil, A. Hamimi, M. Abu Bakar, D. Das, P. Tiwari, P. Chidambaram, M. Jalil, Determining long-term fate of a CO_2 sequestration project utilizing rigorous well integrity risk assessment strategy, in: Offshore Technology Conference Asia, Kuala Lumpur, 2022.
[40] P. Tiwari, D. Das, P. Patil, P. Chidambaram, M. Picha, F. Abu Bakar, Converting development wells to observations wells to aid reservoir and overburden monitoring for CO_2 sequestration in a depleted carbonate field, in: Abu Dhabi International Petroleum Exhibition & Conference, Abu Dhabi, 2021.
[41] M. Picha, A. Chuttani, Storage development plan SDP for abandoning high risk development wells and drilling fit-for-purpose CO_2 injectors offshore carbon capture storage CCS project, in: IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition, Bangkok, 2022.
[42] P. Patil, D. Das, P. Tiwari, P. Chidambaram, R. Leite, M. Picha, H. Hakim, F. Abu Bakar, Subsea Re-abandonment strategies for high-risk wells to minimize leakage risk in a depleted field for CO_2 storage, in: Abu Dhabi International Petroleum Exhibition & Conference, Abu Dhabi, 2021.
[43] Total, "Carbon Capture and Storage, the Lacq Pilot - Project and Injection Period 2006-2013, Total, Paris, 2015.
[44] D. Tanase, J. Tanaka, Progress of CO_2 injection and monitoring of the tomakomai CCS demonstration project, in: 15th Greenhouse Gas Control Technologies Conference, GHGT-15, Abu Dhabi, 2021.
[45] Y. Sawada, J. Tanaka, C. Suzuki, D. Tanase, Y. Tanaka, Tomakomai CCS demonstration project of Japan, CO_2 injection in progress, Energy Proc. 154 (November 2018) 3–8.
[46] Y. Tanaka, Y. Sawada, D. Tanase, J. Tanaka, S. Shiomi, T. Kasukawa, Tomakomai CCS demonstration project of Japan, CO_2 injection in process, Energy Proc. 114 (July 2017) 5836–5846.
[47] M. Sugihara, Y. Nishi, H. Ikeda, K. Nawa, T. Ishido, Monitoring CO_2 injection at the tomakomai field using high-sensitivity continuous gravimetry, Energy Proc. 114 (July 2017) 4020–4027.
[48] T. Meckel, Y. Feng, R. Treviño, D. Sava, High-resolution 3D marine seismic acquisition in the overburden at the tomakomai CO_2 storage project, offshore hokkaido, Japan, Int. J. Greenh. Gas Control 88 (September 2019) 124–133.
[49] P. D'Alesio, R. Poloni, P. Valente, P.A. Magarini, Well integrity assessment and assurance: the operational approach for three CO_2 storage fields in Italy, in: SPE Annual Technical Conference and Exhibition, Florence, 2010.
[50] T. Tsuji, T. Matsuoka, W. Kadir, M. Hato, T. Takashasi, M. Sule, K. Kitamura, Y. Yamada, K. Onishi, D. Widarto, R. Sebayang, A. Prasetyo, A. Priyono, T. Ariadji, B. Sapiie, E. Widianto, A. Asikin, Reservoir characterization for site selection in the Gundih CCS project, Indonesia, Energy Proc. 63 (2014) 6335–6343.
[51] M. Parker, J. Meyer, S. Meadows, Carbon dioxide enhanced oil recovery injection operations technologies (poster presentation), Energy Proc. 1 (1) (February 2009) 3141–3148.
[52] T. Syed, T. Cutler, Well integrity technical and regulatory consideration for CO_2 injection wells, in: SPE International Conference on Health, Safety and Environment in Oil and Gas Exploration and Production, Rio de Janeiro, 2010.
[53] M. Kelly, J. Main, D. Jackman, J. Lundeen, Indonesia: Pilot Carbon Capture and Storage Activity in the Natural Gas Processing Sector, Battelle Memorial Institute, Asian Development Bank (ADB), Ohio, 2019.
[54] J. Meyer, Summary of Carbon Dioxide Enhanced Oil Recovery (CO_2 EOR) Injection Well, American Petroleum Institute (API), Texas, U.S., 2007.
