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Challenges in Cement Integrity in Geothermal Wells: A Study of Dieng Geothermal Field

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ABSTRACT

Cement integrity plays a crucial role in geothermal well construction, ensuring zonal isolation, casing support, and long-term well stability. The Dieng Geothermal Field presents unique challenges in maintaining cement integrity due to extreme reservoir temperatures exceeding 300°C, highly permeable volcanic formations, and the presence of corrosive gases such as CO_2 and H_2S. These conditions can lead to thermal stress, chemical degradation, and loss circulation, all of which compromise cement performance over time. This study examines the key challenges affecting cement integrity in the Dieng Geothermal Field and evaluates potential mitigation strategies. Advanced cement formulations with silica-enhanced additives, acid-resistant materials, and stage cementing techniques are essential in improving cement stability under high-temperature conditions. Additionally, real-time monitoring tools such as cement bond logs (CBL) and ultrasonic imaging technologies are critical for assessing cement integrity and identifying early failure indicators. The findings of this study emphasize the necessity of a tailored cementing approach to address the specific geological and operational challenges of geothermal wells. By implementing optimized cementing techniques and monitoring systems, operators can enhance the longevity and reliability of geothermal wells, ensuring sustainable energy production from the Dieng Geothermal Field.

Keywords: cement integrity, geothermal well, high temperature

I. INTRODUCTION

Cementing is a fundamental process in well construction that involves pumping cement slurry into the annular space between the casing and the formation. Beyond its primary function of zonal isolation, cementing also provides structural support to the wellbore by distributing axial loads from the casing to the formation and protecting the casing from deformation caused by thermal and mechanical stresses. Cement slurry formulations are engineered with specific properties, including compressive strength, tensile strength, and elasticity, to withstand the extreme conditions encountered in geothermal wells.

Geothermal wells present a distinct set of cementing challenges due to their exposure to high temperatures, aggressive chemical environments, and fractured formations. Reservoir temperatures in geothermal fields often exceed 300°C, leading to thermal expansion and stress cycling that can compromise the integrity of the cement sheath. Additionally, exposure to corrosive gases such as CO_2 and H_2S accelerates chemical degradation, causing cement to weaken and become more permeable over time. Furthermore, highly fractured and permeable geological formations in geothermal reservoirs often result in severe loss circulation, where cement slurry is lost into the formation, preventing adequate cement placement and zonal isolation. Addressing these challenges requires the use of advanced cementing materials and placement techniques, including the incorporation of silica flour and synthetic fibers to improve thermal stability and mechanical resilience.

Maintaining cement integrity is crucial for the long-term functionality of geothermal wells. A failure in cement integrity can lead to the formation of micro-annuli, debonding at the casing-cement and cement-formation interfaces, and uncontrolled fluid migration, all of which can compromise well performance and increase operational risks. To monitor and maintain cement integrity, diagnostic tools such as cement bond logs (CBL) and ultrasonic imaging technology play an essential role in detecting early signs of cement failure and implementing corrective measures.

As one of Indonesia's key geothermal fields, the Dieng Geothermal Field presents a unique combination of geological and operational challenges that significantly impact cementing operations. Located in Central Java, this high-temperature geothermal system is characterized by fractured volcanic formations with high permeability, leading to frequent loss circulation issues. Reservoir temperatures exceeding 300°C create substantial thermal stress on cement structures, while the presence of acidic gases such as CO_2 and H_2S further accelerates cement degradation. The geological complexity of the field, with its variation in rock porosity and permeability, necessitates a highly tailored approach to cementing. This paper examines the specific geological conditions of Dieng and their impact on cement integrity, emphasizing the need for innovative solutions to ensure long-term well stability and optimal geothermal energy production.

II. GEOLOGICAL AND ENVIRONMENTAL OF DIENG GEOTHERMAL FIELD

Dieng geothermal field is located within the Dieng Volcanic Complex, which is part of the Quaternary volcanic chain in Central Java. Physiographically, this area lies within the North Serayu Basin and is controlled by the subduction process of the Indo-Australian plate beneath the Eurasian plate. The complex was formed through multiple phases of volcanic activity, resulting in stratovolcanoes, parasitic vents, and eruption craters. The stratigraphy of the Dieng field consists of volcanic products from older to younger formations, dominated by basaltic lava, andesitic lava, and pyroclastic deposits. Additionally, in several wells such as MG-2 and MG-3, diorite intrusions have been found, contributing to the high reservoir temperatures.

