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## Determination of an Appropriate Method and Economic Cost Estimation for Plug and Abandonment of H-11 Well in The Tambun Field

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**ABSTRACT** - In accordance with applicable regulations in Indonesia, oil and gas wells that are nearing the end of their well life cycle and are no longer economically viable for production must undergo plug and abandon (P&A) operations, with the costs of such operations borne by the operating company. Hence, the operating company needs to conduct a study to ensure that P&A operations can be carried out cost effectively while still complying with safety guidelines, operating standards, and applicable national regulations. This study discusses a comparison of appropriate methods for plug and abandonment (P&A) activities in directional wells and examines the technically and economically of the SNI 13-6910-2002 and NORSOK Standard D-010 methods. The Tambun field consists of several production wells, including the H-11 well, which is a directional well. This well serves as a reference for determining the implementation of plug and abandonment activities once the well's condition reaches its economic limit. Plug and abandonment (P&A) activities at the Tambun field are carried out by designing a work plan to determine the zone sections to be cemented by calculating the volume of cement, additives, and completion fluids using the rig method. The results of this study are to determine the appropriate method and estimated costs that need to be prepared to carry out well abandonment activities in accordance with the year of well abandon using the SNI 13-6910-2002 and NORSOK Standard D-010 methods. The cost estimate for H-11 well using SNI 13-6910-2002 is 505,737.59 USD, while for NORSOK Standard D-010 it is 1,170,558.11 USD. Therefore, based on the comprehensive technical evaluation, operational safety, regulatory compliance, and economic evaluation, the SNI 13-6910-2002 method is recommended for plug and abandonment of the H-11 well in Tambun field.

**Keywords:** plug and abandonment, cost estimation, cement plug, SNI 13-6910-2002, NORSOK Standard D-010.

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## 1. Introduction

The upstream oil and gas industry is a capital-intensive sector that relies on advanced technology to minimize operational risks. One of the major challenges associated with oil and gas operations is their potential environmental impact. Exploration and production activities may directly or indirectly alter environmental conditions (Abrahamsen & Selvik 2020; Afrisca & Darmawan 2020). Consequently, governments, operating companies, and other stakeholders are responsible for protecting and managing the environment to prevent pollution, mitigate environmental degradation and maintain ecosystem sustainability (Herndon & Smith 1976; Abrahamsen & Selvik 2020).

Production sharing contract (PSC) contractors are required to decommission production facilities and supporting infrastructure by permanently disabling their operational capability, including performing permanent plug and abandonment (P&A) of wells. The primary objective of P&A is to isolate hydrocarbon-bearing formations and prevent fluid migration from the reservoir to the surface, thereby ensuring environmental protection and public safety. In addition, operators are required to restore the affected site and submit an Abandonment and Site Restoration (ASR) reserve fund report for each field, including the estimated costs of well abandonment as part of ASR budget nomination (SKK Migas 2023).

Well abandoned activities or commonly known as plug and abandonment (P&A) refers to the permanent closure of wells that are no longer economically viable for hydrocarbon production (Abrahamsen & Selvik 2020; Afrisca & Darmawan 2020). This process involves installing permanent barriers capable of containing formation pressure and preventing hydrocarbons or formation fluids from migrating to surface (Herndon & Smith 1976). Based on Work Procedure Guidelines of SKK Migas No. 040/PTK/SKKIA0000/2023/S9Rev.02, P&A is defined as the permanent plugging of well that are no longer required for production, have no further development potential, or have been classified as dry holes (SKK Migas 2023).

Permanent well abandoned may be required for several reasons, including severe formation problems, irretrievable downhole equipment (fish), or the attainment of well's economic limit, beyond which continued production is no longer profitable (Kaiser & Liu 2014; Corina 2020). The oil and gas production of a well naturally declines over time until it reaches an economic threshold established by the operating company, after which continued production is considered uneconomic (Prasetya 2018; Corina 2020).

Kaiser & Dodson (2007) and Kaiser & Liu (2014) classified well status into several categories, including drilling, completed, temporary shut-in, temporarily abandoned, and permanently abandoned. At the end of the production contract, wells are permanently abandoned under one or more of the following conditions:

- Hydrocarbons are discovered in marginal quantities that do not justify commercial production, resulting in immediate abandonment after drilling.
- Production declines over time until it falls below the established economic limit.
- Irreparable well integrity failures or leaks pose unacceptable operational or environmental risks.
- The production contract expires, and no future field redevelopment is planned.

Given the potential signatures, permanent well abandoned should be implemented in accordance with applicable regulations to ensure environmental protection and sustainable resource management (Lukmana 2019). The Indonesian National Standard SNI 13-6910- 2002 states that “all wells should be abandoned in such a way as to ensure belowground isolation of hydrocarbons and to maintain fluid movement from the formation into the wellbore”.

Effective plug and abandonment (P&A) is essential for maintaining long-term well integrity by preventing fluid migration between geological formation and the surface, thereby reducing environmental risks throughout the well life cycle (Darmawan 2021). Recent studies indicate that integrating well integrity evaluations into field development planning and ageing-well management improves operational reliability while reducing uncertainty in engineering decision-making (Prayitno et al., 2026). Accordingly, an effective P&A design should provide reliable well barriers while complying with applicable technical and environmental standards.

Permanent well abandonment in Indonesia is regulated in SNI-13-910-2002, which was established by the [National Standardization Agency \(2002\)](#). The standard divides permanent abandonment into two principal stages: reservoir abandonment and surface plugging. [Kaiser \(2017\)](#) further described the overall abandonment process as consisting of planning, obtaining regulatory approvals, conducting permanent well abandoned operations, removing the wellhead and completing final reporting. Well abandoned activities or commonly known as Plug and Abandonment (P&A) are activities carried out when the condition of the well is considered uneconomical to produce. The activity carried out to stop the well is to apply pressure to the well so that the formation pressure does not burst to the surface. [Technology Subgroup \(2011\)](#) states that well abandoned is necessary to create barriers that prevent hydrocarbon leakage from the formation into the wellbore or to the mudline or surface and prevent pollution of water sources around the well environment. Several cement placement techniques are commonly used during P&A operations, including the balanced plug, dump bailer, and two-plug methods ([Suhascaryo & Anugrah 2023](#); and [Suranta et al., 2026](#)).

The Tambun field is one of oil and gas producing fields located in the Northern part of the West Java working area, with sandstone and limestone as the primary reservoir formations. The H-11 well was selected as the case study for planning permanent abandonment and estimating the associated costs required to fulfil abandonment and site restoration (ASR) obligations. Production data indicate that the H-11 well no longer contains economically prospective zones for further development. Consequently, the well has reached the end of its productive life and should be permanently abandoned, particularly because it is located near a densely populated area. The main objective of this study is to compare two methods that could be used to carry out permanent well abandonment in accordance with national and international standards at H-11 well based on SNI 13-6910-2002 and [NORSOK Standard D-010](#) to achieve the most efficient and cost-effectiveness results.