[55] B. Freifeld, C. Oldenburg, P. Jordan, L. Pan, S. Perfect, J. Morris, J. White, S. Bauer, D. Blankenship, B. Roberts, G. Bromhal, D. Glosser, D. Wyatt, K. Rose, Well Integrity for Natural Gas Storage in Depleted Reservoirs and Aquifers, U.S. Department of Energy, National Energy Technology Laboratory, Morgantown, 2016.
[56] T. Watson, Surface casing vent flow repair-A process, in: Canadian International Petroleum Conference, Calgary, 2004.
[57] B. Marbun, D. Prasetyo, H. Prabowo, D. Susilo, F. Firmansyah, J. Palilu, I. Silamba, D. Santoso, W. Kadir, R. Sule, I. Kardani, W. Saprudin, B. Andhika, Well integrity evaluation prior to converting a conventional gas well to CO_2 injector well - Gundih CCS pilot project in Indonesia (phase 1), Int. J. Greenh. Gas Control 88 (September 2019) 447–459.
[58] F. Mulyasari, A. Harahap, A. Rio, R. Sule, W. Kadir, Potentials of the public engagement strategy for public acceptance and social license to operate: case study of carbon capture, utilisation, and storage Gundih pilot project in Indonesia, Int. J. Greenh. Gas Control 108 (June 2021).
[59] M. Sule, Decarbonization Strategy in Indonesia by Implementing CCUS, UKCCSRC Virtual Autumn Conference, 2021.

[60] Asian Development Bank (ADB), Carbon Dioxide-Enhanced Oil Recovery in Indonesia: an Assessment of its Role in a Carbon Capture and Storage Pathway, ADB, Manila, Philippines, 2019.
[61] R. Sule, F. Mulyasari, W. Kadir, Risk analysis of Gundih carbon capture utilization and storage: implications and challenges of risk governance of technological advancement for climate change mitigation, DKI Jakarta, Indonesia, 2022, in: 1st International Conference on Contemporary Risk Studies, ICONIC-RS, South Jakarta, 2022.
[62] T. Tsuji, T. Matsuoka, T. Takahashi, K. Kitamura, K. Onishi, Y. Yamada, M. Sule, W. Kadir, D. Widarto, R. Sebayang, A. Prasetyo, A. Priyono, E. Widianto, B. Sapiie, Pilot CCS Project in Indonesia "Gundih CCS Project": Geological and Geophysical Surveys for Site Selection and Monitoring, EGU General Assembly, 2013.
[63] K. Johnstone, Z. Zulkifli, Jepon-1 CCS Project Wells Review, LIoyd's Register, 2017.
[64] N. Morita, Elastic-plastic behavior and limit load analysis of casings, in: IADC/SPE Asia Pacific Drilling Technology Conference, Bangkok, 2022.
[65] S. Axelsen, R. Gonzalez, G. Mortali, A CO_2 Injection Well: Upsets to Regular Injection Service and Their Effect upon the Corrosion to the Materials of Construction, CORROSION 2016, Vancouver, 2016.
[66] W. Crow, J. Carey, S. Gasda, D. Williams, M. Celia, Wellbore integrity analysis of a natural CO_2 producer, Int. J. Greenh. Gas Control 4 (2) (March 2010) 186–197.
[67] S. Sarkar, M. Toksöz, D. Burns, Fluid Flow Modeling in Fractures, Earth Resources Laboratory, Cambridge, 2004.
[68] K. Gray, E. Podnos, E. Becker, Finite element studies of near-wellbore region during cementing operations: Part I, in: Production and Operations Symposium, Oklahoma, 2007.
[69] D. Checkai, Estimating Permeability Distribution of Leakage, Austin, 2012.
[70] J. Jutten, A. Hayman, Microannulus effect on cementation logs: experiments and case histories, in: SPE Asia Pacific Oil and Gas Conference, 1993. Singapore.
[71] B. Aas, J. Sørbø, S. Stokka, A. Saasen, R. Statoil, Ø. Lunde, T. Vrålstad, Cement placement with tubing left in hole during plug and abandonment operations, in: IADC/SPE Drilling Conference and Exhibition, Texas, 2016.
[72] I. Kutasov, Empirical correlation determined downhole mud, Oil Gas J. 86 (50) (1988) 61–63.
[73] Y. Le Guen, J. Le Gouevec, R. Chammas, B. Gerard, O. Poupard, A. Van Der Beken, L. Jammes, CO_2 storage—managing the risk associated with well leakage over long timescales, in: SPE Asia Pacific Oil and Gas Conference and Exhibition, Perth, 2008.