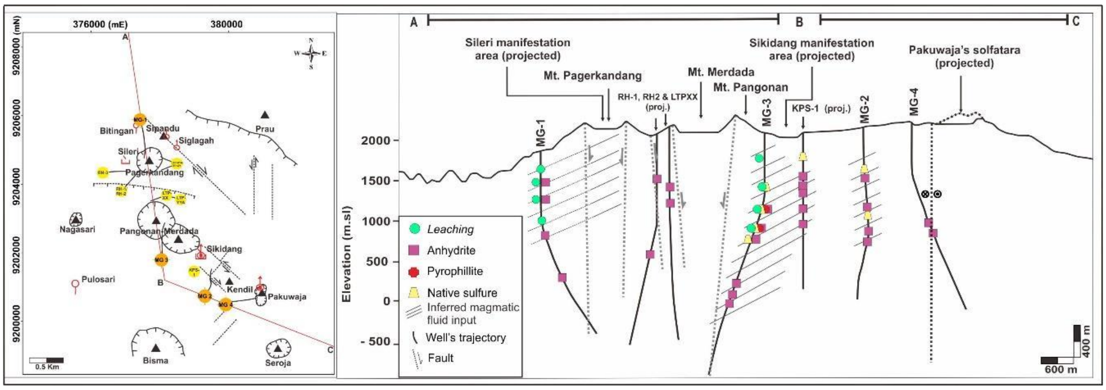

Figure 1. Geological overview of the Dieng Field (Shalihin et al., 2020)

The image above shows the distribution of production wells (MG-1, MG-2, MG-3, and MG-4) along with major geothermal manifestations, such as Sileri, Sikidang, and Pakuwaja solfataras. Additionally, this image highlights the presence of alteration minerals indicating intense hydrothermal activity, including leaching (leached zones), anhydrite, pyrophyllite, and native sulfur. The presence of these minerals suggests that certain areas have been influenced by hydrothermal fluids rich in acidic gases like H_2S and CO_2, which can contribute to casing corrosion and cement degradation in geothermal wells.

Geological structure of this field is controlled by a major northwest-southeast trending fault, which serves as the primary pathway for hydrothermal fluids. This fault is also associated with active geothermal manifestations such as Sileri, Sikidang-Merdada, and Pakuwaja, consisting of solfataras, fumaroles, acidic hot springs, and sulfur deposits. In some locations, particularly in the Sikidang-Merdada area, acidic hydrothermal fluids have been identified, indicating the contribution of magmatic fluids rich in corrosive gases like H_2S and HCl. Moreover, hydrothermal alteration processes in the Dieng field have led to the formation of various alteration minerals, including smectite, illite, chlorite, quartz, epidote, wairakite, and actinolite, reflecting the complex hydrothermal conditions in the area.

Reservoir temperature in this field exceeds 250°C, with thermal anomalies associated with magma intrusions. Some wells drilled beyond 3,000 meters in depth have encountered open fracture zones, leading to total loss circulation during drilling. Additionally, leaching and dissolution zones indicate that rocks have undergone dissolution due to hydrothermal fluids, creating subsurface cavities that may affect formation stability.

III. CEMENT INTEGRITY IN DIENG GEOTHERMAL FIELD

a. Challenge in Cement Integrity

Based on the existing geological conditions, several factors may affect cement integrity in geothermal wells in Dieng. Some potential issues include:

1. **Fractured Zones and Active Faults – Risk of Loss Circulation**

   Dieng geothermal field is controlled by major northwest-southeast (NW-SE) trending faults, forming high-permeability pathways. These structures facilitate significant hydrothermal fluid migration and create open fractures in some zones. Wells such as MG-1, MG-3, and MG-4 (see figure 1) have experienced total loss circulation at depths exceeding 1,800 meters, indicating substantial drilling fluid loss into the formation. This directly affects the cementing process, as pumped cement may flow into fractures instead of filling the annular space properly. Poor cement distribution can lead to voids or weak cement bonding with the casing and rock formation, increasing the risk of hot fluid leakage into unintended zones. To mitigate this issue, lost circulation control techniques such as using Lost Circulation Materials (LCM) before cementing or employing staged cementing can help ensure cement remains in the desired position without excessive loss into fractures.