The study first applied the National Standard SNI 13-6910-2002 method in planning the plug and abandonment process, as this standard specifies the required cement length intervals for sealing the well in the perforation zone, open holes, casing stubs, the annulus, surface plugs, plug testing, fluids to be left in the wellbore, and site cleanup. Second, based on [NORSOK Standard D-010](#), the regulation includes provisions for primary well barriers to prevent fluid flow into the wellbore or to the surface. Furthermore, a secondary well barrier serves as an additional plug to assist the primary well barrier in blocking fluid flow, while an environmental isolation plug is designed to ensure the safety of the borehole within the casing and the annulus. The method used to install the cement plug is the balance plug method. This method was chosen due its common use in plug-and-abandonment operations. It does not require specialized equipment that could increase P&A costs, and is easier to implement than other methods. SNI 13-6910-2002 and [NORSOK Standard D-010](#) both provide guidance for plug and abandonment planning. However, limited comparisons are available for their technical and economic performance of Indonesian mature onshore wells. This comparison is particularly relevant for the H-11 well since the selected abandonment strategy should not only comply with Indonesian regulations but also ensure adequate well integrity, operational safety, and cost-effectiveness. Therefore, the assessment of both standards gives a practical basis to select the most suitable abandonment method for mature wells under the Indonesian operating conditions.

## 2. Methodology

### 2.1 Theory

The plug and abandonment (P&A) design for the H-11 well in the Tambun Field was developed in accordance with the Regulation of the [Minister of Energy and Mineral Resources No. 15/2018](#), Article 10, which stipulates that contractor shall apply Indonesian National Standards (SNI) and or internationally recognized standards in implementing post-operation activities, as specified in the approved Post-Operation Activity plan ([Minister of Energy and Mineral Resources Regulation 2018](#)).

## 2.2 SNI 13-6910-2002 method

### 2.2.A Open-hole isolation

Isolation zone in open holes, cement plugs should be placed at least 100 ft below the layer up to 100 ft above the layer containing oil, gas or water to isolate the fluids in the layer where they are encountered and prevent flow to other layers or to the surface. Placement of additional cement plugs is required to prevent potential fluids from migrating into the wellbore. Cement plugs should be installed in the deepest casing by the plunger method at least 100 ft below the casing shoe to 100 ft above the casing shoe, if there is an open hole below the casing. Alternative methods of cement plugs along the casing shoe are as follows:

- Cement retainer with cement plug. The cement retainers should provide effective back-pressure control and be installed between 50 ft and 100 ft above the casing shoe. Meanwhile, the cement plug should be installed at least 100 ft below the casing shoe and to 50 ft below the retainer.
- Permanent bridge plug. A permanent bridge plug should be installed 150 ft above the casing shoe with a minimum 50-ft cement plug placed above the bridge plug. This method is recommended when circulation losses are anticipated or encountered. The bridge plug should be tested in accordance with applicable regulations.

### 2.2.B Isolating of perforated intervals

Cement plug installation shall be carried out by pushing through all uncemented perforations. The cement plug press shall extend at least 100 ft above the perforation interval to 100 ft below the perforation interval or to the nearest casing plug. Acceptable methods to replace preference and placement of cement plugs are:

- Installation of cement retainer and cement plug are both mandatory. Cement retainers shall be capable of effective back pressure control and shall be installed at least 50 ft and a maximum of 100 ft above the perforation interval. While cement plugs must be able to reach a minimum of 100 ft below the perforation interval and 50 ft above the retainer.
- The permanent-type bridge plug shall be installed at 150 ft above the crest and the perforation interval at least 50 ft above the bridge plug.
- Installation of cement plugs at least 200 ft long using the plunger method with the base of the plug at a distance of 100 ft above the top of the perforation interval.

### 2.2.C Casing stump plugging

The methods used when the casing is cut and removed, the casing stump must be plugged with:

- Stumps within the casing string must be plugged with cement plugs a minimum of 100 ft above and 100 ft below the stump. Alternatives used to replace the cement plug covering the stump, as follows: cement retainer or permanent type bridge plug should be installed at least 50 ft above the stump with at least 50 ft of cement; and cement plugs that are at least 200 ft long shall be installed with the base of the plug at least 100 ft above the stump.
- Zone plugging or open hole isolation shall be implemented as applicable, if the stump is 1

### 2.2.D Annular isolation

Any annular space connected to an open hole extending to the mud line shall contain a cement barrier with a minimum length of 200 ft.

### 2.2.E Surface plugs

A surface cement plug shall have a minimum length of 150 ft and be installed with its top located 150 ft below the mud line. The smallest casing string extending to the surface shall also be filled with cement.

### 2.2.F Plug verification

After plug placement, verification shall be performed as follows:

- The operator has an obligation to perform a load test with a minimum weight of 15,000 pounds on the cement retainer plug, or bridge plug. If the cement is above the separation plug or retainer, no test is required.

- The operator has an obligation to carry out a compressive test of the cement plug with a minimum pressure of 1000 psi for 15 minutes per section, The result shall not be less than 10% of the test pressure.

#### 2.2.G Fluid left in the well

Each consistent interval of the hole between the various cement plugs should be filled with fluid of sufficient specific gravity or appropriate to the zone conditions to have sufficient hydrostatic pressure to exceed the maximum formation pressure in the interval between plugs at the time of abandonment.

#### 2.2.H Site clearance

All wellheads, casing strings, piles and associated structures shall be removed to a depth of at least 30 ft below the resistant surface for onshore operations and 150 ft below the mud line for offshore operations. The Contractor shall ensure that the site is free of any interference. Where subsea wellheads or other obstructions do not pose a nuisance to other persons using the seabed or authorized users of the area, the need to remove them to protect the site may be limited or eliminated. Government environmental regulations must be realized to restore the area to its original condition.

### 2.3 NORSOK standard D-010 method

According to NORSOK Standard D-010, permanently abandoned wells should be periodically monitored to evaluate the long-term performance of well barriers and their potential interaction with geological and chemical processes. Well barriers are designed to prevent fluid leakage and minimise risks during drilling, production, workover, and abandonment operations (NORSOK Standard 2013; Achang et al. 2020).

The standard classifies well barriers into two categories:

- Primary well barrier. This is a barrier located adjacent to hydrocarbons. Assuming the primary well barrier is functioning effectively, it has the capacity to limit hydrocarbons that are pressurization. If the primary well barrier is not functioning, this is due to a leak or a valve that fails to close.
- Secondary well barrier. A barrier that serves to block the flow of pressurized hydrocarbons out of the well. If there is a failure of the secondary well barriers, there is the potential for the tertiary barrier to effectively block the flow of hydrocarbons.

A general description of the two categories of well barriers can be understood as, in the process of stopping the flow of oil wells, hydrostatic pressure serves as the primary barrier, while surface equipment such as blow out preventer (BOP) and casing cement serve as secondary barriers. Having at least one effective well barrier between the surface and the potential flow source is essential, except for subsurface formations with hydrocarbons and/or potential flow that require two well barriers. When performing plugging activities in reservoirs, it is important to consider the potential that can occur in connection with this part of the well (if the formation collapses, etc.) and to be able to create certain well barrier elements. Every complete borehole must be isolated. Whether or not there is pressure or flow potential, the last open hole section of a borehole cannot be permanently abandoned without installing a permanent well barrier.

