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from economic and environmental point of view**

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DEDICATION

I proudly and affectionately dedicate this milestone to:

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Abstract

Modern drilling in narrow pressure windows faces serious risks from conventional "stop-start" hydraulics, which cause wellbore instability, fluid losses, and high Non-Productive Time (NPT). This dissertation presents a technical, economic, and environmental evaluation of continuous circulation technology, focusing on the Eni Circulating Device (E-CD) in the TAGI and Siegenian formations of the Berkine Basin, Algeria. By comparing field data from a conventional well (HBNEP-6) and a continuous circulation well (LEWN-1), this study analyzes the impact of steady-state hydraulics. Results show that maintaining a continuous flow of 1,800 to 2,200 L/min stabilizes the Equivalent Circulating Density (ECD), preventing connection gases and cuttings settling. Mechanically, the E-CD system eliminated pressure-related stuck pipe incidents, which previously caused 180 hours of lost time on the baseline well. Economically, the technology achieved a Net Economic Saving of \$1,072,100 by minimizing downhole trouble time. Environmentally, it eliminated subsurface mud losses and reduced atmospheric emissions by 361.8 tons of CO₂ by shortening active rig operations by 7.5 days. This research confirms that continuous circulation optimizes drilling safety, financial performance, and environmental care in high-risk exploration.

Keywords: Managed Pressure Drilling (MPD), Continuous Circulation System (CCS), Eni Circulating Device (E-CD), Equivalent Circulating Density (ECD), Non-Productive Time (NPT), Berkine Basin.

Résumé

Le forage moderne dans des fenêtres de pression étroites est confronté à des risques majeurs dus à l'hydraulique conventionnelle « arrêt-démarrage », qui provoque l'instabilité des puits, des pertes de fluide et un temps non productif (NR) élevé. Ce mémoire présente une évaluation technique, économique et environnementale de la technologie de circulation continue, axée sur *l'Eni Circulating Device* (E-CD) dans les formations du TAGI et du Siegenian du bassin de Berkine, en Algérie. En comparant les données de terrain d'un puits conventionnel (HBNEP-6) et d'un puits à circulation continue (LEWN-1), cette étude analyse l'impact d'un hydraulique stable. Les résultats montrent que le maintien d'un débit continu de 1 800 à 2 200 L/min stabilise la densité équivalente en circulation (ECD), évitant les gaz de connexion et la sédimentation des débris. Sur le plan mécanique, le système E-CD a éliminé les incidents de coincement de garniture liés à la pression, qui avaient causé 180 heures de temps perdu sur le puits de référence. Économiquement, cette technologie a permis une économie nette de 1 072 100 \$ en réduisant les temps morts. Environnementalement, elle a éliminé les pertes de boue souterraines et réduit les émissions de CO₂ de 361,8 tonnes en écourtant les opérations de forage de 7,5 jours. Cette recherche confirme que la circulation continue optimise la sécurité, la rentabilité et la protection de l'environnement lors d'explorations à haut risque.

Mots-clés : Forage à Pression Contrôlée (MPD), Système de Circulation Continue (CCS), Eni Circulating Device (E-CD), Densité Équivalente en Circulation (ECD), Temps Non Productif (NPT), Bassin de Berkine.

ملخص

يواجه الحفر الحديث في مجالات الضغط الضيقة مخاطر كبيرة بسبب نظام الهيدروليك التقليدي القائم على "التوقف والتشغيل"، مما يسبب عدم استقرار البئر، وفقدان الموائع، وزيادة الوقت غير الإنتاجي (NPT). تقدم هذه الرسالة تقييمًا تقنيًا، واقتصاديًا، وبيئيًا لتكنولوجيا التدوير المستمر، مع التركيز على أداة إيني للتدوير المستمر (E-CD) في تكوينات TAGI والسيجيني بحوض بركين في الجزائر. من خلال مقارنة البيانات الميدانية لبئر تقليدي (HBNEP-6) وبئر تدوير مستمر (LEWN-1)، تحلل هذه الدراسة تأثير الهيدروليك المستقر. وتظهر النتائج أن الحفاظ على تدفق مستمر يتراوح بين 1800 و2200 لتر/دقيقة يضمن استقرار الكثافة المكافئة للمائع (ECD)، ويمنع غازات الربط وترسب نواتج الحفر. ميكانيكيًا، ألغى نظام E-CD تمامًا حوادث استعصاء الأنابيب الناتجة عن الضغط، والتي تسببت سابقًا في ضياع 180 ساعة في البئر المرجعي. واقتصاديًا، حققت هذه التكنولوجيا وفراً مالياً صافياً قدره 1,072,100 دولار من خلال تقليص أوقات التوقف. وبيئيًا، قضى النظام على تسرب الطين تحت الأرض وخفض انبعاثات ثنائي أكسيد الكربون CO₂ بمقدار 361.8 طن نتيجة تقليص مدة تشغيل جهاز الحفر بمقدار 7.5 أيام. يؤكد هذا البحث أن التدوير المستمر يحقق التوازن المثالي بين سلامة العمليات، والأداء المالي، وحماية البيئة في مناطق الاستكشاف عالية المخاطر.

الكلمات المفتاحية: الحفر ذو الضغط المُتحكم في (MPD)، نظام التدوير المستمر (CCS)، أداة إيني للتدوير المستمر (E-CD)، الكثافة المكافئة للمائع أثناء التدوير (ECD)، الوقت غير الإنتاجي (NPT)، حوض بركين.

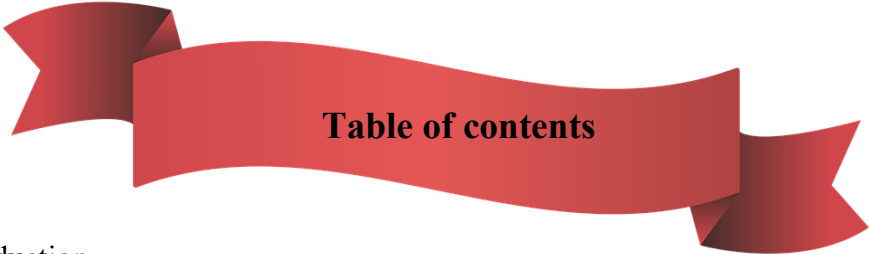


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List of abbreviations

Abbreviation	Full Meaning / Definition
BHP	Bottom Hole Pressure
BOP	Blowout Preventer
CAGR	Compound Annual Growth Rate
CBHP	Constant Bottom Hole Pressure
CCS	Continuous Circulation System
CCV	Continuous Circulation Valve
CFS	Continuous Flow System
CO2	Carbon Dioxide
DGD	Dual Gradient Drilling
ECD	Equivalent Circulating Density
E-CD	Eni Circulating Device
HMI	Human-Machine Interface
HPHT	High-Pressure, High-Temperature
IADC	International Association of Drilling Contractors
KPI	Key Performance Indicator
MCD	Mud Cap Drilling
MPC	Model Predictive Control
MPD	Managed Pressure Drilling
NPT	Non-Productive Time
NSD	Nonstop Driller
OBM	Oil-Based Mud
PMCD	Pressurized Mud Cap Drilling
RCD	Rotating Control Device
RFC	Returns Flow Control
SG	Specific Gravity
TAGI	Trias Argilo-Gréseux Inférieur (Lower Triassic Argillaceous-Sandstone formation)
TD	Total Depth
UBD	Underbalanced Drilling
USD	United States Dollar



General introduction



General introduction

When we consider the realities of modern oil and gas exploration, the technical challenges can be incredibly daunting. Engineers are constantly pushing into deeper, more complex geological zones where the margins for error are razor-thin. One of the biggest hurdles face-to-face with the drill crew is navigating formations with exceptionally narrow drilling pressure windows. In these sensitive environments, maintaining perfect pressure balance inside the wellbore is a constant battle. Under conventional methods, even a slight miscalculation can trigger serious operational hazards, such as sudden formation fluid influxes, known as kicks, or severe fluid losses into the rock [1]. These complications don't just put the safety of the entire rig floor at risk; they also lead to major financial losses by causing massive amounts of Non-Productive Time (NPT) [2]. Because of this, finding a smarter way to manage wellbore pressure has shifted from being a premium technical choice to an absolute necessity for modern drilling.

To address these vulnerabilities, Managed Pressure Drilling (MPD) emerged as a true game-changer for the industry. The International Association of Drilling Contractors (IADC) formally defines MPD as an adaptive drilling process designed to precisely regulate the pressure profile throughout the wellbore [2]. Instead of relying on passive, heavy mud weights, MPD actively balances downhole pressures to create a safer, much more controlled environment. It represents a highly flexible approach that fundamentally improves operational safety, optimizes our fluid programs, and prevents expensive formation damage [1], [2].

Yet, even with standard MPD, a chronic weak spot remains in conventional operations: the mandatory cycle of turning the mud pumps off and on every single time the crew adds a new joint of drill pipe. The moment circulation stops, the Equivalent Circulating Density (ECD) drops immediately to a static state. This sudden pressure drop is often just enough to let formation gases sneak into the wellbore or cause heavy rock cuttings to fall backwards, forming dangerous debris beds that can trap the drill string. To bridge this critical gap, Continuous Circulation Systems (CCS) were engineered to work alongside the broader MPD framework, keeping the drilling fluid in perpetual motion even during pipe connections.

This dissertation provides a comprehensive, real-world evaluation of continuous circulation technology, focusing specifically on the design and performance of the Eni Circulating Device (E-CD). By examining comparative fieldwork data from the highly challenging exploration perimeters of the Berkine Basin in Algeria, this study aims to show how steady-state hydraulics can resolve chronic, systemic drilling risks. Our research looks

closely at the operational outcomes of two specific wells: the conventional baseline well, HBNEP-6, which suffered extensive pressure-related downtime, and the case study well, LEWN-1, where the E-CD platform was successfully put to the test.

To systematically address these challenges and evaluate the viability of this technology, this dissertation sets out to answer three fundamental research questions:

- What is the theoretical and operational framework of Managed Pressure Drilling, and how do its different methods establish control over volatile downhole pressure environments?
- How do the mechanical engineering principles and dynamic fluid mechanics of the Eni Circulating Device (E-CD) eliminate the critical pressure fluctuations inherent in conventional stop-start drilling operations?
- When implemented in the field, does continuous circulation technology deliver measurable improvements in hole cleaning, non-productive time reduction, financial savings, and environmental footprint mitigation compared to conventional methods?



Chapter I: Introduction to managed pressure drilling (MPD)



I.1. Introduction

Modern drilling operations encounter significant challenges in maintaining wellbore pressure integrity, particularly when navigating formations with exceptionally narrow drilling windows (Fig.I.1). These pressure management difficulties frequently result in operational hazards, including formation fluid influxes ("kicks"), lost circulation events, and other well control complications [1]. Managed Pressure Drilling (MPD) has consequently developed as a transformative solution, providing continuous, precise regulation of annular pressure profiles. This advanced methodology not only enhances operational safety but also improves drilling efficiency while substantially reducing non-productive time (NPT) [2]. With the growing complexity of contemporary drilling environments, MPD technology has seen rapidly expanding global implementation. The present chapter systematically examines MPD's historical evolution, technical classification, operational advantages, specialized equipment requirements, and diverse field applications.

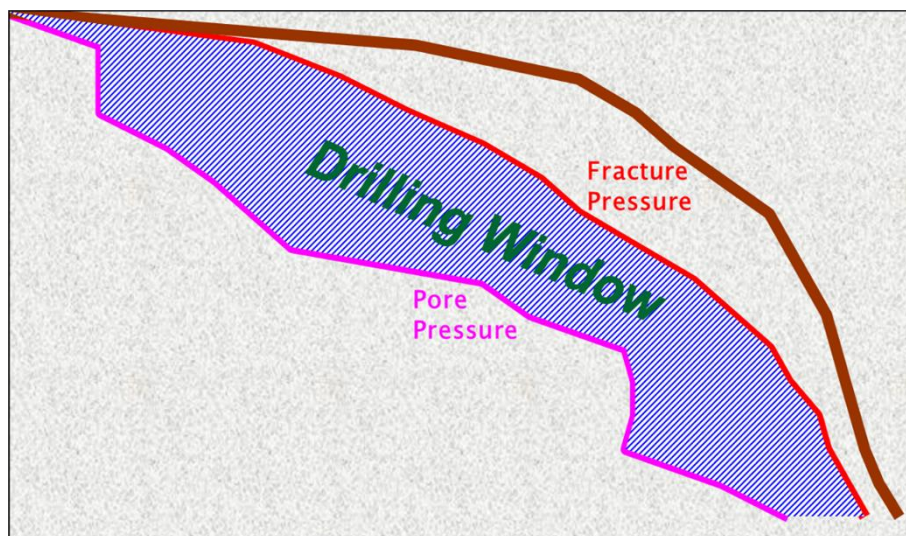


Fig.I. 1: Typical pressure window and drilling hazards (kick/loss zones) [3].