2. **High Reservoir Temperature – Risk of Cement Degradation and Thermal Cracking**

   Dieng geothermal reservoir exhibits high temperatures exceeding 250°C, especially near dioritic intrusions identified in wells MG-2 and MG-3 (see figure 1). These extreme temperatures pose significant challenges to cement integrity, particularly due to repeated heating and cooling cycles during geothermal fluid production. As the well begins production, the cement sheath expands due to high temperatures, but when operations cease or pressure changes occur, cooling causes contraction. This cycle can induce thermal cracking in the cement, ultimately creating pathways for hot fluid migration toward the upper sections of the well. Additionally, conventional cement often loses its strength at excessively high temperatures, leading to long-term material degradation. To counteract these issues, heat-resistant cement with high silica content is necessary, as it maintains its mechanical properties under extreme temperature conditions.

3. **Acidic Hydrothermal Fluids – Risk of Cement Corrosion and Weakening**

   Some regions of the Dieng geothermal field, particularly in the Sikidang-Merdada area, contain acidic hydrothermal fluids rich in H_2S and HCl. The presence of alteration minerals such as anhydrite, pyrophyllite, and native sulfur indicates magmatic fluid contributions that are highly corrosive. Low-pH fluids can degrade both cement and casing over time. Chemical reactions between acidic fluids and cement materials may lead to softening or partial dissolution, reducing cement adhesion to the casing and rock formation. Additionally, casing corrosion due to interactions with H_2S and HCl gases can accelerate wellbore structural degradation. If cement lacks acid resistance, well integrity may fail sooner than expected. To address this challenge, acid-resistant cement formulations incorporating pozzolan or fly ash should be used, as they maintain structural strength in acidic environments.

4. **Clay Minerals and Hydrothermal Alteration – Risk of Weak Cement Bonding**

   Hydrothermal alteration in the Dieng field has produced clay minerals such as smectite and illite, which expand when exposed to fluids. When hydrated, these minerals increase in volume and weaken the mechanical properties of the surrounding rock formation. If clay-rich zones exist near the well annulus, cement bonding with the formation can be compromised, increasing the likelihood of micro-annulus formation or unwanted fluid migration paths. Furthermore, dissolution zones and subsurface cavities resulting from leaching processes in some wells can hinder uniform cement distribution. These voids create potential migration pathways for gas or hot fluids into undesired zones. To mitigate this problem, high-bonding cement should be used along with optimized primary cementing techniques, including the use of centralizers to ensure proper casing positioning and uniform cement distribution within the formation.

5. **Formation Pressure and Gas Migration Potential**

   Hydrothermal fluids in the Dieng field exhibit relatively high formation pressures, especially near fractures and active fault zones. If formation pressure exceeds cement hydrostatic pressure during placement, fluids or gases may enter the cement before full hydration occurs. This intrusion can lead to channeling or micro-annuli, where small gaps form between the casing and formation due to gas migration during cement setting. If left unresolved, this condition may create gas migration pathways, potentially leading to blowouts or well leaks in the future. To reduce this risk, gas-tight cement with special formulations to prevent gas penetration during cementing should be used. Additionally, pressure hold techniques during cementing can help maintain sufficient hydrostatic pressure, preventing formation fluids from interfering with the cement hydration process.

b. Development and Solution Plan

Based on the geological conditions of the Dieng geothermal field, several potential cement integrity issues may arise, including high reservoir temperatures, acidic fluid attacks, lost circulation zones, high differential pressures, and the presence of fractures and faults. To address these challenges, a strategic approach is required in planning and developing solutions. The following development and solution plan can be implemented:

1. **Selection of Cement Formulation Resistant to High Temperatures and Acidic Environments**

   Dieng geothermal field has a high reservoir temperature, exceeding 250°C, and contains fluids rich in CO_2 and H_2S, which can degrade conventional cement. Therefore, special cement formulations are required, such as:
   - **Silica-Enriched Cement**
     Adding 35-40% silica flour by cement weight enhances resistance to high temperatures and prevents cracking due to thermal expansion.
   - **Pozzolan- or Fly Ash-Based Cement**
     Improves resistance to corrosive fluids by reducing cement porosity.
   - **Geopolymer-Based Cement**
     A more acid-resistant alternative with high adhesion and durability in extreme thermal conditions.