The permanent well barrier will extend across the entire well section, including all annuli and act as a barrier, both vertically and horizontally. Because of this, well barrier elements placed in the casing and as part of the permanent well barrier, should be placed at depth intervals where there are well barrier elements of validated quality in all annulus. The properties a permanent well barrier needs to have are impermeable, long-term integrity, non-shrinking, ductile (not brittle), able to withstand mechanical/impact loads, resistance to various chemicals/substances (H<sub>2</sub>S, CO<sub>2</sub> and hydrocarbons), and discussion, to ensure bonding with cost.

### 2.4 Methodology

This study employed a mixed-method approach consisting of qualitative and quantitative. The H-11 well P&A plan was developed through qualitative approach. The quantitative approach was used for the calculation of the required cement slurry, additives, completion fluid, rig selection and the corresponding abandonment costs. The detailed research methodology is shown in Figure 1 as a flowchart. The integrated methodology was created to make sure the comparison between the SNI 13-6910-2002 and the NORSOK Standard D-010 methods was performed using the same well data, same operational assumptions and same cost estimation procedures. This approach allows to consistently evaluate the technical design, operational duration, and economic performance of the two standards for the H-11 well.

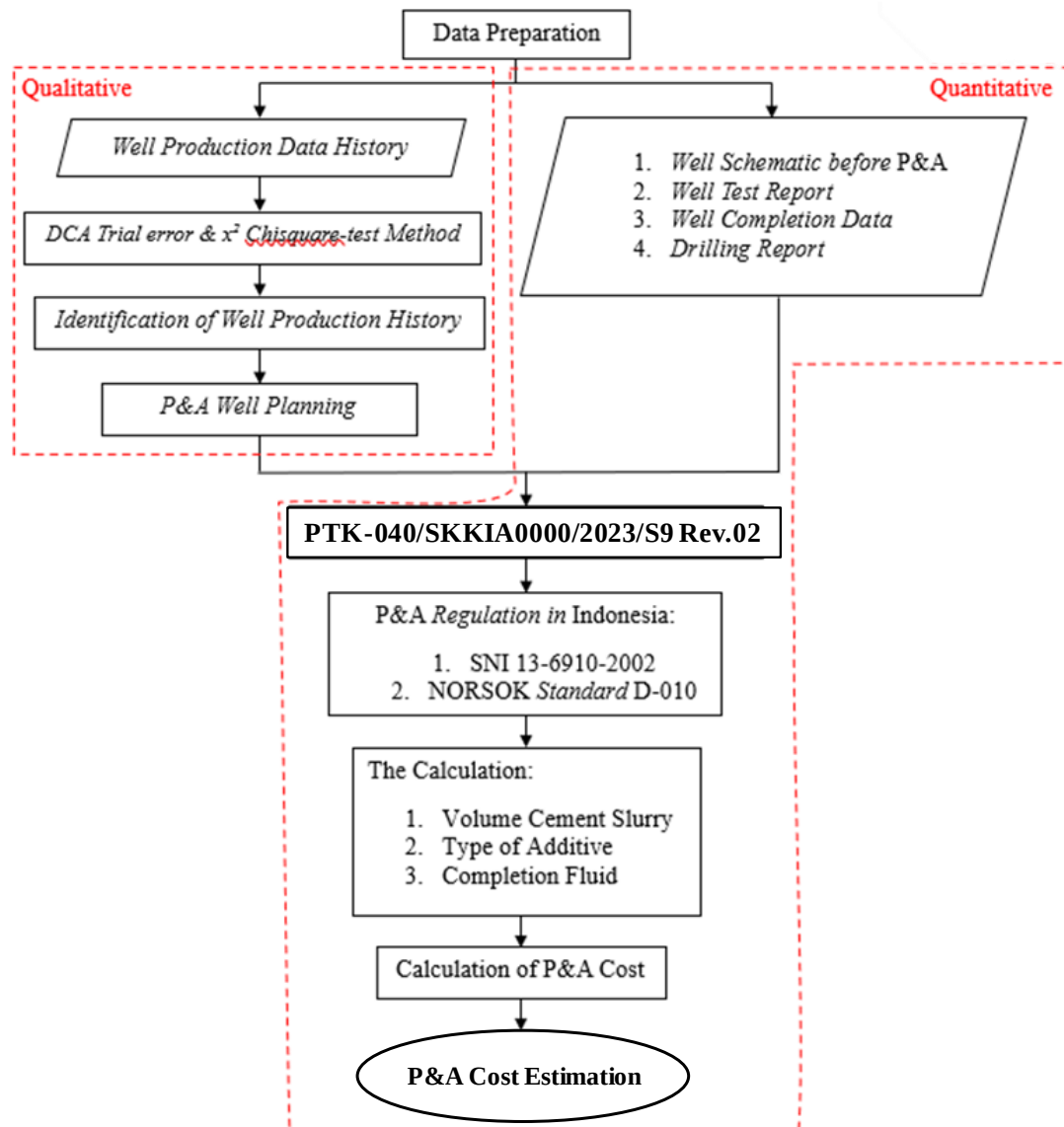


Figure 1.  
Flowchart methodology of the study

#### 2.4.A Qualitative analysis using decline curve analysis (DCA), trial-and-error, and chi-square methods

Decline curve analysis (DCA) is one of the methods that can be used to calculate the reserve estimate of a well. Calculations with this method are more commonly used because it only requires historical production data. The decline in production value observed in the production history data is a depiction of the reservoir productivity of a well without the problem of decreased production caused by several external factors, which reservoir conditions must be stable to be able to extrapolate the decline in the form of a curve (Arps 1944; Rukmana et al., 2018). According to Arps (1944) and Rukmana et al. (2018). The DCA is divided into three types, namely exponential, hyperbolic, and harmonic. The value to determine the type of decline used is commonly known as "b". The value of b only ranges from 0 to 1. If the value of  $b=0$  then the curve type is exponential. If the value of  $0 \leq b \leq 1$  then the type of curve is a hyperbolic curve. Meanwhile, if the value of  $b = 1$  then the type of curve is harmonic. The type of decline curve is determined before the calculation of the estimated reserves of a reservoir. The determination of the type of decline curve used in the research is the trial error and  $x^2$  Chisquare-test method because it has more concrete results.

#### 2.4.B Quantitative analysis of cementing calculations

Successful cementing depends not only on appropriate equipment and operational techniques but also on accurate engineering calculations and planning. The cementing design was developed using the following procedures:

- Determine the top and bottom depths of each cement plug
- Taking into account the capacity of the space to be cemented and the required cement slurry volume within the casing, the cement slurry volume can be calculated using the following equations.