I.2. History and evolution of MPD

Managed Pressure Drilling (MPD) developed as a novel solution for handling ongoing pressure control problems encountered in sophisticated drilling operations. Operators faced serious wellbore instability issues when conventional methods failed to control narrow pressure windows, which led to dangerous and expensive problems like kicks and formation collapse. This operational reality created an urgent need for more precise pressure management solutions.

The foundations of modern MPD were laid in the late 1990s through pioneering applications in the deepwater Gulf of Mexico, where drillers first implemented backpressure techniques to maintain control during circulation and pipe tripping [1]. These field experiments demonstrated the potential for real-time pressure management without operational interruptions.

A significant milestone came in the early 2000s when the IADC formally defined MPD as "an adaptive drilling process used to control the annular pressure profile throughout the wellbore precisely" [2]. This official recognition marked MPD's transition from experimental practice to established technology, complete with standardized methodologies and specialized equipment (Fig.I.2).

The development of MPD was motivated by several key factors:

- The increasing frequency of narrow-margin drilling windows, especially in deepwater and HPHT (high-pressure, high-temperature) environments.
- Growing concerns over safety, well control risks, and formation damage.
- A significant rise in Non-Productive Time (NPT) due to wellbore instability and pressure-related problems [4].

The technology matured rapidly following its standardization, with techniques like CBHP and DGD enabling dynamic pressure management across various applications. By 2015, MPD had evolved from a specialized solution to an essential practice for demanding drilling scenarios, including ultra-deepwater operations, unconventional shale developments, and depleted reservoir drilling. Continuous innovations in automation and control systems push MPD's capabilities further, solidifying its role as a transformative technology in modern well construction [2].

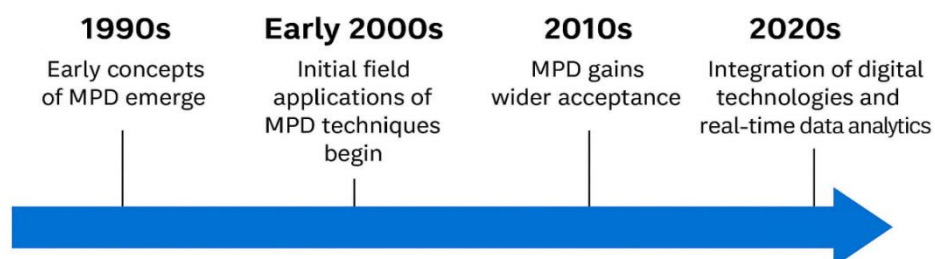


Fig.I. 2: Timeline of MPD evolution [2].

I.3. Definition and classification of MPD

Managed Pressure Drilling (MPD) is a sophisticated drilling technique that provides precise regulation of wellbore annular pressure profiles. MPD systematizes bottom hole pressure (BHP) management to limit well control problems, including kicks and losses, which conventional drilling methods do not accomplish. It enhances drilling efficiency by reducing non-productive time (NPT) and improving safety through real-time pressure adjustments. MPD utilizes specialized equipment to maintain continuous circulation and optimize pressure management, making it particularly useful in narrow-pressure window formations [5].

The IADC classifies MPD into several categories based on the method used to control annular pressure (Tab.I.1). The most widely implemented techniques include:

I.3.1 Constant bottom hole pressure (CBHP)

CBHP, the most common MPD method, maintains precise bottomhole pressure by dynamically adjusting surface backpressure via a choke system. This approach is especially valuable in narrow pressure-window wells, as it provides continuous pressure control during both circulation (dynamic) and non-circulation (static) conditions, preventing instability [5].

I.3.2 Dual gradient drilling (DGD)

DGD uses two separate fluid gradients to mimic lighter mud near the seafloor while maintaining higher pressure downhole. This technique solves deepwater drilling challenges where long risers create problematic pressure differences. By managing these distinct pressure zones, DGD enables safer operations in narrow-margin environments [6].

I.3.3 Mud cap drilling (MCD)

This technique utilizes a weighted mud cap (typically viscous fluid or foam) placed above an intentionally underbalanced formation interval. Unlike conventional circulation, returns are not brought to surface but instead directed into the formation. MCD is specifically designed for severe loss scenarios in highly fractured or vugular formations where conventional circulation is impractical [5].

I.3.4 Pressurized mud cap drilling (PMCD)

An advanced variant of MCD, PMCD employs a closed-loop system with surface pressure control via a rotating control device (RCD). This configuration provides enhanced pressure

management capabilities, making it particularly effective for high-risk operations in extreme loss circulation zones where conventional and standard MCD methods prove insufficient [5].

Tab.I. 1: Managed pressure drilling (MPD) Methods & Applications [5].

MPD Method	Best For	Key Equipment
CBHP MPD	HPHT, narrow margins	RCD, automated choke
PMCD	Severe loss of circulation	Heavy mud cap, light fluid
DGD	Deepwater drilling	Subsea pumps, mud-lift system
RFC MPD	Early kick detection	Coriolis meter, closed-loop
UBD-MPD Hybrid	Tight gas/shale reservoirs	Nitrogen injection, low-ECD mud

I.4. Objectives and benefits of MPD

Managed Pressure Drilling (MPD) has emerged as a game-changing technology for navigating challenging downhole pressure environments. Unlike conventional methods, MPD actively controls the annular pressure profile, enabling operators to safely drill through narrow pressure windows and other high-risk formations with unprecedented precision [7].

MPD provides several key operational benefits (Fig.I.3):

- **Pressure control:** Through continuous CBHP maintenance, MPD creates a balanced pressure system that prevents formation fluid influx (kicks) and fracturing-induced losses (Fig.I.4) [8].
- **Wellbore stability:** The system's ability to sustain perfect pressure equilibrium significantly reduces instability issues, including formation collapse in weak zones and swelling in reactive shales [9].
- **Reduced non-productive time (NPT):** By virtually eliminating well control incidents and maintaining constant circulation, MPD can reduce NPT by up to 40% compared to conventional drilling [10].
- **Improved efficiency in HPHT and depleted zones:** MPD unlocks previously undrillable HPHT reservoirs and revitalizes mature fields by enabling safe operations in depleted formations [11].
- **Cost optimization:** The technology delivers cost savings through multiple channels: streamlined casing programs, reduced mud consumption, and minimized downtime [8].

- **Safety enhancement:** Advanced monitoring systems provide real-time pressure data, dramatically lowering blowout risks while protecting personnel and equipment [7].

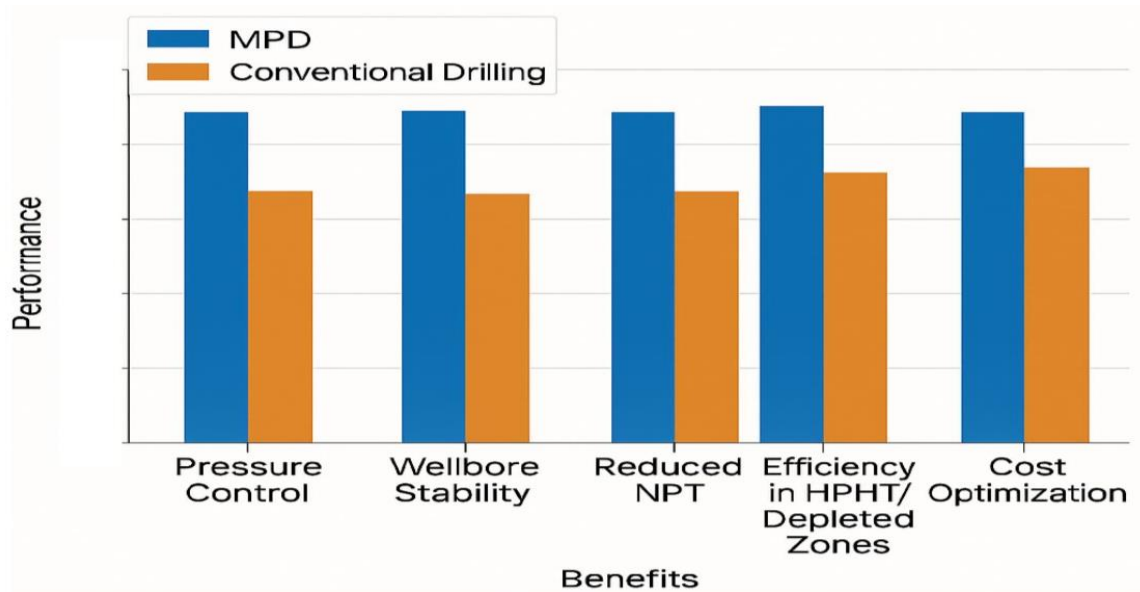


Fig.I. 3: Bar chart of MPD benefits vs conventional drilling.

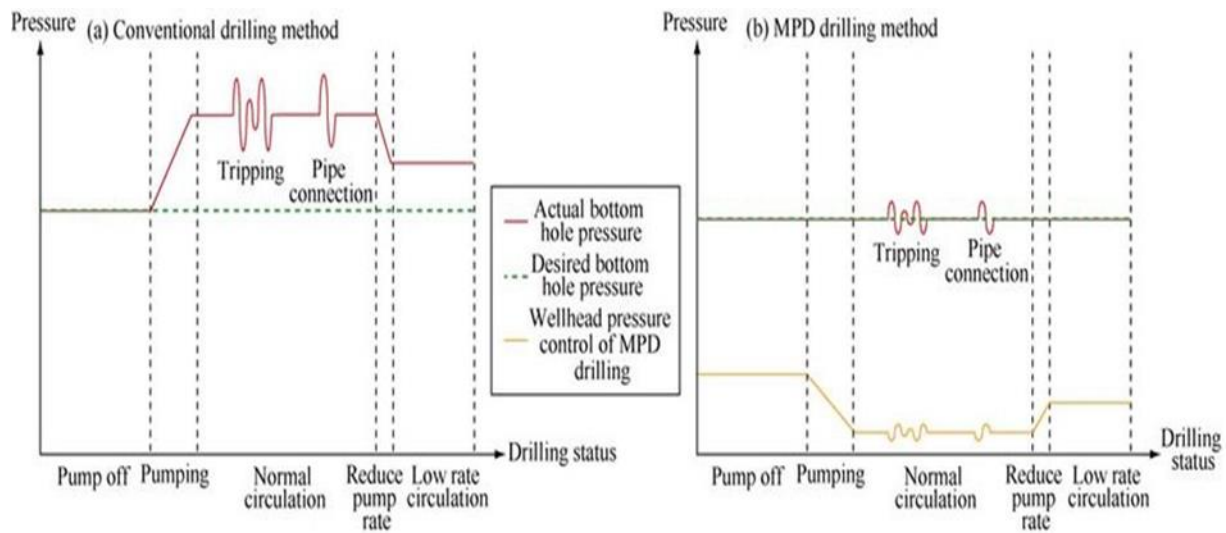


Fig.I. 4: Bottom hole pressure comparison between conventional drilling and MPD drilling [12].

I.5. MPD equipment and control systems

Managed Pressure Drilling (MPD) systems are crucial in modern drilling operations, providing precise control over wellbore pressure to enhance both safety and efficiency. These

systems incorporate a range of specialized equipment (Fig.I.5) and advanced control technologies to manage pressure effectively throughout the drilling process.

Rotating control device (RCD):

The Rotating Control Device (RCD) is a key component of MPD systems, designed to isolate the wellbore from the surface equipment. It enables continuous circulation while maintaining pressure control during drilling operations. By safely managing formation fluids and gases, the RCD significantly reduces the risk of well control incidents [13].

Automated backpressure pumps:

Automated backpressure pumps are integral to maintaining the required wellbore pressure. These pumps automatically adjust the backpressure to ensure that the target bottom hole pressure is consistently maintained, even in challenging geological conditions. This ability to respond to changes in the well environment helps optimize safety and operational performance [14].

Choke manifolds and flow meters:

Choke manifolds are essential for regulating the flow of fluids from the wellbore, offering precise control over wellbore pressure. Flow meters, on the other hand, measure the rate and volume of fluid circulation, providing real-time data that enables operators to manage pressure effectively and ensure the stability of the wellbore [15].

Continuous circulation systems:

Continuous circulation systems are designed to maintain uninterrupted fluid flow during tripping operations. This ensures that wellbore pressure remains under control, preventing pressure fluctuations that could lead to wellbore instability or uncontrolled kicks. By keeping fluid circulation constant, these systems minimize the risks associated with key drilling phases [16].

Advanced pressure control algorithms:

To enhance the performance of MPD systems, advanced algorithms such as Model Predictive Control (MPC) are often utilized. These algorithms continuously adjust control parameters in real-time, ensuring that pressure is maintained at optimal levels. This leads to improved safety, efficiency, and overall performance in the drilling process [9].

Simulation and modeling tools:

Simulation tools play a critical role in optimizing MPD systems by modeling the dynamics of the drilling environment. These tools provide valuable insights into the system's behavior under various conditions, allowing engineers to design better control strategies and predict the system's response to changing operational factors. As a result, they help improve the reliability and safety of drilling operations [17].