2. **Use of Additives to Enhance Cement Durability**

   Several additives can be used to improve the mechanical and chemical properties of cement under extreme conditions, including:
   - **Latex or Elastomers** → Increases cement flexibility to withstand expansion and contraction due to temperature changes.
   - **Micro Silica or Nano Silica** → Reduces cement permeability and enhances resistance to chemical attacks.
   - **Calcium Aluminate Cement (CAC)** → Highly resistant to H_2S and CO_2 attacks while maintaining strength at high temperatures.

3. **Cementing Techniques to Address Lost Circulation**

   Dieng field contains many high-permeability zones due to fractures and faults, leading to total lost circulation during cementing. Some mitigation techniques that can be applied include:
   - **Cement Squeeze Method**
     This technique uses high-density cement slurry to seal fractured zones before the main cementing process.
   - **Use of Lost Circulation Material (LCM)**
     LCM made from natural fibers or granular particles can be applied before cementing to fill fractures and prevent cement slurry losses.
   - **Foamed Cement**
     Lightweight foamed cement can help reduce hydrostatic pressure during cementing and minimize the risk of lost circulation.

4. **Optimization of Primary Cementing Techniques to Improve Bonding**

   The primary cementing process must be well-designed to ensure proper isolation of production zones and prevent channeling. Several key steps include:
   - **Pre-Flush and Spacer Fluid**
     Used to clean the wellbore before cementing, improving the bonding between cement and rock formations.
   - **Optimization of Centralizer Placement**

Proper placement of centralizers (e.g., every 10-15 meters) ensures that the casing remains centered in the well and that cement is evenly distributed.

5. **Use of Insulated Casing and Casing Coating to Prevent Cement Degradation**
   Aggressive geothermal fluids can cause casing corrosion, potentially damaging the cement sheath. Several solutions that can be applied include:
   - **Thermal Insulated Casing**
   Insulated casing layers reduce cement exposure to extreme temperatures, preventing thermal cracking.
   - **Casing with Epoxy Coating or Corrosion-Resistant Alloy (CRA)**
   Protects the casing from corrosion, which could otherwise weaken the surrounding cement.

IV. CONCLUSION

Dieng geothermal field has a complex geological structure, characterized by active faults, fractured zones, aggressive fluid environments, and high reservoir temperatures. These factors contribute to challenges in well cementing operations, particularly in maintaining cement integrity. Based on the analysis, the main potential issues include thermal cracking in cement, corrosion due to acidic fluids, lost circulation, and weak bonding between cement, casing, and the formation.

To address these challenges, the following strategies are recommended:

1. Selection of Heat-Resistant and Acid-Resistant Cement Materials
   - Silica-Enriched Cement
   - Pozzolan Cement
   - Geopolymer Cement
2. Use of Special Additives to Enhance Cement Mechanical Strength
   - Nano Silica (to reduce permeability and increase chemical resistance)
   - Latex (to improve flexibility and prevent cracking due to thermal expansion)
   - Calcium Aluminate Cement (CAC) (to enhance resistance against H_2S and CO_2)
3. Implementation of Proper Cementing Techniques to Overcome Lost Circulation
   - Foamed Cement (low-density cement to reduce hydrostatic pressure)
   - Squeeze Cementing (to seal fractured zones before primary cementing)
   - Lost Circulation Material (LCM) (natural fiber- or granular-based materials to fill fractures)
4. Optimization of Primary Cementing Techniques to Improve Cement Bonding with Casing and Formation
   - Pre-Flush and Spacer Fluid (to clean the wellbore and improve adhesion)
   - Optimal Centralizer Placement (ensuring uniform cement distribution)
5. Casing Protection with Corrosion-Resistant Materials and Thermal Insulation
   - Thermal Insulated Casing (to reduce cement exposure to extreme temperatures)
   - Epoxy-Coated or Corrosion-Resistant Alloy (CRA) Casing (to protect against aggressive geothermal fluids)

By implementing this comprehensive strategy, long-term cement integrity in the Dieng geothermal wells can be maintained, ensuring successful geothermal operations, minimizing well failure risks, and supporting sustainable energy production. To achieve optimal results, continuous evaluation is required through Cement Bond Log (CBL) and Casing Inspection Log, along with adjustments based on field operational data.

This analysis confirms that the success of cementing in the Dieng geothermal wells depends on the right combination of materials, methods tailored to geological conditions, and effective mitigation strategies. With a holistic approach, the geological challenges in the Dieng field can be addressed more effectively.

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