- Calculation of Casing Capacity
 
$$\text{Casing Capacity (bbl/ft)} = \frac{\text{ID}^2}{1029.4} \quad (1)$$
 ID = Inside diameter of casing (inch)

- Calculation of the Perforation Interval Length
 
$$= \text{bottom of perforation} - \text{top of perforation} \quad (2)$$

- Calculation of Cement Column Length To account for the required safety factor, the cement column length is determined as:

$$\text{Length of the perforation column} + (\text{top of perforation} - \text{top of cement}) \\ (\text{bottom of cement} - \text{bottom of perforation}) \quad (3)$$

- Calculation of Cement Slurry Volume
 
$$= \text{Length of cement column, ft} \times \text{Casing Capacity} \quad (4)$$

#### 2.4.C Calculate the volume of cement slurry that fills the perforation

- Calculating Number of Perforation Holes
 
$$= \text{Length of the perforation column, ft} \times \text{density of perforation, spf} \quad (5)$$

- Calculating the volume of cement filling the perforation holes
 
$$= \frac{\text{total perforation holes} \times \text{hole/ft} \times \text{cement slurry cuft/hole}}{5.615} \quad (6)$$

Note:

Based on the Injectivity Test, Cement Slurry is divided into three parts:

- Tight Formation = 0.1 cuft/hole
- Moderate = 0.2 cuft/hole
- Loss/Sucking (>1 BPM) = 0.4 cuft/hole

#### 2.4.D Determine the top of cement inside the well.

- Calculating the height of cement when stringing in the hole, ft
 
$$= \frac{\text{Volume cement, bbl}}{\text{sann casing, bbl/ft} \times \text{sann DP, bbl/ft}} \quad (7)$$

- Calculation top of cement when string in hole,
 
$$\text{ft} = \text{bottom of cement} - \text{height cement when string in hole} \quad (8)$$

#### 2.4.E Calculate the total cement slurry volume:

$$\text{Volume of cement slurry in casing column} + \text{volume} \\ \text{of cement slurry filling perforation holes} + \text{dead volume} + \% \text{Excess, bbl} \quad (9)$$

#### 2.4.F Calculate the required number of cement sacks

$$\text{Sack of Cement, sack} = \frac{\text{Total volume cement slurry, bbl} \times 42}{\text{yield cement}} \quad (10)$$

#### 2.4.G Determine the volume of additives required for slurry preparation.

$$v_a = w_c \times v_u \quad (11)$$

Where  $v_a$ ,  $w_c$ , and  $v_u$  are Volume of additives to make slurry, gal, Quantity of dry cement used, sack, and Volume of additive per bag of cement, gal/sack, respectively.

2.4.H Calculate the completion fluid volume

$$= \text{Casing capacity (bbl/ft)} \times \text{Length of column (ft)} \quad (12)$$

2.4.I Determine the minimum rig horsepower requirement.

$$\text{Rig Capacity, HP} = \frac{W \times V_h}{33.000} \times \frac{1}{n} \quad (13)$$

where  $W$ ,  $V_h$ , and  $V_h$  Weight of drill pipe, Upward speed of traveling block, ft/min, and Efficiency hook to draw work.

2.4.J Estimate the Abandonment and Site Restoration (ASR) cost using the Time Value of Money (TVM)

Concept by:

- Determining the Volume and Components of the ASR Activity Plan
- Establishing an Estimated Market Value for each Cost Contributing Component
- Calculating the Volume of Activity Plan Components multiplied by the unit cost of each ASR Cost Component.
- Obtaining current ASR Cost Value
- Using the concept of time value of money, the cost at year  $N$  will be obtained by calculating the future value (year  $N$ ).

$$FV_n = PV \times (1 + r)^n \quad (14)$$

where  $FV_n$ ,  $PV$ ,  $r$ , and  $n$  are ASR cost in year  $n$ , ASR cost at the time of calculation, Average inflation rate, and Remaining ASR fund collection period. Furthermore,

$$\frac{FV_n - \text{asr fund balance}}{n} = \text{Total ASR Fund Reserve in the Year of Calculation} \quad (15)$$

### 3. Result and discussion

#### 3.1 Data preparation and DCA result

The data used in this study were obtained from H-11 well in the Tambun field located in Northern West Java. The available data included the well schematics, tubing and casing specifications, well perforation depth, cementing records (Figure 2), and historical production data. These datasets were used to design the plug and abandonment (P&A) program, including the calculation of cement, additive, and completion fluid requirements, work procedures, operational duration, and cost estimation. The P&A planning for the H-11 well was carried out in accordance with SNI 13-6910-2002 and NORSOK Standard D-010 methods. Based on the historical production data, a Decline curve analysis (DCA) was performed with a 40-year production forecast. The predicted production performance of the H-11 well is presented in Figure 3.

#### 3.2 Plug and abandonment (P&A) planning

The H-11 well was directionally drilled to a final depth of 8733.59 ftMD. The casing installation stage began with hammering the 30" casing conductor to a depth of 0 - 118.1 ftMD. Next, a hole was drilled using a 26" bit, and a 20" surface casing was installed with a depth of 0 - 2424.5 ftMD. The well was subsequently drilled using a 17½" bit, and a 13 3/8" intermediate casing was installed to 3595.8 ftMD. Drilling then continued with a 12¼-in bit, followed by installation of a 9¾-in production casing to 7,124.30 ftMD. Finally, an 8½-in hole was drilled, and a 7-in liner was installed from 6886.02 - 8730.3 ftMD.

#### 3.3 Plug and abandonment design based on SNI 13-6910-2002

The plug and abandonment plan for the H-11 well was developed using SNI 13-6910-2002 (National Standardization Agency 2002). The proposed abandonment configuration is illustrated in Figure 4.

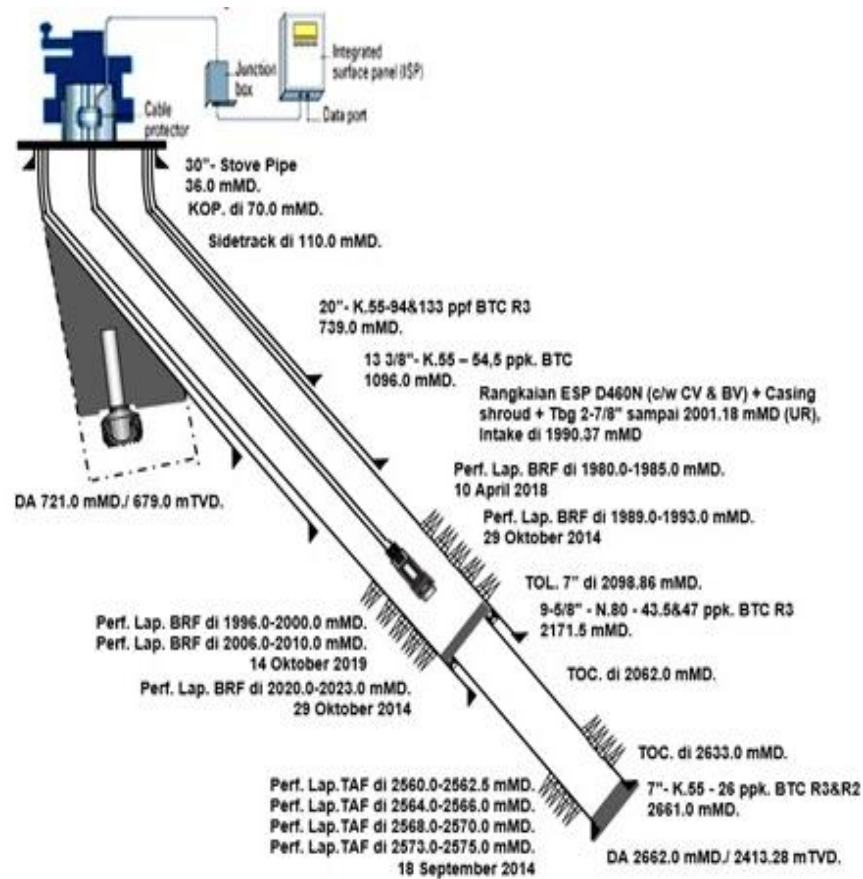


Figure 2.  
Well schematic, tubing, casing specifications and well perforations depth of the H-11 well before plug and abandonment (P&A).