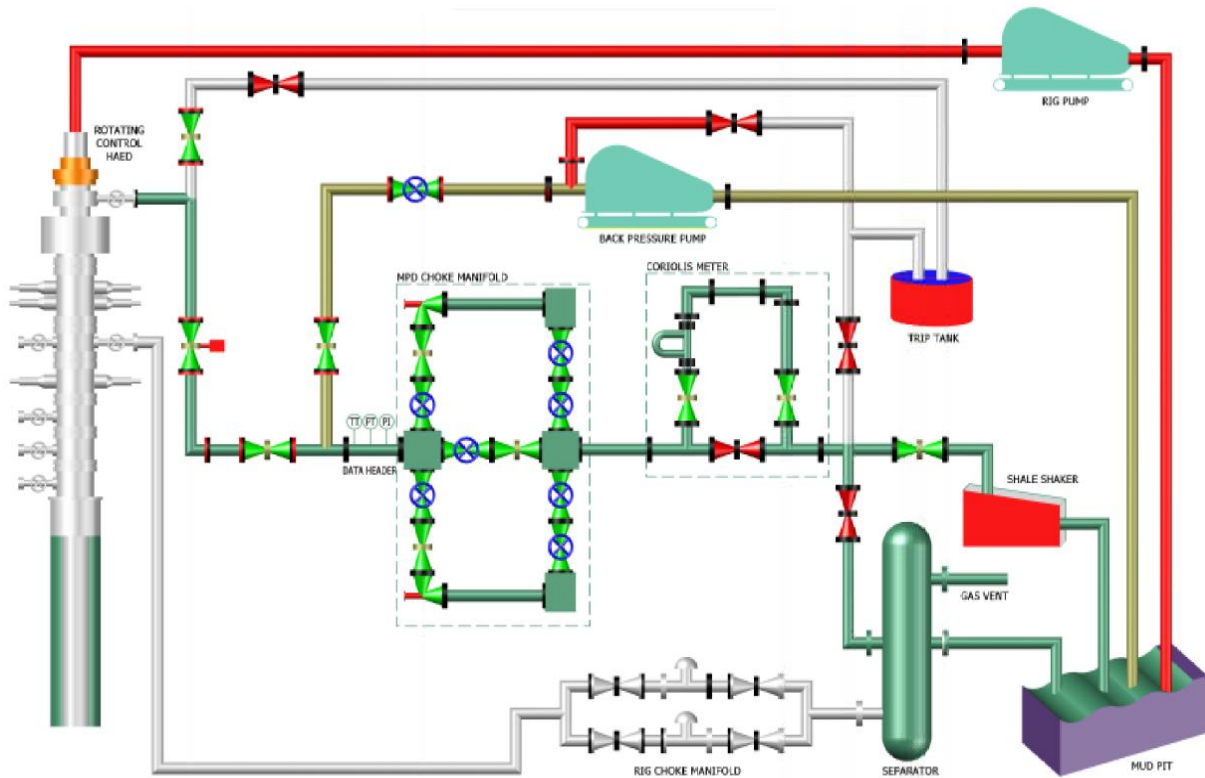


Fig.I. 5: Schematic diagram of a Managed Pressure Drilling (MPD) system and its integrated equipment [18].

I.6. Global adoption and statistics

Managed Pressure Drilling (MPD) has emerged as a widely implemented technology that significantly improves drilling efficiency and operational safety in challenging well conditions. The technology has seen rapid global expansion, with North America currently representing the largest market, followed by growing adoption in the Asia-Pacific region and the Middle East [19].

I.6.1. Worldwide MPD market size and projected growth

The Managed Pressure Drilling (MPD) market has seen notable growth in recent years, fueled by a combination of rising global energy demand, the expansion of unconventional oil and gas exploration, and the adoption of advanced technologies such as real-time data analytics and automated pressure control. As of 2023–2024, the global market for MPD is estimated to be valued between USD 3.0 billion and 4.2 billion. Forecasts suggest this figure could reach approximately USD 4.5 billion to 5.8 billion by the period 2029–2032 (Fig.I.6), reflecting a steady compound annual growth rate (CAGR) ranging from 3.7% to 7.2% [19].

This upward trend is largely driven by the need for more precise pressure control in complex well conditions, particularly in high-pressure, high-temperature (HPHT) environments. Additionally, the integration of MPD systems with intelligent drilling technologies, coupled with a growing industry focus on safety and environmental responsibility, is encouraging broader adoption. Regions leading this expansion include North America, Asia-Pacific, and Europe, where investment in drilling innovation continues to grow [20].

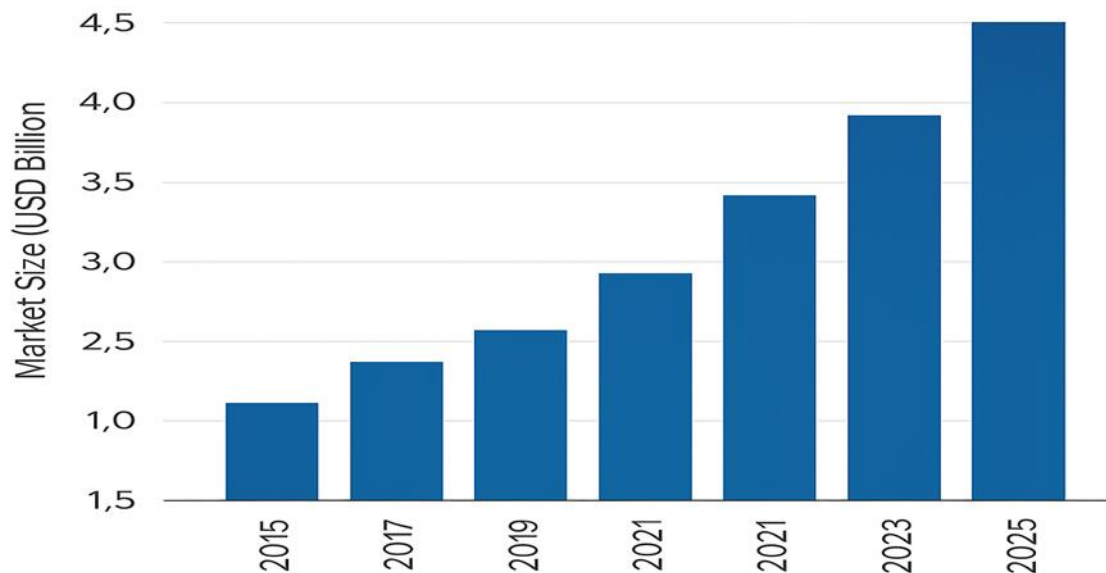


Fig.I. 6: Bar chart of global MPD market size and projected growth (USD Billion) [20].

I.6.2. MPD usage distribution across continents

The distribution of MPD usage varies significantly across continents (Fig.I.7), reflecting regional drilling challenges and infrastructure. North America remains the dominant user,

supported by advanced operations and investment in innovation. The Middle East and Asia-Pacific are rapidly increasing in adoption, especially in technically demanding fields. Other regions like Africa and South America show growing interest as exploration expands into complex formations [20].

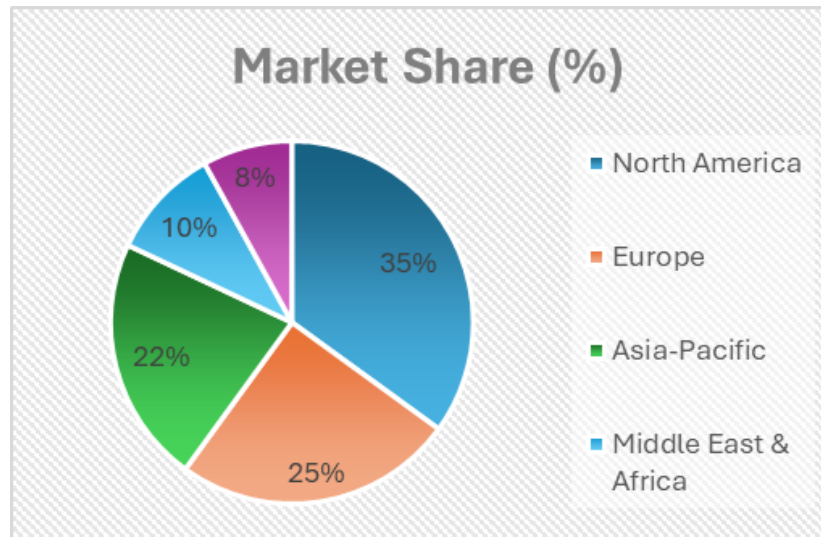


Fig.I. 7: MPD market share by continent [21].

Interpretation:

The pie chart illustrates the regional distribution of the global Managed Pressure Drilling (MPD) market. We can clearly observe that North America dominates with 35% of the total market share, highlighting its leadership in MPD technology adoption and investment. Europe comes next with 25%, supported by advanced offshore operations and mature oilfields. We see that the Asia-Pacific region commands 22%, reflecting rapid industrialization and rising exploration in challenging geological formations. Meanwhile, the Middle East & Africa region accounts for 10%, which shows a growing interest in MPD due to the technical challenges of their reservoirs. Lastly, the remaining 8% represents other emerging markets, which are gradually adopting MPD technologies as exploration shifts into more technically demanding environments.

I.6.3. Key drivers and regional focus of MPD adoption

The application of Managed Pressure Drilling (MPD) differs considerably across global regions, shaped by local operational demands, geological characteristics, and technological capabilities. As presented in (Tab.I.2), North America maintains the highest MPD utilization, propelled by technological leadership, extensive shale development, and stringent regulatory

requirements [19]. Europe's MPD implementation reflects its unique operational landscape, where environmental considerations and offshore efficiency needs, particularly in the North Sea, drive adoption [22].

The Asia-Pacific region shows growing MPD deployment, responding to increasing energy needs and expanding offshore exploration in areas such as the South China Sea and Australian waters [23]. Similarly, the Middle East and Africa are progressively adopting MPD to enhance production in mature fields and complex reservoirs, with applications spanning both established onshore and emerging offshore developments [24].

In Latin America, MPD addresses critical deepwater challenges, playing a particularly important role in Brazil's pre-salt offshore operations [25]. These regional patterns are quantified in (Tab.I.3), which details the distribution between onshore and offshore applications. North America demonstrates predominant onshore MPD use for unconventional resources, while Europe and Asia-Pacific emphasize offshore applications. The Middle East and Africa exhibit strong onshore implementation alongside developing offshore usage, and Latin America presents a balanced approach with moderate onshore and substantial offshore MPD deployment.

Tab.I. 2: Key Drivers of MPD Adoption by Continent [19].

Continent	Key Drivers
North America	Technological innovation, shale development, strict regulations
Europe	Offshore efficiency, environmental standards, North Sea operations
Asia-Pacific	Rising energy demand, offshore expansion, tech adoption
Middle East & Africa	Mature/complex reservoirs, production optimization
Latin America	Deepwater challenges, production stabilization

Tab.I. 3: MPD usage focus (onshore vs offshore) by continent [23].

Continent	Onshore Usage (%)	Offshore Usage (%)	Notable Applications
North America	High	Moderate	Shale plays, unconventional wells
Europe	Moderate	High	North Sea, mature offshore fields

Asia-Pacific	Moderate	High	South China Sea, Australia offshore
Middle East & Africa	High	Growing	Complex/mature onshore, new offshore
Latin America	Moderate	High	Brazil pre-salt, deepwater

I.7. Conclusion

This chapter examined the basics of managed pressure drilling (MPD) while documenting its history and outlining its categories and goals. Our discussion revealed that MPD improves well control while cutting down non-productive time and facilitating safer and more efficient drilling operations in challenging geological settings. We analyzed the main equipment used in MPD systems and investigated its worldwide adoption trends through data analysis and regional examinations. The introductory foundation leads into Chapter II, which explores the technical details and integration methods of continuous circulation systems as a critical component of the MPD framework



Chapter II: Continuous circulation system – Focus on the ENI Circulating Device



II.1. Introduction

Continuous circulation technology has emerged as a vital innovation for maintaining constant bottomhole pressure in critical drilling applications. This chapter systematically examines continuous circulation systems, with special attention to the ENI Circulating Device (E-CD), through four key aspects: historical development and industry definitions, comparative evaluation against conventional drilling and MPD approaches, technical analysis of system generations and connection methodologies, and operational planning requirements. Our investigation demonstrates how these systems enhance drilling safety, operational efficiency, and precise pressure management, while exploring their expanding application in complex well scenarios.

II.2. Introduction to continuous circulation

Continuous circulation is an advanced drilling methodology that sustains constant fluid flow during critical operational phases, including pipe connection procedures. This technique maintains precise bottom hole pressure (BHP) control by eliminating circulation interruptions, effectively mitigating two primary drilling hazards, such as formation influxes or wellbore instability [26].