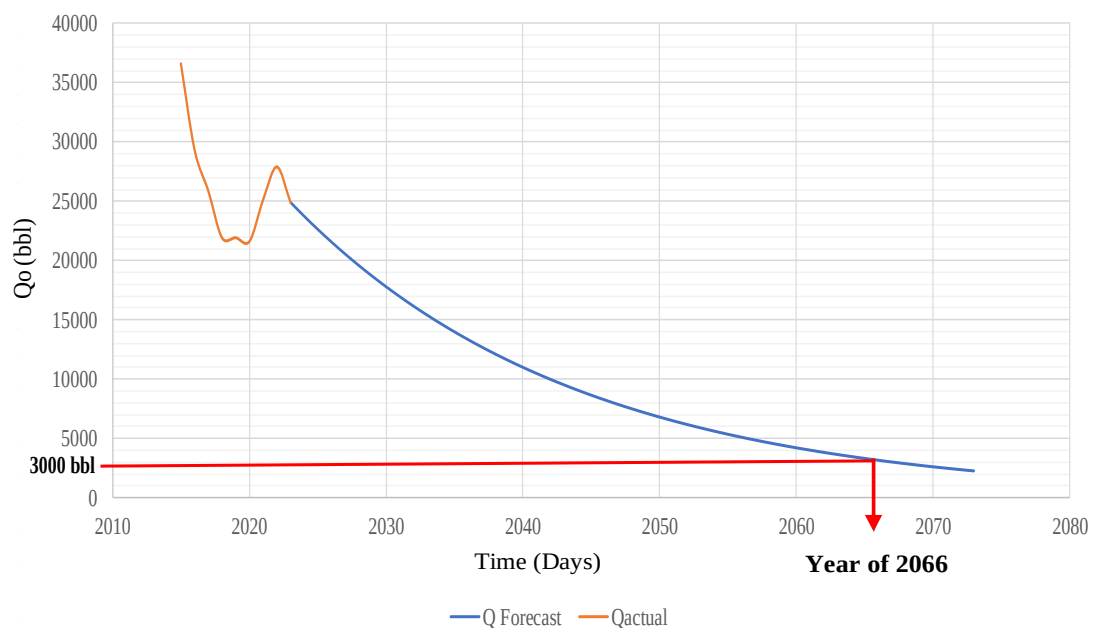


Figure 3.  
Decline curve analysis (DCA) forecast for the H-11 well result with  $q$ -limit 300 bbl and 40 years of production forecast through year of 2066.

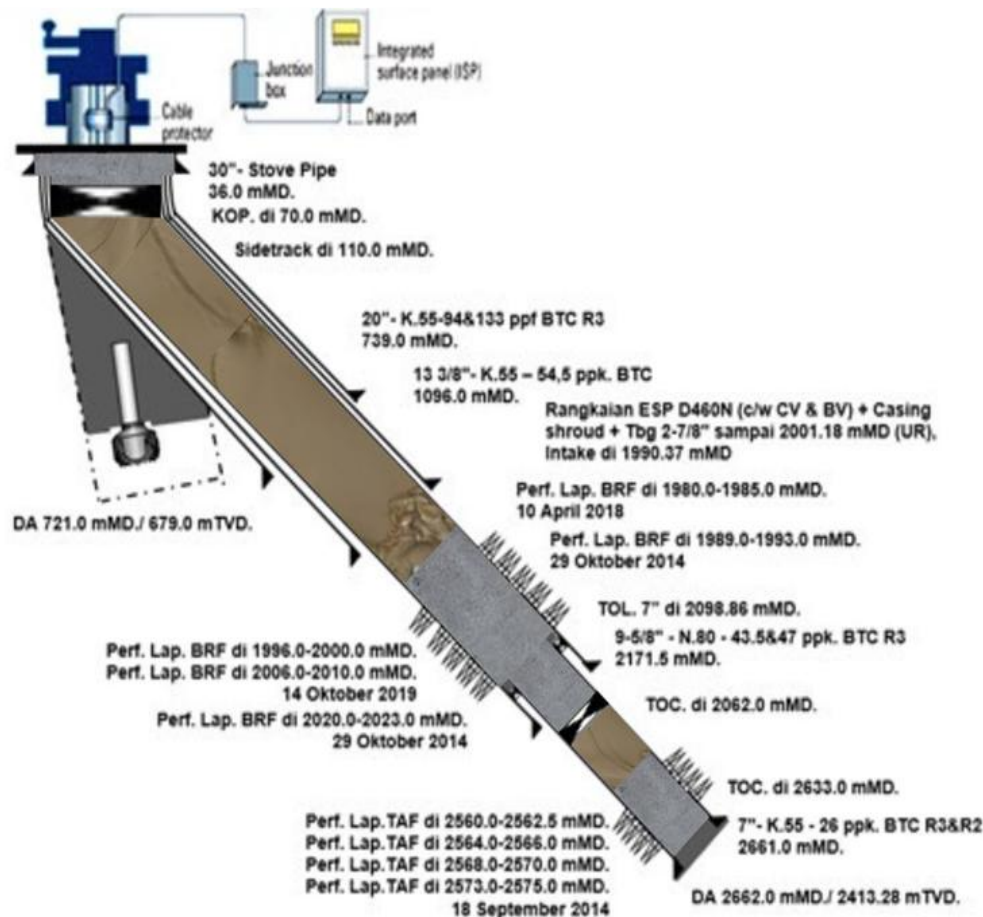


Figure 4.

Well schematic of the H-11 well after plug and abandonment (P&A) program conducted using SNI 13-6910-2002 method.

The proposed P&A program consists of the following cement plugs:

- Isolation of the perforated interval (8,298.95–8,638.45 ftMD). A cement plug is installed across the entire perforated interval in accordance with SNI 13-6910-2002, which requires the plug to extend at least 100 ft above and 100 ft below the perforated interval or to the nearest casing plug. Where adjacent perforated intervals exist, a single continuous cement plug may be used.
- Isolation of the perforated interval and casing stump (6,396.06–6,986.02 ftMD). A cement plug is installed to isolate both the perforated interval and the casing stump. This design complies with SNI 13-6910-2002, which requires the cement plug to extend at least 100 ft above and 100 ft below the casing stump while also satisfying the isolation requirements for the perforated interval.
- Surface plug (0–150 ftMD). A surface cement plug with a minimum length of 150 ft is installed in the smallest casing string extending to the surface, consistent with the requirements of SNI-13-6910-2002.

### 3.4 Plug and abandonment design based on NORSOK standard D-010

The plug and abandonment (P&A) work plan on well H-11 in Figure 5 refers to the NORSOK Standard D-010 method (NORSOK Standard, 2013), described as follows:

- Close the perforation interval (primary well barrier) by placing a cement plug at a depth of 8300.52 - 8638.45 ftMD. For this planning stage, the procedure was adapted from NORSOK Standard D-010, which specifies that the primary well barrier cement plug is installed to isolate formations that may allow fluid migration to the surface or between formations. The barrier is designed to isolate formations with normal to abnormal pressure and to prevent fluid migration from the formation to surface or seabed.

- Install the secondary well barrier by placing a cement plug at a depth of 8202.09 - 8300.52 ftMD, immediately above the primary well barrier. This procedure was adapted from NORSOK Standard D-010, which explains that the secondary well barrier functions as a backup barrier against potential fluid inflow and is installed above the primary well barrier to provide additional well integrity.
- Close the perforated interval zone or primary well barrier and top of liner by placing a cement plug at a depth of 6397.64 - 7222.77 ftMD. This planning stage was adapted from NORSOK Standard D-010, in which the primary well barrier cement plug isolates formations that could permit fluid migration. In addition, because the liner top is generally not cemented to the same extent as the casing annulus, an additional cement plug is required during plug and abandonment operations. The cement plug is extended to the next casing shoe to ensure complete isolation of the liner top and to establish an effective secondary well barrier.
- Install the secondary well barrier by placing a cement plug at a depth of 6299.21–6397.64 ft MD, immediately above the primary well barrier. This procedure was adapted from NORSOK Standard D-010, which specifies that the secondary well barrier functions as a backup barrier against potential fluid flow and enhances overall well integrity.
- Isolate each section of casing shoe by placing a cement plug at a depth of 3497.37 - 3694.22 ftMD. This planning stage was adapted from NORSOK Standard D-010, which recommends installing a cement plug at each casing shoe to serve as a secondary well barrier, providing additional protection in the event of primary barrier failure.
- Isolate each section of casing shoe by placing a cement plug at a depth of 2326.11 - 2522.96 ftMD. This procedure was adapted from NORSOK Standard D-010, which explains that placing a cement plug at each casing shoe to function as a secondary well barrier and provide backup support to the primary well barrier.
- Isolate the near surface zone by placing a cement plug at a depth of 0 - 150 ftMD. This planning stage was adapted from NORSOK Standard D-010, which recommends installing a cement plug across shallow formations containing freshwater to prevent contamination. Since freshwater aquifers are typically located in shallow formations, a surface cement plug is required to isolate these intervals and protect groundwater resources.

**Best Practices:** Best practices were identified through a comprehensive literature review of published field case studies on plug and abandonment operations. The review indicates that regulatory requirements should be incorporated into the early planning stage to ensure technical feasibility, operational safety, environmental protection, and regulatory compliance. Ultimately, the operator is responsible for selecting the most appropriate abandonment strategy based on well conditions, safety considerations, environmental risks, and economic performance.

**Cement Design:** Cement plugs should be designed according to the anticipated bottom-hole pressure and temperature at each plug location. Bottom-hole pressure primarily determines slurry density, whereas bottom-hole temperature governs the selection and concentration of cement additives to ensure adequate pumpability and compressive strength development. For the H-11 well, API Class G cement was selected together with silica flour, liquid dispersant, liquid retarder, fluid-loss-control additive, bonding agent, and defoamer. The additive concentration varies for each cement plug according to the downhole conditions and design requirements.

**Cement Placement:** Cement should be placed under controlled and well-conditioned wellbore conditions. In this study, the balanced plug method was selected because it is widely used in plug and abandonment operations, requires relatively simple equipment, and provides a cost-effective cement placement technique. The method involves lowering a drill pipe to the planned plug depth before pumping cement into the wellbore. A pre-flush is pumped ahead of the cement slurry to minimize mud contamination, followed by a spacer fluid to separate the drilling fluid from the cement slurry and improve cement placement quality.

### 3.5 Plug and abandonment calculation

The cement volume calculation for the perforated interval of the H-11 well was performed using the procedures described in the methodology. The perforated interval length between the uppermost and lowermost perforations is 16.40 ftMD. After applying the required safety margins of 100 ft above and 100 ft below the perforated interval in accordance with the applicable standards, the total cement plug length becomes 644.62 ftMD. The calculated cement slurry volume required to fill the casing is 24.67 bbl. The perforated interval has a perforation density of 82.02 shots/ft, requiring an additional 1.46 bbl of cement slurry to fill the perforation tunnels for the SNI 13-

6910-2002 design. The calculated cement column height during tubing placement is 773.49 ftMD, resulting in a top of cement (TOC) at 7,441.73 ftMD. Including the casing volume, perforation volume, dead volume, and excess slurry, the total cement slurry requirement is 36.96 bbl. Based on a slurry yield of 1.57 ft<sup>3</sup>/sack, the total cement requirement is 133 sacks. The complete cement volume calculations for both SNI 13-6910-2002 and NORSOK Standard D-010 are summarized in Table 1 dan Table 2, respectively.

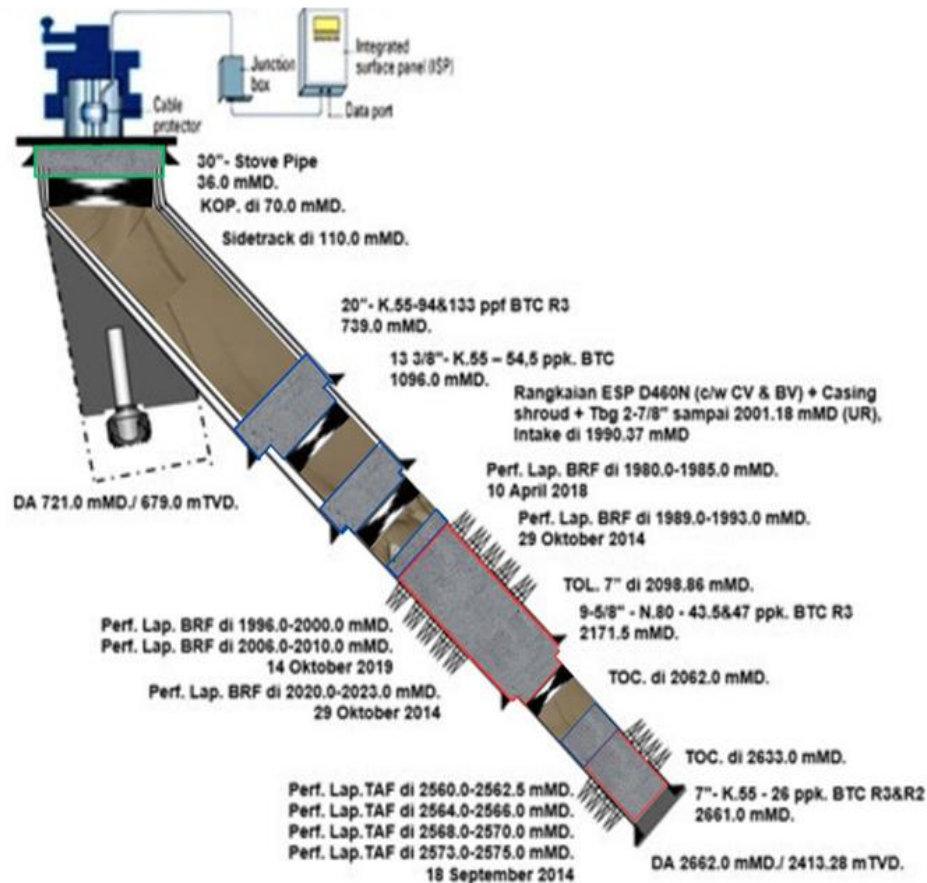


Figure 5.