II.2.1. Definition and purpose

Conventional drilling methods require stopping fluid circulation during pipe connections, leading to potentially harmful pressure fluctuations that can compromise formation stability. Continuous circulation systems (CCS) overcome this limitation by maintaining uninterrupted fluid flow throughout all operational phases, including pipe handling. This capability is particularly vital in high-risk applications, such as narrow pressure windows or sensitive formations, where maintaining consistent equivalent circulating density (ECD) is essential for wellbore integrity and operational safety (Fig.II.1) [27].

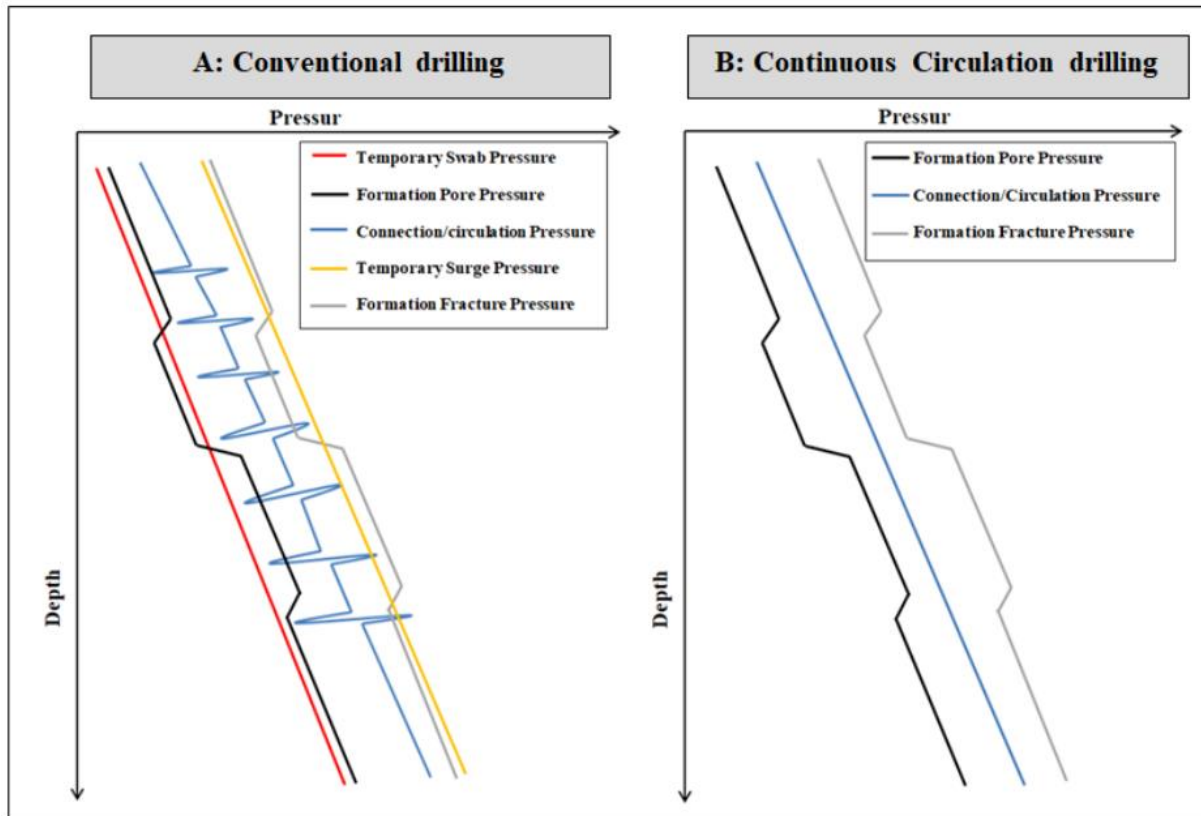


Fig.II. 1: Pressure profile A: Conventional drilling, B: Continuous circulation drilling [28].

II.2.2. IADC Definition

The International Association of Drilling Contractors (IADC) defines the continuous circulation method as: “An MPD technique used to maintain flow down the drill pipe while making a connection, thereby maintaining equivalent circulating density (ECD) and thus keeping a constant pressure profile in the well annulus to prevent an influx of formation fluids or potential hole collapse due to instability” [29].

This aligns with the goals of managed pressure drilling (MPD) in maintaining well control, reducing non-productive time (NPT), and enhancing operational safety.

II.3. History and development of Continuous Circulation Systems (CCS)

Continuous Circulation Systems (CCS) were developed to address pressure fluctuations and non-productive time (NPT) caused by conventional pipe connection methods. The technology has evolved from early mechanical designs to modern automated systems, maintaining uninterrupted fluid flow. These advancements ensure stable equivalent circulating density (ECD), which is particularly critical in narrow pressure windows and high-risk formations.

II.3.1. Early innovations (1963)

The first practical idea for continuous circulation drilling came from Vail and Smith in 1963. They proposed a system for continuous air drilling using a sub with a hinged disk that acted like a valve. This disk could automatically shift positions to control airflow from a side port, helping maintain a steady flow even during connection times. It was an innovative concept for its time, but despite its promise, it didn't gain much traction in the following decades [28].

II.3.2. Dormancy and rediscovery: 2005

After decades of silence, the idea resurfaced in 2005. That year saw the first field trial of a modern continuous circulation system (CCS). The goal was to prevent pressure swings caused by starting and stopping fluid circulation. The setup included a sealed chamber with a special triple blowout preventer (BOP) designed to keep circulation going while connecting or disconnecting pipe [28].

II.3.3. Development of sub-based systems: 2006–2012

In the years that followed, several new designs brought the concept closer to real-world application:

In 2006, Torsvoll and his team introduced a Continuous Circulation Valve (CCV), installed in the drill string. It used a manually operated ball valve to reroute flow from the top drive to a side port, maintaining bottom-hole pressure during connections [30].

In 2009, Calderoni built on the original 1963 concept with the Enhanced Circulation Device (E-CD). This tool used a hinged flapper and a check valve to maintain circulation. It didn't rely on electronics or actuators, which made it suitable for challenging environments like HPHT wells [31].

In 2011, another step came with the Nonstop Driller (NSD) system, developed by MacGregor and others. It used a combination of a side-port ball valve and a poppet-type valve, all controlled manually, to continue circulation during pipe handling [28].

In 2012, Weir and colleagues introduced a version of the CCS with two side ports and a soft-sealing ball. This ball, driven by pressure differences, prevented fluid from backflowing during tool connections [28].

II.3.4. Modernization and automation: 2014–2018

In 2014, Cunningham and his team presented the Continuous Flow System (CFS), a more advanced setup with a full-bore sub and internal valves. It allowed for wireline operations and remote actuation during connections, keeping the mud flow stable [32].

In 2018, the most recent leap came with Halliburton's E-CD Plus system. This was the first fully automated CCS. It used a robotic arm to handle connections and a human-machine interface (HMI) to control the process. Operators could monitor and guide the system remotely, keeping people out of the red zone and significantly improving both efficiency and safety [33].

II.4. Continuous circulation vs. Conventional drilling

Continuous Circulation Systems (CCS) have revolutionized drilling operations by addressing key challenges inherent in traditional methods. This section delves into the operational differences, pressure control mechanisms, safety implications, and connection procedures between CCS and conventional drilling.

II.4.1. Operational differences

Conventional drilling:

In traditional drilling, operations are periodically halted to add or remove drill pipe sections. This interruption requires stopping the mud pumps, leading to fluctuations in bottom-hole pressure (BHP) and potential wellbore instability. Such pauses can result in issues like formation fluid influxes (kicks) or stuck pipe incidents [28].

Continuous circulation drilling:

CCS allows for uninterrupted drilling fluid circulation, even during pipe connections. By maintaining constant BHP, CCS minimizes pressure fluctuations, enhances hole cleaning, and reduces the risk of downhole complications. This continuous flow ensures that cuttings are efficiently transported to the surface, improving overall drilling efficiency [33].

II.4.2. Pressure control and safety

Maintaining consistent BHP is crucial for well control and safety. CCS offers superior pressure management by eliminating the surge and swab effects associated with starting and stopping circulation. This stability reduces the likelihood of kicks and other well control

incidents. Additionally, CCS minimizes the risk of differential sticking and wellbore collapse, especially in formations with narrow pressure margins [30].

II.4.3. Connection procedures comparison

The process of adding new drill pipe sections differs significantly between conventional drilling and CCS (Tab.II.1):

Tab.II. 1: Side-by-Side Comparison of Connection Procedures [28].

Aspect	Conventional Drilling	Continuous Circulation Drilling
Circulation	Stopped during connections	Maintained throughout connections
Pressure Stability	Subject to fluctuations (surge/swab effects)	Consistent BHP maintained
Hole Cleaning	Interrupted, increasing the risk of cuttings settling	Continuous, enhancing the cutting removal
Risk of Kicks	Higher due to pressure variations	Lower due to stable pressure conditions
Operational Efficiency	Reduced due to frequent stops	Enhanced by minimizing non-productive time

II.4.4. Understanding ECD in continuous circulation and conventional drilling

When comparing continuous circulation systems (CCS) with conventional drilling (Tab.II.2) , the key differences are how each handles circulation during connections, pressure control, and wellbore stability. One of the most important technical aspects that highlights these differences is the Equivalent Circulating Density (ECD), the pressure the drilling fluid applies to the wellbore.

In drilling, ECD reflects the effective density of drilling fluid at the bottom of the well. It takes into account both the fluid's weight and the extra pressure caused by circulating it through the well.

When fluid is moving (dynamic conditions), the ECD is calculated as:

$$ECD_{dynamic} = \rho_{mud} + \frac{\Delta P_{annulus}}{0.052 \times D}$$

Where:

- ρ_{mud} is the mud weight (in pounds per gallon, ppg).
- $\Delta P_{annulus}$ is the pressure loss in the annulus due to flow (in psi).
- D is the true vertical depth (in feet).
- 0.052 is a unit conversion factor.

But when the pumps are off (static conditions), there's no more flow so the frictional loss disappears:

$$ECD_{static} = \rho_{mud}$$

This drop in ECD can be dangerous, especially in wells with tight pressure margins, because it reduces the pressure holding back the formation. If the pressure drops too much, you could get a kick, formation collapse, or differential sticking [27].

Tab.II. 2: ECD and pressure control: Side-by-Side comparison [34].

Aspect	Conventional Drilling	Continuous Circulation
Circulation During Connections	Stops completely during pipe connections.	Maintained at all times.
Static ECD	Only equals the mud weight (ρ_{mud}).	Not applicable; no interruption in flow.
Dynamic ECD	Increases due to friction when circulating.	Same as conventional, but maintained continuously
Pressure Drop at Connections	Yes, causes ECD to fall and pressure to drop.	No, circulation keeps ECD stable.
Pressure Stability	Disrupted frequently	Constant and predictable.
Risk of Kicks/Instability	Higher, especially in narrow margin wells.	Lower pressure is consistently controlled.
Operational Safety	Requires careful pump ramp-up/down management.	Safer and more automated.

In conventional drilling, every time the crew makes a pipe connection, they have to stop the pumps. That pause drops the ECD sometimes just enough to let formation fluids enter the

well (a kick), or even collapse weak formations. This is especially risky in high-pressure/high-temperature (HPHT) or depleted zones [27].

By contrast, continuous circulation systems allow drilling fluid to keep flowing even during connections. This means:

- Bottomhole pressure remains stable throughout the operation.
- The risk of well control incidents is significantly reduced.
- You avoid the pressure cycles that can lead to borehole ballooning or fracture.

Studies and field trials have shown that continuous circulation can reduce non-productive time (NPT) due to pressure-related problems and improve overall safety and efficiency [34].

II.4.5. Non-Productive Time (NPT) reduction

Implementing CCS has demonstrated significant reductions in NPT. By eliminating the need to halt operations for pipe connections, CCS streamlines the drilling process, leading to time and cost savings. Studies have shown that CCS can reduce drilling days by up to 5 days per well, translating to substantial operational efficiencies [34].

II.5. Managed Pressure Drilling (MPD) vs. Continuous circulation

II.5.1. Conceptual and functional overlap

Managed Pressure Drilling (MPD) and Continuous Circulation Systems (CCS) are both advanced technologies designed to maintain better control over wellbore pressure. While they serve similar purposes, the way they achieve pressure control is quite different (Tab.II.3).

MPD focuses on managing surface pressure using equipment like rotating control devices (RCDs), chokes, and control software. The system is dynamic; it continuously adjusts surface backpressure to keep the bottom-hole pressure within a safe window. MPD is especially useful in wells with narrow pressure margins or unstable formations, where even small pressure changes can cause serious problems like kicks or formation damage [5].

In contrast, Continuous Circulation Systems maintain wellbore stability by keeping the drilling mud flowing without interruption, even during pipe connections. This avoids the pressure surges and drops that typically occur when circulation stops, making it easier to drill through sensitive zones. CCS accomplishes this through mechanical tools attached to the drill

string, such as specialized subs with side ports and valves that divert the flow during connections [28].