Well schematic of H-11 well after plug and abandonment (P&A) program conducted using NORSOK Standard D-010 method.

Table 1.

Cement slurry P&A of the H-11 well using SNI 13-6910-2002 method

| No | Cement plug                             | Length of cement (ftMD) | Cement volume (bbl) | Cement quantity (sack) |
|----|-----------------------------------------|-------------------------|---------------------|------------------------|
| 1  | Bottom section (8298.95 - 8638.45 ftMD) | 339.50                  | 25.58               | 92                     |
| 2  | Middle section (6396.06 - 6986.02 ftMD) | 589.96                  | 69.79               | 250                    |
| 3  | Top section (0 - 150 ftMD)              | 150                     | 13.98               | 50                     |
|    | Total                                   |                         | 109.35              | 392                    |

Table 2.  
Cement slurry P&A of the H-11 well using NORSOK standard D-010 method

| No    | Cement plug                                                  | Length of cement (ftMD) | Cement volume (bbl) | Cement quantity (sack) |
|-------|--------------------------------------------------------------|-------------------------|---------------------|------------------------|
| 1     | Primary Well Barrier Section 1<br>(8300.52 - 8638.45 ftMD)   | 337.93                  | 25.51               | 92                     |
| 2     | Secondary Well Barrier Section 2<br>(8202.09 - 8300.52 ftMD) | 98.43                   | 6.77                | 25                     |
| 3     | Primary Well Barrier Section 3<br>(6397.64 - 7222.77 ftMD)   | 825.13                  | 82.59               | 296                    |
| 4     | Secondary Well Barrier Section 4<br>(6299.21 - 6397.64 ftMD) | 98.43                   | 10.21               | 37                     |
| 5     | Secondary Well Barrier Section 5<br>(3497.37 - 3694.23 ftMD) | 196.85                  | 10.53               | 38                     |
| 6     | Secondary Well Barrier Section 6<br>(2326.12 - 2522.97 ftMD) | 196.85                  | 10.53               | 38                     |
| 7     | Environmental Well Barrier Section 7<br>(0 - 150 ftMD)       | 150.00                  | 13.98               | 50                     |
| Total |                                                              |                         | 160.11              | 576                    |

### 3.1 Cement plug configuration

Cement plugs are positioned in the perforation interval isolation zone, top isolation of the liner, and surface insulation in accordance with SNI 13-6910-2002 as shown in Figure 4 and Table 1. According to the SNI 13-6910-2002 method, the plugging of the perforation zone intervals requires cement placement with a minimum distance of 100 ft above and below the perforation zone intervals, and a single cement plug is installed. Since the distance between the top of the liner and the perforation zone in both wells is close, a combined calculation was performed by integrating the two requirements for the perforation zone with the top-of-liner plugging, where the cement plug must extend at least 100 ft above and 100 ft below the perforation zone. A surface plug is installed at a depth of 0 - 150 ft; therefore, based on this method, the cement plug must be at least 150 ft long.

The existence of an over pressured zone is not taken into consideration when placing the cement plug. Therefore, if an issue arises during the P&A work, mitigation is required. It is not necessary to insert a cement plug for every component of the casing shoe section, provided that the cement plug pressure can sustain the well formation pressure. Since there are no additional hydrocarbon zones surrounding the well and the hydrocarbon zone is thought to be the only one, the isolation of the hydrocarbon-bearing zone is disregarded.

Meanwhile, with reference to NORSOK Standard D-010 method in Figure 5 and Table 2, cement plugs are positioned in the interval isolation zone, top of liner isolation, hydrocarbon bearing isolation zone as a secondary well barrier, isolation for each section of casing shoe, and isolation of the surface water zone (fresh water). It is necessary to place a cement plug across the transition interval, where the plug length is at least 200 feet or at least reaches normal pressure in certain casing sections, in order to account for the existence of an over pressured zone or abnormal pressure. Cementing must be done in each segment of the casing shoe while taking into consideration variations in the rock lithology of each formation. Considering a zone that contains other hydrocarbon intervals around the well, so that a cement plug is needed in that zone.

P&A work plan using the NORSOK Standard D-010 method on H-11 well, conducted at the perforation interval depth of 8300.52 - 8638.45 ftMD, a primary well barrier was installed as an isolation measure to prevent

the flow of residual fluid in the formation. Furthermore, an additional plug or secondary well barrier was installed at a depth of 8202.09 - 8300.53 ftMD to ensure the prevention of fluid flow from the perforated zone. Subsequently, the primary well barrier cement plug was also re-installed in the second perforation interval and combined with the cementing of each casing shoe and the top of the liner, due to the close proximity at a depth of 6397.64 - 7222.77 ftMD, followed by a secondary well barrier to prevent any potential backup inflow at a depth of 6299.21 - 6397.64 ftMD.

After that, at depths of 3497.36 - 3694.23 ftMD and 2326.12 - 2522.97 ftMD, a secondary well barrier was implemented to place cement plugs in each section of the casing shoe. Finally, a cement plug will be placed at a depth of 0 - 150 ft as an environmental cement plug, aimed at isolating the fresh water zone to prevent contamination and the surface zone to ensure no hydrocarbon fluid flows rise to the surface. The results of this study are consistent with the well barrier philosophy as specified in NORSOK Standard D-010 which recommends to use several independent barriers to enhance the long-term well integrity and to reduce the risk of fluid migration. Therefore, the NORSOK method needs more cement plug sections compared to the SNI 13-6910-2002 method. This increases the cement consumption and the operation time. Similar observations were reported by [Suhascaryo and Anugrah \(2023\)](#) who showed that additional cement barriers improve well isolation reliability but increase operational complexity and abandonment cost.

### 3.2 Work program

The method used for planning the P&A operations is the rig method, as Well H-11 does not present any issues requiring the use of a rig-less method and has normal well pressure. Based on the depth and horsepower (HP) required at well H-11 to carry out P&A operations, an ADI 12 rig with a power rating of 550 HP, even though only 488.05 HP was required at a depth of 8,733.6 ftMD.

The working time required to carry out the H-11 well with SNI 13-6910-2002 method takes 9.8 days operation, meanwhile with NORSOK Standard D-010 method is about 18 days of operation. Summary of the work programs for the P&A activities in the H-11 well are shown in [Table 3](#) and [Table 4](#), respectively. The additional cement plug installation and well barrier verification needed to satisfy the barrier philosophy of the NORSOK Standard D-010 method is the primary reason for the longer operational duration required by this method. On the other hand, SNI 13-6910-2002 method requires fewer cementing stages, but still fulfills the minimum technical requirements that set out by Indonesian regulations. Thus, the difference in operational length is a question of technical design differences, not operational efficiency.

Table 3.  
Work programs for the P&A activities in the H-11 well using SNI 13-6910-2002 method

| No                         | Activities            | Working Time (hours) |
|----------------------------|-----------------------|----------------------|
| 1                          | Work Planning         | 68                   |
| 2                          | Cement Plug Section 1 | 52                   |
| 3                          | Cement Plug Section 2 | 64                   |
| 4                          | Cement Plug Section 3 | 51                   |
| Total Working Time (hours) |                       | 235                  |
| Total Working Time (Days)  |                       | 9.8                  |

Table 4.  
Work programs for the P&A activities in the H-11 well using NORSOK Standard D-010 method.

| No                         | Activities            | Working Time (hours) |
|----------------------------|-----------------------|----------------------|
| 1                          | Work Planning         | 68                   |
| 2                          | Cement Plug Section 1 | 48                   |
| 3                          | Cement Plug Section 2 | 44                   |
| 4                          | Cement Plug Section 3 | 71                   |
| 5                          | Cement Plug Section 4 | 36                   |
| 6                          | Cement Plug Section 5 | 58                   |
| 7                          | Cement Plug Section 6 | 55                   |
| 8                          | Cement Plug Section 7 | 53                   |
| Total Working Time (hours) |                       | 433                  |
| Total Working Time (Days)  |                       | 18                   |

### 3.1 Economic analysis

Based on calculations in 2026 using the SNI 13-6910-2002 method, the estimated cost for the H-11 well is USD 179,276.30. Meanwhile, using the NORSOK Standard D-010 method, the cost is USD 414,945.09. As for the estimated costs required based on calculations in 2066 for the H-11 well using the SNI 13-6910-2002 method, the cost is 505,737.59 USD, and the NORSOK Standard D-010 method is 1,170,558.11 USD. A summary of the estimated P&A well costs is shown in Table 5. The dominant contributor is the rig cost which is USD 158,589.18 in the NORSOK Standard D-010 method against USD 78,738.06 in the SNI 13-6910-2002 method. Likewise, the cement plug unit cost rises from USD 43,090.60 to USD 157,122.00 because of the seven cement plug sections used by the NORSOK method instead of three. The additional plug sections also increase the cement slurry volume from 109.35 bbl to 160.11 bbl and extend the operational duration from 9.8 to 18 days, which results in a significantly higher total abandonment cost.

Factors affecting the total estimated cost of plug and abandonment (P&A) activities are the use of both SNI 13-6910-2002 and NORSOK Standard D-010 methods, the difference in well depth, the number of plug sections, the length of the cement area, the volume of cement required, the volume of additives used, and the volume of completion fluid added, as well as the cost of rig rental.

The results show that the higher abandonment cost of the NORSOK Standard D-010 approach is mainly due to its more conservative well barrier design requiring additional cement plug sections and longer rig time. This method does increase the operational costs, but provides for an additional layer of redundancy to ensure well integrity and operational safety. Meanwhile, SNI 13-6910-2002 method required the less cement plug section, but still satisfy the technical requirements for well isolation based on Indonesian standards. Therefore, for the H-11 well in Tambun field, the SNI method represents the most cost-effective abandonment strategy without compromising regulatory compliance or operational safety.

## 4. Conclusion

Based on the results of the analysis and study that has been carried out, the H-11 well is expected to reach its economic limit and be permanently abandoned in 2066. The proposed plug and abandonment operation employs the balanced plug cementing method using a conventional 550-HP drilling rig with 3½-in drill pipe for the 8,733.59-ftMD well. From a technical perspective, the SNI 13-6910-2002 design requires an estimated operational duration of 9.8 days, whereas the NORSOK Standard D-010 design requires approximately 18 days because of the installation and verification of additional well barriers. Economic analysis indicates that the projected abandonment cost in 2066 is USD 505,737.59 using SNI 13-6910-2002, compared with USD 1,170,558.11 using NORSOK Standard D-010. Considering the technical assessment, operational duration,

regulatory compliance, and economic evaluation, SNI 13-6910-2002 is recommended as the preferred abandonment method for the H-11 well. Compared with the NORSOK approach, the SNI method reduces the operational period from 18 days to 9.8 days and decreases the projected abandonment cost by approximately 57%, while satisfying the applicable Indonesian technical standards for permanent well abandonment requirements.

Table 5.  
Summary of the P&A H-11 well cost estimation using SNI 13-6910-2002 and NORSOK Standard D-010 methods.

| No | Cost components             | Cost estimation (USD) |                       |
|----|-----------------------------|-----------------------|-----------------------|
|    |                             | SNI 13-6910-2002      | NORSOK Standard D-010 |
| 1  | Engineers                   | 15,295.41             | 22,818.06             |
| 2  | Rig                         | 78,738.06             | 158,589.18            |
| 3  | Cement Slurry and Additives | 11,222.62             | 17,591.07             |
| 4  | Cementing Plug Unit         | 43,090.60             | 157,122.00            |
| 5  | Bridge Plug                 | 14,932.00             | 27,922.00             |
| 6  | Completion Fluid            | 3,765.56              | 7,005.41              |
| 7  | H <sub>2</sub> S Safety     | 3,790.43              | 6,962.02              |
| 8  | Fuel                        | 8,441.62              | 16,935.35             |
|    | Estimated Value in 2026     | 179,276.30            | 414,945.09            |
|    | Estimated Value in 2066     | 505,737.59            | 1,170,558.11          |

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## 6. Declarations

### 6.1 Author contributions

L.A. Yusgiantoro: Supervision, conceptualization, methodology, formal analysis, data curation, resources, writing original draft, writing review & editing. D. Kristanto: Supervision, conceptualization, methodology, formal analysis, data curation, writing original draft, writing review & editing. D.S. Wicaksono: Conceptualization, methodology, investigation, validation, data curation, formal analysis, resources, writing original draft. K. Larasati: Conceptualization, methodology, investigation, data curation, formal analysis, validation, visualization, writing original draft. V.R. Stephanie: Conceptualization, methodology, investigation, data curation, formal analysis, validation, visualization, writing original draft. G. Irawan: Supervision, conceptualization, methodology, formal analysis, data curation, resources, writing review & editing.

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

### 6.3 Competing interest

The authors declare that there is no funding in the study.

## 6.4 The use of AI-assisted technologies

None

## 7. Glossary of terms and symbols

| Terms & Symbol | Definition                       | Unit   |
|----------------|----------------------------------|--------|
| ASR            | Abandonment and site restoration |        |
| BPM            | Barrel per minute                |        |
| CTU            | Coiled tubing unit               |        |
| CF             | Completion fluid                 |        |
| DCA            | Decline curve analysis           |        |
| HP             | Horse power                      |        |
| KOP            | Kick off point                   |        |
| MD             | Measuring depth                  |        |
| NW             | North West                       |        |
| P&A            | Plug and abandonment             |        |
| SF             | Safety factor                    |        |
| TVD            | True vertical depth              |        |
| Sann           | Annulus capacity                 | bbl/ft |
| $\eta$         | Efficiency                       | %      |
| W              | Weight                           | lbs    |
| Vh             | Power rating                     | ft/min |

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