Although the two systems differ in approach, one being surface-driven and the other bottomhole-focused, they both aim to reduce pressure fluctuations. They can be used together. In challenging wells, a continuous circulation system can be integrated into an MPD setup to provide even smoother pressure control during connections and tripping operations [35].

II.5.2. Complementary and substitute use

Whether CCS and MPD are used together or separately depends largely on the complexity of the well. In high-risk wells, combining the two methods can deliver superior performance by minimizing pressure variation from both surface operations and downhole activities [35]. For instance, continuous circulation can complement MPD by eliminating surge and swab pressures during pipe connections, thus reducing the chance of kicks or formation damage [28].

However, in more straightforward wells, continuous circulation alone might be sufficient and more cost-effective, especially when the main concern is avoiding pressure spikes during pipe connections [28]. So, while CCS can sometimes substitute for MPD in simpler scenarios, the technologies are often better viewed as complementary, particularly in complex or high-cost drilling environments [35].

Tab.II. 3: MPD and CCS (Key differences and similarities) [35].

Aspect	Managed Pressure Drilling (MPD)	Continuous Circulation System (CCS)
Primary objective	Manage wellbore pressure dynamically from the surface	Maintain uninterrupted circulation to avoid pressure spikes
How it works	Uses RCDs, chokes, pumps, and software to regulate pressure	Uses downhole subs with valves and ports to redirect flow
During pipe connections	May require adjusting surface backpressure	Circulation continues automatically
Cost and complexity	High – needs complex setup and real-time monitoring	Lower – more mechanical, fewer surface requirements
Ideal use case	Tight pressure windows, unstable zones	Wells where connection-induced surges are a risk
Integration possibility	Can include CCS for extra stability	Often used as part of MPD strategy
Level of automation	High – often fully automated	Moderate – some systems now offer remote control

II.6. Overview of CCS technologies

Continuous circulation systems (CCS) have evolved significantly in recent years, giving rise to a variety of technologies that aim to maintain the uninterrupted flow of drilling fluids during drill pipe connections. The main goals of these systems are to mitigate pressure fluctuations, prevent formation damage, and reduce non-productive time (NPT).

One of the earliest and most prominent systems is the E-CD (ENI Circulation Device) developed by ENI and commercialized through Halliburton. The E-CD system allows continuous circulation by using a sub with a side port that redirects the mud flow during pipe connections. The design involves a hinged flapper valve and a check valve that control flow redirection and sealing, ensuring minimal disturbance to the wellbore pressure [28].

In 2018, Halliburton introduced a more advanced version of this system known as the E-CD Plus. This next-generation solution incorporates automation to improve safety and efficiency by eliminating the need for personnel in the red zone during operations. The system includes a human-machine interface (HMI), an automated connection tool mounted on a robotic arm, and real-time software control for fluid diversion. This innovation reduces operational complexity and enhances wellsite safety by minimizing human intervention [35].

Other industry developments have included various sub-based continuous circulation systems, such as the Nonstop Driller (NSD) and Continuous Flow Sub (CFS), which provide alternative mechanical designs to maintain fluid flow during tripping or connections [28].

These systems differ slightly in their internal mechanisms, ranging from ball valves to sliding sleeves and poppet valves, but all share the fundamental principle of allowing circulation to continue uninterrupted.

II.7. The Eni Circulating Device (E-CD)

II.7.1. Design and working principle

The Eni Circulating Device (E-CD) is a proprietary continuous circulation system developed by Eni to maintain constant bottomhole pressure during drilling operations, particularly during drillpipe connections. The system comprises specialized subs installed on the drillstring and a manifold system on the rig floor. These components work in tandem to divert drilling fluid flow, allowing for uninterrupted circulation even when adding or removing drillpipe sections [31].

As shown in (Fig.II.3), the e-sub part is made of two valves: a radial one (placed down) and an axial one (placed at the top).

This section (Fig.II.3) and (Fig.II.4) represent the radial connection through the HP flexible hose. The X-Over adapter is the yellow device ending with a female connection.

In the lower picture of (Fig.II.3), as can be seen, the e-cd sub is upside down (to ensure the axial flapper stays in the closed position before applying test pressure) for being pressure tested.

II.7.1.1. The E-CD sub

The E-CD Sub is a short tool equipped with dual flapper valves, designed with the same pin and box threads as standard drill pipe. It's installed on top of each stand as shown in (Fig.II.2) and allows continuous mud circulation during connections, especially useful in operations where pressure control and wellbore stability are critical. The number of subs used depends on the well section targeted for continuous circulation. They are typically made up during stand preparation using the Top Drive [3].



Fig.II. 2: The E-CD Sub: Surface Handling, Rig Integration, and Stand Installation [3].

Here's a breakdown of its main components and how they function:

Box connection:

This is the upper threaded part of the sub, allowing it to connect securely to the drill pipe string above. It forms part of the mechanical structure that holds the tool in place during drilling operations.

Axial check valve:

Positioned in line with the main flow path, this valve works much like a flapper. It automatically opens or closes depending on the pressure and flow direction of the drilling mud. When the rig's rotary hose is disconnected, this valve closes to stop mud from flowing backward, effectively isolating the flow.

Radial check valve:

Mounted perpendicular to the main bore, this spring-loaded valve provides an alternate path for mud circulation. When the main rotary hose is disconnected, mud can still be pumped through a side port connected to the rig's pump manifold. This keeps circulation going without interruption.

Pin connection:

At the bottom of the sub, the pin connection threads into the drill string below. Together with the box connection, it ensures the E-CD sub fits seamlessly into the string and maintains structural strength.

Inner sleeve:

This sleeve sits just above the axial check valve. It's there to reduce potential problems during tricky operations like running or setting liners and during cementing. It helps protect internal parts and keeps everything flowing smoothly [3].

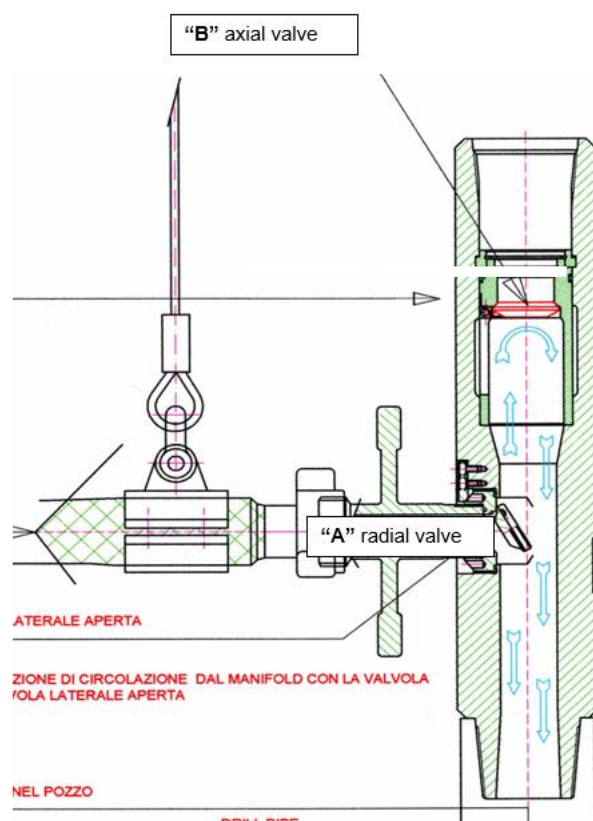


Fig.II. 3: The radial connection in E-CD sub [3].



Fig.II. 4: Visual overview of the ENI circulating device sub [3].

II.7.1.2. Manifold system

This is the central hub responsible for controlling and distributing drilling fluid during continuous operations. Connected directly to the rig's mud pumps, the manifold routes fluid through flexible hoses to the radial check valves of the E-CD subs. It is equipped with valves, pressure gauges, and flow meters to monitor and regulate flow to multiple E-CD units simultaneously (Fig.II.5). During a connection, when the top drive is disengaged, the manifold takes over the fluid supply, ensuring uninterrupted circulation [31].

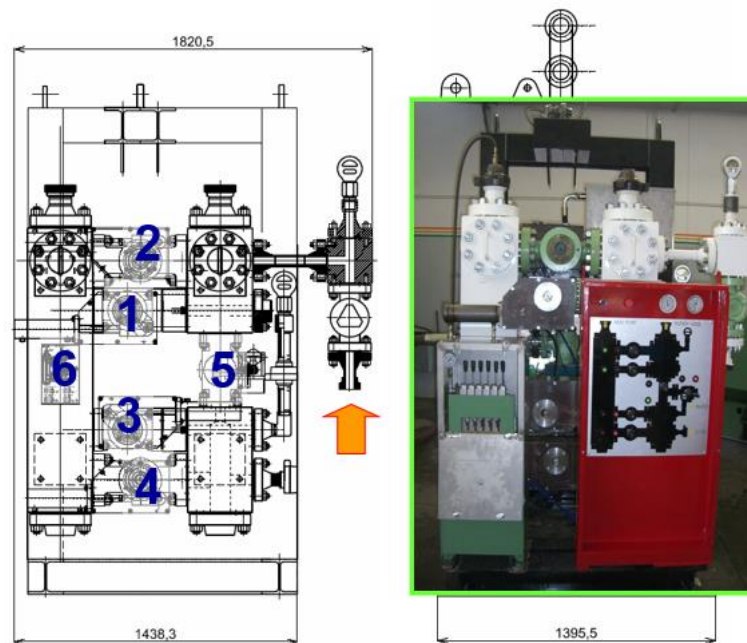


Fig.II. 5: The E-CD manifold system [36].

II.7.2. Integration of the ENI circulating device into rig systems

The ENI Circulating Device (E-CD) is seamlessly integrated into standard drilling rigs without the need for major modifications. Its design allows it to function as a specialized sub installed between standard drill pipe (DP) stands, using compatible pin and box connections. During drilling operations, a series of E-CD subs are made up on top of each DP stand before running them into the hole, ensuring continuous circulation throughout the connection process.

A critical component of this integration is the diversion manifold system, which works with the rig's mud pumps (Fig.II.6). The manifold is equipped with multiple valves, pressure gauges, and flow control instruments, and is linked via flexible high-pressure hoses to the radial check valves of each E-CD sub. This setup enables automated or remotely controlled redirection of mud flow to the E-CD when the top drive is disconnected during pipe connections.

Operationally, when the driller pauses to make a connection, the E-CD system, supported by the manifold, immediately maintains circulation through the side port, bypassing the need to stop and restart mud pumps. This reduces the risk of formation damage, wellbore instability, and influxes, common in conventional drilling during static conditions.

The integration is further enhanced by the use of Human-Machine Interface (HMI) systems and real-time monitoring software, enabling better control, safer operation, and improved efficiency [31].



Fig.II. 6: The connection of the E-CD manifold with rig components [37].

II.7.3. Mud system valve control during connection with E-CD

When making a pipe connection with the E-CD system, the key to maintaining continuous circulation lies in the precise coordination of valves between the rig's mud system, the manifold, and the E-CD sub. The goal is to ensure there is no interruption in drilling fluid flow, even when the top drive is disconnected.

Here is the valve control process step by step:

Normal circulation phase (before connection):

During regular drilling, the axial flow path is open. Mud is pumped from the rig's pumps through the standpipe and top drive, then flows through the axial check valve of the E-CD sub and downhole (Fig.II.7).

- Top drive line: Open.
- Manifold line: Closed.
- Axial valve: Open (activated by flow pressure).
- Radial valve: Closed (no reverse pressure) [31].

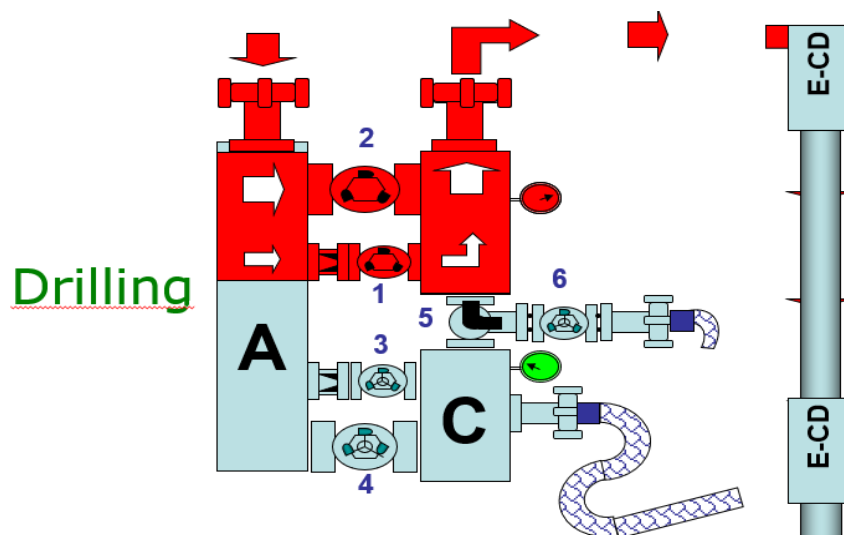


Fig.II. 7: Circulation during drilling [3].

Initiating the connection (Top Drive disengaged):

Just before disconnecting the top drive, the mud flow is temporarily diverted to the manifold system (Fig.II.8):

- The operator gradually closes the top drive valve while opening the manifold valve (Fig.II.9).
- The radial check valve on the E-CD sub opens automatically when it senses pressure from the manifold-side line, allowing mud to enter radially.
- Simultaneously, the axial check valve closes due to pressure loss on the top drive side.

Circulation is maintained through the radial path, preventing hydrostatic pressure drops and reducing the risk of kicks or formation influxes [31].

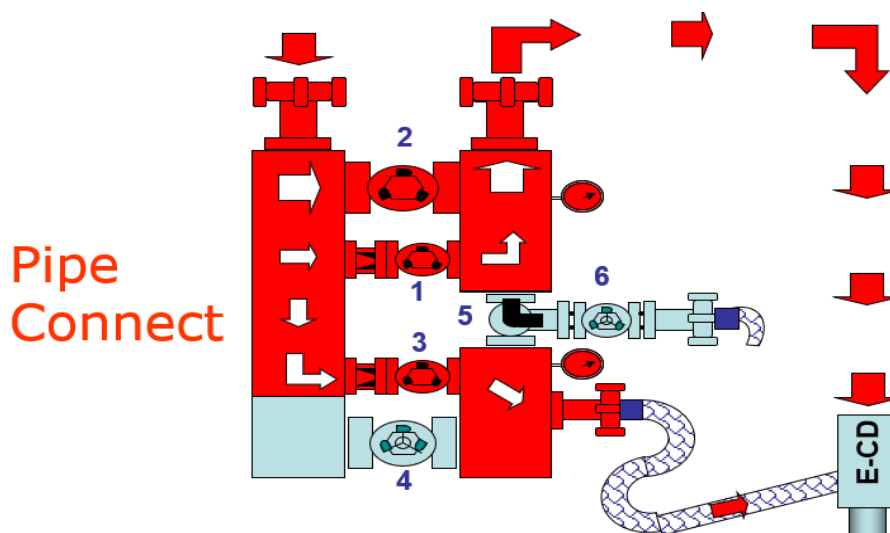


Fig.II. 8: Circulation during pipe connection before disconnecting the top drive [3].

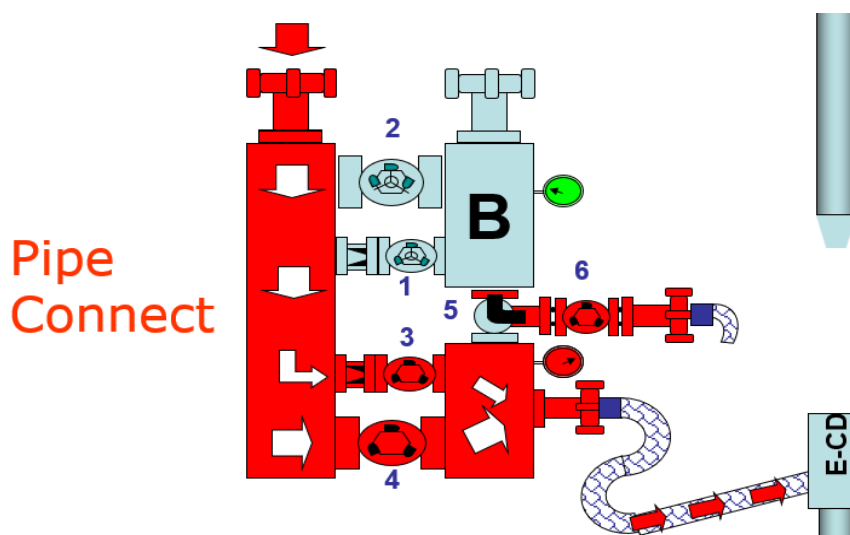


Fig.II. 9: Circulation during pipe connection after disconnecting the top drive [3].

Connection made – Ready to resume drilling:

Once the new pipe stand is connected and the top drive is re-engaged (Fig.II.10):

- Manifold valve: Closed.
- Top drive valve: Reopened.
- The axial check valve senses pressure and reopens, resuming normal flow from the top drive.
- The radial valve shuts automatically as backflow is prevented by its spring-loaded design.

The transition is seamless with no need to stop circulation, minimizing Equivalent Circulating Density (ECD) fluctuations and improving wellbore stability [34].

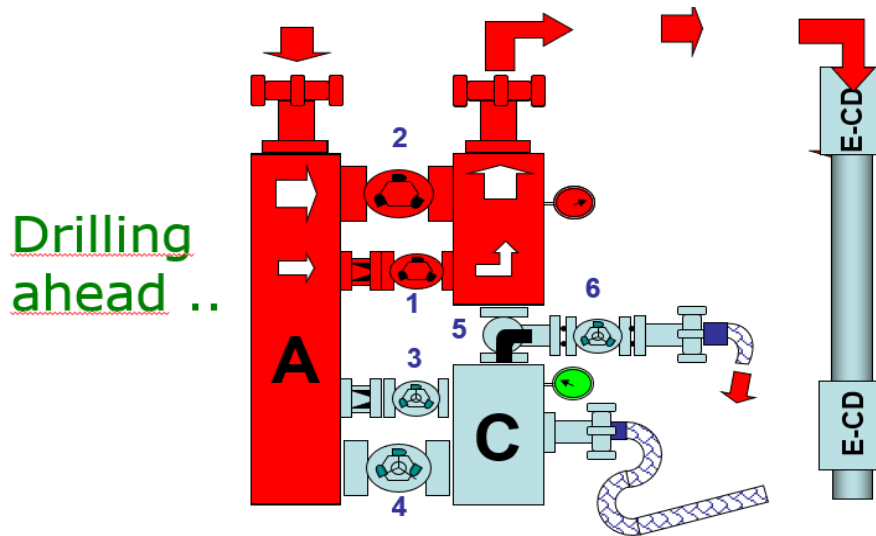


Fig.II. 10: Circulation after connection made and resuming drilling [3].

Tab.II. 4: Connection CCS procedure vs. conventional drilling [28].

Conventional Connection	Connection with CCS
Circulate, record weights.	No activity.
Stop rotation.	Stop rotation.
Shut down pumps, flow check.	No activity.
No activity.	Turn the string to orient the CCS sub lateral port to connect the CCS clamp.
Pick up off the bottom and set the slips.	Pick up off the bottom and set the slips.
No activity.	Set the CCS clamp on the sub, open the sub external plug, and divert the flow from TDS to the clamp.
Close the hydraulic IBOP and disconnect top drive.	Close the hydraulic IBOP and disconnect the top drive
Connect the next stand.	Connect the next stand.
No activity.	Fill up the new stand, divert the flow from the clamp to the TDS, close the external sub plug, and remove the clamp from the sub.
Start the pumps and bring the drilling flow rate.	No activity.

Start rotation and resume drilling.	Start rotation and resume drilling.
-------------------------------------	-------------------------------------

Controlling the valves during pipe connections with the E-CD system is essential for keeping the bottom-hole pressure (BHP) steady, especially during moments when the top drive is disconnected. This helps avoid pressure fluctuations or swab/surge effects that could destabilize the wellbore. By automating this process and enabling remote monitoring, the system also reduces the chances of human error and improves the overall safety of drilling operations [37].

II.7.4. Advantages over traditional and competitor systems

The ENI Circulating Device (E-CD) brings several clear advantages compared to both conventional drilling methods and other continuous circulation technologies:

Uninterrupted Circulation, Even During Connections:

One of the standout features of the E-CD is its ability to maintain continuous mud circulation, even while making or breaking pipe connections. Unlike conventional systems that interrupt circulation during these transitions, the E-CD helps maintain constant bottom-hole pressure. This reduces the risk of formation instability, kicks, or loss, problems that often arise from pressure fluctuations [31].

Simple, passive design with fewer failure points:

At the heart of the E-CD is a straightforward mechanical system using axial and radial check valves. There are no motors, sensors, or electronic controls involved. This passive setup minimizes the risk of equipment failure, making it more reliable and easier to maintain than systems that rely on complex hydraulics or automation [39].

Easy integration with existing rig equipment:

Another advantage is its compatibility with standard top drive rigs and drill pipe strings. There's no need to modify existing infrastructure or invest in specialized tools. Operators can implement continuous circulation with minimal changes, which helps keep both setup time and costs under control [34].

Improved safety through red zone reduction:

During pipe connections, the system transfers circulation through an external hose, allowing the top drive to disengage without stopping flow. This process reduces the need for personnel to enter hazardous zones, enhancing crew safety by limiting exposure during critical operations [31].

Full-bore design supports other downhole operations:

The E-CD also offers operational flexibility thanks to its full-bore internal diameter. This means standard activities like wireline logging, cementing, or running tools can be carried out without needing to remove the sub. In contrast, some competitor devices restrict flow or require removal, adding time and complexity [38].

Operational and cost efficiency:

By helping reduce Non-Productive Time (NPT), protecting the formation from damage, and in some cases, avoiding the need for costlier MPD systems, the E-CD proves to be an economically sound choice. Over time, its efficiency contributes to significant savings in both rig time and operational overhead [34].

II.8. Conclusion

Continuous Circulation Systems (CCS) offer clear operational, economic, and environmental advantages over conventional drilling. By eliminating flow interruptions, CCS reduces Non-Productive Time (NPT), maintains bottom-hole pressure, and minimizes formation damage. These improvements not only enhance drilling efficiency but also reduce environmental risks and associated costs. The next chapter will provide a detailed analysis of these economic and environmental benefits based on real-world data.



Chapter III: Case study – Application in LEWN 1 Well



III.1. Introduction

While the theoretical advantages of continuous circulation are compelling, the true value of any drilling technology is proven on the rig floor. This chapter moves from concept to reality by examining how these systems perform in the demanding environment of the Algerian Sahara. To provide a clear and fair assessment, this study takes a side-by-side look at two different approaches used in the same operational area.

On one hand, we analyze the well HBNEP-6, which represents the conventional "baseline." This well was drilled using standard methods, where pumping is stopped during every pipe connection, a process that introduces constant pressure fluctuations. On the other hand, we examine LEWN-1, our primary case study, which utilized the E-CD system. This technology allowed for a fundamentally different operation by keeping the fluid in motion and the pressure steady, even during connections.

By comparing the actual field data from these two wells, we can move beyond theory. This chapter breaks down the results into three practical categories: how much time was saved on the clock, how the costs compared in the final budget, and how much we were able to reduce our environmental footprint. This comparison serves as evidence for whether continuous circulation is a necessary evolution for complex drilling projects in this region [36], [38].

III.2. Overview of LEWN 1 well

The LEWN-1 (Ledjmet West Nord - 1) well sits at the heart of the Berkine Sud exploration perimeter (Fig.III.1). Its location was strategically chosen just north of the GSE-operated CAFC fields, placing it in a prime position surrounded by several proven discoveries within the TAGI and Lower Devonian (Siegenian) reservoirs [40].

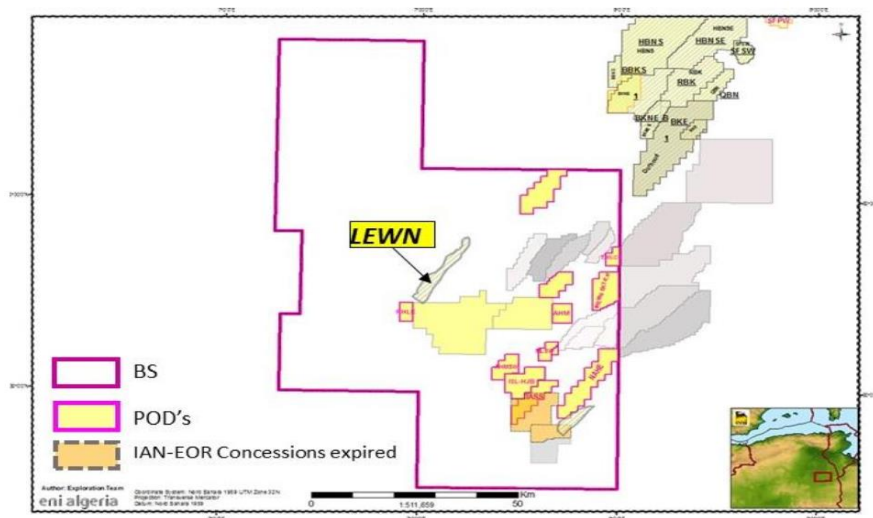


Fig.III. 1: The location of LEWN 1 well [40].

To understand the potential of LEWN-1, we look to its "neighbors," the surrounding offset wells that define the region's success. To the west, the LEN-1 and LESE-1 wells (drilled in 2019) successfully confirmed hydrocarbons in both target reservoirs. This success is echoed to the north by the WTS well cluster and to the northeast by the RHLE-1 discovery. Because of their proven results, the RHLE-1, LEN-1, and LESE-1 wells serve as the primary benchmarks for this study, providing the vital data needed to monitor and evaluate the Triassic and Lower Devonian units during the drilling of LEWN-1 [40].

From a structural perspective, the LEWN prospect is nestled within a distinct fault block. It is framed to the east and west by NE-SW trending strike-slip faults, the "signature" geological features of the Berkine Basin, while its southern boundary is defined by a WNW-ESE trending fault. This complex structural "container" is what makes the area both a challenging and rewarding environment for advanced drilling technologies [40].

III.3. Technical objectives and E-CD system configuration

With the complex geological "container" of the LEWN prospect defined, the strategy for LEWN-1 was built around a proactive rather than reactive approach. In conventional drilling, like that seen on HBNEP-6, the well experiences a "pulse" every time a connection is made, pumps stop, pressure drops, the pipe is added, and then pumps restart with a sudden surge. For LEWN-1, the objective was to eliminate this pulse by using the Eni Circulating Device (E-CD) [40].

The heart of this configuration is the specialized sub integrated into the drill string. This tool acts like a bypass valve, allowing the rig's manifold to maintain fluid flow even when the top drive is disconnected. Humanizing this process means looking at the "uninterrupted flow" as a safety net. By keeping the mud moving, the rig crew ensures that the Equivalent Circulating Density (ECD) stays perfectly flat. This prevents the formation from "breathing," a common issue where the wellbore expands and contracts with pressure changes, eventually leading to the collapses or "tight spots" often found near the Berkine Basin's major faults [36].

The technical configuration was tailored to meet three specific human and operational goals:

Steady-state stability:

By maintaining a constant Bottom-Hole Pressure (BHP), the system removes the stress of "connection gas" or "kicks" that often keep a drilling team on edge. It creates a predictable environment where the pressure stays safely between the pore pressure and the fracture limit at all times.

Continuous hole cleaning:

In conventional setups, cuttings (the rock bits being drilled) settle to the bottom whenever the pumps stop. This creates a "bed" of debris that can trap the drill pipe. With E-CD, the cuttings are in a state of perpetual motion, moving toward the surface without pause, which significantly reduces the risk of a "stuck pipe" event.

Protecting the reservoir's integrity:

Every time a pump restarts in a conventional well, it sends a "surge" of pressure into the formation. Over time, these spikes can weaken or "micro-fracture" the reservoir. The E-CD system treats the formation with care, maintaining gentle, steady pressure to preserve the rock's natural state [40].

III.4. Operational performance and NPT analysis

The most compelling argument for the adoption of continuous circulation is found in the reduction of Non-Productive Time (NPT). In drilling, time is not merely a logistical factor; it is a direct indicator of wellbore health. By analyzing the performance of HBNEP-6, our baseline for conventional drilling, we can see the high price of pressure instability.

According to the HBNEP-6 Final Program and Operational KPI Report [41], the well suffered a cumulative 304.5 hours of well-related trouble. This significant delay was largely driven by the "stop-start" nature of conventional connections. Every time the pumps were paused, the pressure dropped, and every time they were restarted, it surged. These fluctuations created a cycle of "breathing" in the formation, leading to connection gases and the major mud losses documented in the report [41].

To move from a reactive to a proactive operation on LEWN-1, the engineering team utilized the E-CD system to maintain a "steady-state" environment. The following comparison illustrates how this technology successfully neutralized the risks that plagued the baseline well (Tab.III.1):

Tab.III. 1: Comparative ECD profile and connection stability [40], [41].

Time (min)	Phase	Conventional ECD (HBNEP- 6)	E-CD ECD (LEWN-1)	Impact on Wellbore
0–20	Drilling	2.02 SG	2.02 SG	Stable circulation
20–35	Connection	1.92 SG (Drop)	2.02 SG (Stable)	Risk of Influx (Conventional)
35–40	Restart	2.12 SG (Surge)	2.02 SG	Risk of Losses (Conventional)
40–60	Drilling	2.02 SG	2.02 SG	Stable circulation

Comment:

The technical values in Table III.1 demonstrate why LEWN-1 was able to avoid the complications seen in the previous project. While the conventional profile (HBNEP-6) consistently falls below the critical 2.00 SG pore pressure threshold during connections, the LEWN-1 profile remains perfectly stabilized. This constant pressure protects the integrity of the TAGI and Siegenian reservoirs and ensures that cuttings remain in constant motion, effectively eliminating the primary triggers for NPT [40], [41].

III.5. Economic evaluation and cost-benefit analysis

While technical stability is the primary engineering objective, the ultimate success of an exploration project is judged by its financial efficiency. In the high-stakes environment of the Berkine Basin, the decision to deploy the E-CD system on LEWN-1 was a strategic investment designed to avoid the costly pitfalls identified in the baseline well, HBNEP-6.

III.5.1. The operational burden and financial impact of the HBNEP-6 stuck pipe

To quantify the value of the continuous circulation system, we must first look at the "hidden" expenses of the conventional approach. For the crew on HBNEP-6, the stuck pipe event represented a massive operational and personnel burden. It required 180 hours (7.5 days) of high-intensity, around-the-clock "fishing" and jarring operations. This placed immense mechanical strain on the rig equipment and significant psychological pressure on the personnel managing the critical well-control situation [41].

Applying the commercial rates from Contract N°11 [42], the financial impact is stark. At a daily spread rate of 150,000\$, the project spent 1,125,000\$ in rig time alone without making any drilling progress.

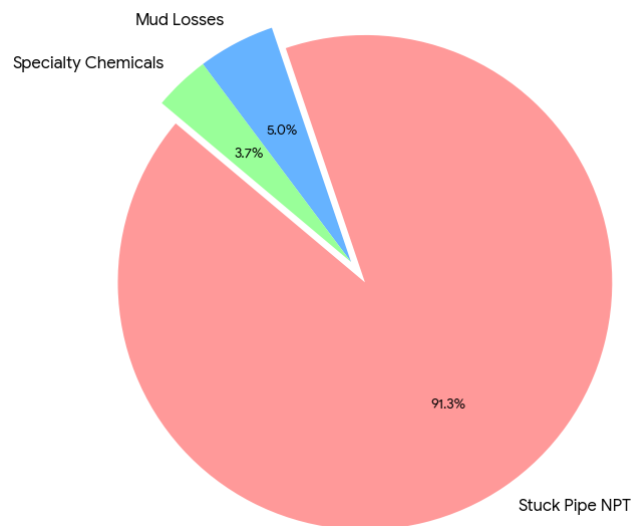


Fig.III. 2: Breakdown of HBNEP-6 wasted capital [42].

As shown in the Relative Circle above, the weight of the Stuck Pipe NPT accounts for over 91% of the total wasted capital. This visualization confirms that the primary financial risk in conventional drilling is the loss of time caused by pressure instability [41], [42].

III.5.2. The E-CD investment: A quantitative comparison

In contrast, the economic story of LEWN-1 is one of predictable, controlled spending. Instead of losing millions to a reactive crisis, the project invested in a proactive technical solution. The total service fees for the E-CD system were approximately 160,000\$ for the duration of the reservoir section [40], [42].

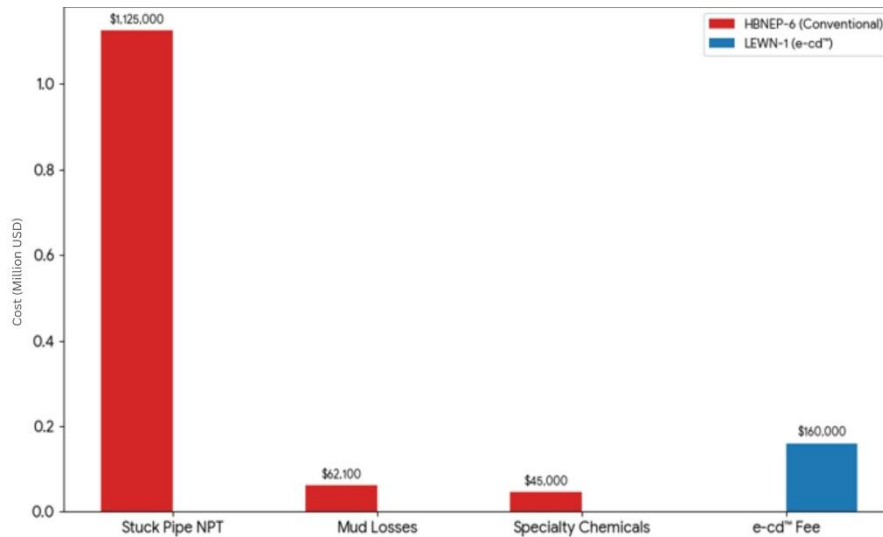


Fig.III. 3: Comparative costs HBNEP-6 vs. LEWN-1 [42].

The Column Chart above captures this "Economic Shield." It highlights how the controlled investment in the E-CD fee on LEWN-1 (blue column) eliminated the massive red columns representing the 1,125,000\$ in NPT and the combined 107,100\$ in mud losses and specialty chemicals that burdened HBNEP-6.

III.5.3. Final economic conclusion

The comparison of these two wells reveals a Net Economic Saving of 1,072,100\$. This result reframes the perception of advanced technology costs: the E-CD system was not an added expense but a high-return, cost-saving mechanism. By spending 160,000\$, the operator protected the project from over \$1.2 million in predictable losses. This demonstrates that in the TAGI and Siegenian reservoirs, continuous circulation is the most financially sound method for ensuring a well reaches its Total Depth (TD) on time and on budget [40], [41], [42].

III.6. Environmental impact analysis

While the financial savings of LEWN-1 are a primary driver for technology adoption, the environmental advantages of the E-CD system provide an equally critical justification. In

modern petroleum engineering, minimizing the environmental footprint is a core operational requirement. By maintaining a constant hydraulic state, the implementation of continuous circulation fundamentally improved the waste profile of LEWN-1 compared to the conventional baseline established by HBNEP-6.

III.6.1. Reduction in hydrocarbon-based waste and formation protection

The most direct environmental benefit observed was the prevention of Oil-Based Mud (OBM) discharge into the subsurface formations. As documented in the HBNEP-6 Final Report [41], conventional pressure surges during pump startups led to the loss of 69 m³ of OBM into the sensitive Siegenian sandstone. These losses represent a significant environmental "leak," leaving hazardous hydrocarbon-based materials in the formation.

By maintaining a constant Equivalent Circulating Density (ECD) on LEWN-1, these hydraulic shocks were eliminated, effectively preventing fluid loss. This proactive integrity management ensures that the reservoir remains uncontaminated and reduces the total volume of drilling fluid that must be manufactured and eventually treated [40].

III.6.2. Chemical footprint and efficiency in consumption

The prevention of the "stuck pipe" event also resulted in a cleaner chemical profile for the well. To manage the crisis on HBNEP-6, the crew utilized approximately 45,000\$ worth of specialized chemical "pills," lubricants, and spotting fluids to free the drill string [42].

The Relative circle (Donut Chart) below (Fig.III.4) illustrates the distribution of these environmental "costs" in the baseline well, highlighting how the use of the E-CD system effectively reduced this waste profile to zero for the reservoir section of LEWN-1.



Fig.III. 4: Environmental waste profile - HBNEP-6 vs. LEWN-1 [41],[42].

As shown, the environmental waste in HBNEP-6 was driven by both significant mud losses (58%) and heavy chemical usage (42%). On LEWN-1, the "Avoided Waste" circle represents a 100% reduction in these specific pollutants, as the steady-state hole cleaning prevented the need for any emergency chemical intervention [40], [42].

III.6.3. Emissions mitigation through operational efficiency

A critical, often overlooked environmental factor is the correlation between Non-Productive Time (NPT) and carbon emissions. During the 7.5 days that HBNEP-6 was immobilized by the stuck pipe event, the rig continued to consume industrial quantities of diesel to power the camp, generators, and maintenance systems (Fig.III.5).

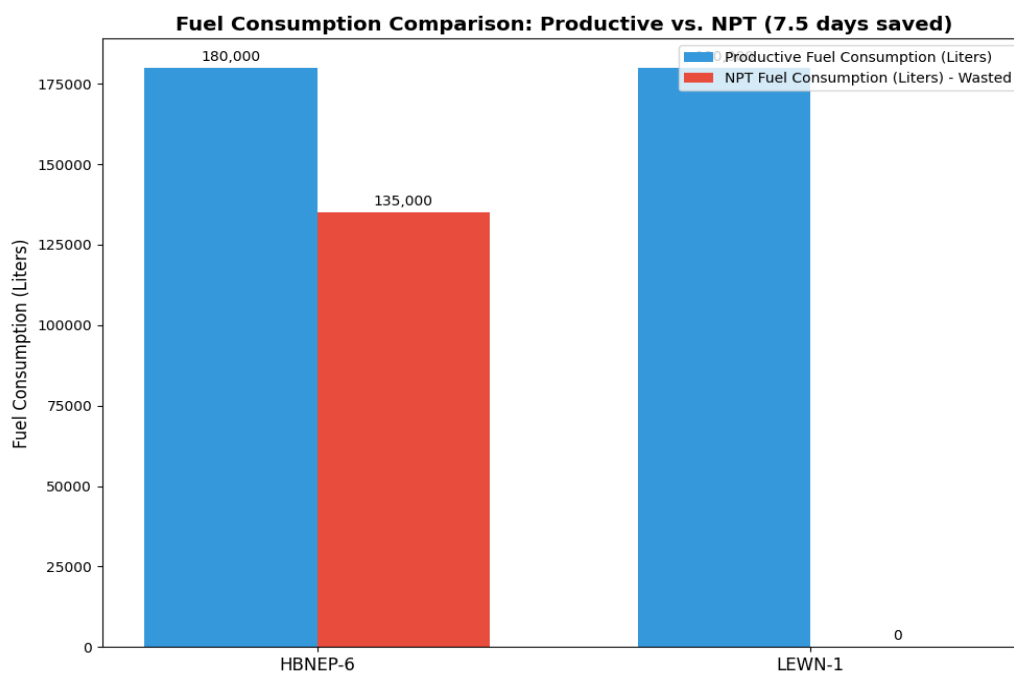


Fig.III. 5: Estimated fuel consumption and NPT impact [41],[42].

Based on an estimated daily consumption of 18,000 liters, the Column Chart reveals that the 7.5 days of NPT on HBNEP-6 resulted in the wasteful combustion of approximately 135,000 liters of diesel. By eliminating this period of inactivity, the E-CD system on LEWN-1 prevented the release of an estimated 361.8 metric tons of CO₂. This demonstrates that a shorter, more efficient drilling duration represents a significant reduction in the total "carbon cost" of the exploration project [41], [42].

III.6.4. Solids control and waste volume management

Because the E-CD maintains a constant flow velocity, cuttings are brought to the surface in a uniform stream rather than in "slugs" following a connection. This allows the solids control equipment, such as the shakers and centrifuges, to operate at a steady, optimized state. Technical observations from LEWN-1 [40] indicate that this steady-state processing resulted in "drier" cuttings. Reducing the liquid content of the waste significantly decreases the total weight and volume of materials that must be transported to disposal pits, further lowering the environmental impact of the drilling waste management cycle [40], [42].

III.7. Comprehensive analysis of the advantages of E-CD implementation in LEWN-1

The deployment of the Eni Circulating Device (E-CD) during the reservoir section of LEWN-1 provided a fundamental shift in hydraulic management. By replacing the conventional "stop-start" methodology with a continuous flow regime, the project transitioned from a reactive operational state to a proactive, steady-state environment. The following analysis synthesizes the specific technical and operational advantages derived from the LEWN-1 Rapport d'Implantation [40] and the HBNEP-6 KPI data [41].

III.7.1. Stabilization of the hydraulic window and ECD precision

The primary technical achievement of the E-CD was the total elimination of the "sawtooth" pressure profile that typically characterizes drill pipe connections. In the baseline well, HBNEP-6, each connection caused the Equivalent Circulating Density (ECD) to drop from a dynamic 2.02 SG to a static 1.92 SG. This fluctuation allowed the TAGI reservoir to "breathe," drawing in connection gases that required lengthy circulation periods to clear. In contrast, the E-CD on LEWN-1 maintained a constant circulation rate of 1,800–2,200 L/min throughout every connection [40]. By keeping the ECD locked at a constant 2.02 SG, the system neutralized the "swab" effect, ensuring the reservoir remained perfectly balanced and preventing the influx of formation fluids.

III.7.2. Optimization of cuttings transport and rheological stability

Beyond pressure management, the continuous flow fundamentally improved the efficiency of hole cleaning. In conventional wellbores, the 15-to-20-minute period of pump inactivity during a connection allows rock cuttings to settle under gravity, forming debris beds.

As recorded in HBNEP-6, this settlement led to "pack-offs" and increased mechanical friction. On LEWN-1, because the drilling fluid velocity never reached zero, the cuttings remained in perpetual suspension. This led to a significant reduction in torque and drag, directly preventing the settled-solids packing that caused the catastrophic 180-hour stuck pipe event in the baseline well [41]. This operational continuity protected the drill string and ensured that the rheology of the Oil-Based Mud (OBM) remained stable without the need for emergency lubricants.

III.7.3. Formation integrity and surge mitigation

The fragile nature of the Siegenian and TAGI sandstones makes them highly susceptible to micro-fracturing during the high-pressure "surges" associated with restarting pumps after a conventional connection. Technical documentation from LEWN-1 [40] highlights how the E-CD system acted as a hydraulic buffer. By maintaining a steady flow, the system prevented these spikes (which often peak at 2.12 SG) from reaching the formation face. This resulted in a total preservation of wellbore integrity; while HBNEP-6 suffered a loss of 69 m³ of mud valued at **62,100\$**, the steady-state profile of LEWN-1 ensured zero fluid invasion, protecting the productive potential of the reservoir sandstone [41], [42].

III.7.4. Synergy of economic and environmental performance

Finally, the implementation of the E-CD achieved a unique synergy between project profitability and environmental stewardship. From a project management perspective, the system converted high-risk "Trouble Time" into "Productive Time," resulting in a Net Economic Saving of 1,072,100\$ [42]. Simultaneously, the avoidance of the stuck pipe event eliminated the wasteful combustion of approximately 135,000 liters of diesel and the release of 361.8 tons of CO₂. This comprehensive performance proves that for the complex exploration perimeters of the Berkine Basin, continuous circulation is not merely a technical luxury but the most efficient methodology for balancing operational safety, environmental responsibility, and financial success [40], [41], [42].

III.8. Operational constraints and system limitations

While the performance of the E-CD system in LEWN-1 was demonstrably superior to conventional methods, its implementation is not without significant operational challenges. A balanced engineering assessment requires identifying the logistical and mechanical "costs" associated with this high-performance technology.

III.8.1. Surface equipment footprint and rig-floor congestion

The deployment of the E-CD system requires a substantial physical footprint on the rig site. In addition to the standard drilling equipment, a dedicated manifold, high-pressure lines, and a control unit must be integrated into the existing layout. According to the Contract N°11 logistics annex [42], this increases the congestion in the "Red Zone" of the rig floor. For the crew on LEWN-1, this meant managing more complex maintenance schedules and monitoring a higher number of potential leak points in the high-pressure fluid circuit, which requires constant vigilance during high-speed drilling operations [40].

III.8.2. The personnel learning curve and synchronization

Operating with continuous circulation introduces a new layer of procedural complexity. The "handover" process, the moment the flow is switched between the main pumps and the E-CD unit, requires perfect synchronization between the Driller and the specialized E-CD operator. Any communication breakdown or mechanical delay during this transition can lead to unintended pressure spikes. While the crew on LEWN-1 eventually achieved high efficiency, the early phases of the project showed slightly longer connection times as the personnel adapted to the new safety protocols and communication sequences compared to the routine procedures used on HBNEP-6 [41].

III.8.3. Mechanical compatibility and drill string integrity

The E-CD system is not a "plug-and-play" solution; it requires the use of specialized side-entry subs or specifically designed drill pipe components. This limitation restricts the operator's flexibility in choosing or replacing Bottom-Hole Assembly (BHA) components on short notice. Furthermore, the internal valves within the system are subject to wear from high-velocity, abrasive drilling muds. As noted in the LEWN-1 technical follow-up [40], maintaining the seals and internal integrity of the device requires a more rigorous inspection regime than standard drilling tools, adding to the total maintenance workload of the drilling department.

III.8.4. The economic and risk-based threshold

Finally, there is an "Economic Threshold" for the viable use of this technology. With a service fee of approximately 8,000\$ per day [42], the E-CD represents a high operational cost. While this was easily justified in the high-risk TAGI and Siegenian sections of LEWN-1, it may not be cost-effective for simpler, "standard" wells where the narrow pressure window or the risk of connection gas is not present. Therefore, the strategic recommendation is that the E-

CD should be viewed as a precision tool for high-complexity exploration wells rather than a universal replacement for conventional drilling in every perimeter [40], [42].

III.9. Conclusion

Evaluating the drilling data from the Berkine Basin brings us to a clear conclusion: shifting from conventional drilling to continuous circulation is a game-changer for high-risk exploration. Comparing the operational hurdles of HBNEP-6 with the smooth execution of LEWN-1 proves that steady-state hydraulics are the backbone of a safe, cost-effective, and responsible drilling campaign. Mechanically, the E-CD system solved the biggest headache in narrow pressure windows: the constant pressure swings during pipe connections. By keeping the mud moving at a steady rate, we locked the Equivalent Circulating Density (ECD) precisely in place. This stopped formation gases from sneaking into the wellbore and kept rock cuttings from settling into dangerous debris beds, completely avoiding the stuck pipe disaster that previously cost the project 180 hours of lost time. Ultimately, investing in this technology pays off. Using the E-CD system on LEWN-1 didn't just protect the drill string; it protected the budget by saving over \$1.07 million in avoided delays. Just as importantly, it protected the environment by preventing mud losses into the sandstone and cutting out 361 tons of CO₂ emissions by finishing the well days ahead of schedule. For the challenging perimeters of Berkine Sud, continuous circulation proves that operational safety, financial efficiency, and environmental care go hand in hand.



General conclusion



General conclusion

The research and comparative fieldwork presented across this dissertation provide definitive proof that transitioning from conventional drilling practices to continuous circulation technology is an operational necessity for complex, narrow-margin exploration in the Berkine Basin. By establishing a clear technical, economic, and environmental trajectory across all chapters, this study demonstrates how steady-state hydraulics directly solve chronic structural challenges that have historically plagued well construction in Algerian perimeters.

Evaluating the foundational concepts established early in the research shows that conventional stop-start drilling introduces violent pressure fluctuations during pipe connections. When the main mud pumps are shut down, the Equivalent Circulating Density drops immediately to a purely static mud weight state. As detailed in the theoretical framework, this sudden hydraulic loss triggers critical wellbore instability, connection gases, and severe cuttings settling. The introduction of the Eni Circulating Device directly overcomes this vulnerability. By using a robust, passive dual-valve mechanism in a specialized drill-string sub, the system maintains an uninterrupted flow rate of 1,800 to 2,200 liters per minute through an integrated side port during pipe handling.

The field data analyzed in this work conclusively validated this engineering theory. While the conventional baseline well, HBNEP-6, suffered a catastrophic 180-hour stuck-pipe incident caused by a massive cuttings pack-off during pump-off connection periods, the case study well, LEWN-1, experienced flawless cuttings transport and zero pressure-related Non-Productive Time. Keeping the drilling fluid in perpetual motion successfully neutralized the ultra-narrow drilling windows of the sensitive TAGI and Siegenian sandstone formations.

Beyond engineering performance, the deployment of the E-CD system on LEWN-1 demonstrated a profound synergy between project profitability and environmental stewardship. Although advanced continuous circulation tools carry a distinct daily service premium, they function as a highly effective operational insurance policy. By transforming high-risk trouble time into productive drilling days and avoiding expensive fluid-loss remediation, the technology yielded a Net Economic Saving of \$1,072,100 compared to the conventional baseline. Simultaneously, minimizing the total active duration of the drilling campaign generated immediate environmental benefits. The steady-state hydraulic profile eliminated the subsurface loss of oil-based mud into fragile formations. Furthermore, by cutting out seven and a half days of idle rig operation, the project avoided the wasteful combustion of approximately

135,000 liters of diesel fuel, resulting in a direct atmospheric mitigation of 361.3 tons of carbon dioxide emissions.

As exploration pushes deeper into the heavily faulted structures of South Berkine, managing downhole pressures using standard hydrostatic mud weights alone will become increasingly unviable. Based on the concrete performance metrics established in this study, the following actions are recommended for regional operators:

- **Standardization of E-CD:** Implement continuous circulation as a mandatory operational requirement for all exploratory and development wells that intersect the TAGI and Lower Devonian reservoirs and have an estimated hydraulic operating window narrower than 0.15 ppg.
- **Full automation integration:** Transition from standard mechanical E-CD subs to automated connection platforms, such as the E-CD Plus system. Utilizing robotic handling arms and automated control interfaces removes crew members from the high-pressure red zone of the rig floor, significantly optimizing personnel safety.
- **Hybrid MPD optimization:** For ultra-deep, high-pressure/high-temperature blocks, future well designs should integrate the bottomhole-focused continuous circulation system directly with a surface-driven Managed Pressure Drilling automated choke manifold. Combining continuous mud flow with automated surface backpressure will provide a comprehensive, bulletproof hydraulic shield from the reservoir to the surface.

In conclusion, this dissertation confirms that steady-state hydraulics represent the true future of well engineering in challenging geological perimeters. By successfully merging mechanical safety, strict cost optimization, and environmental responsibility, the E-CD technology sets a modern, sustainable benchmark for high-efficiency well construction in the Algerian energy sector.

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