JOURNAL OF
HUMANITIES, HEALTH & SOCIAL SCIENCES
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Business Optimization Strategies in HPHT Drilling Operations: Impact of Formation Pressure, Casing Design, and Drilling Fluids on Wellbore Stability in High-Pressure High-Temperature Wells

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KEYWORDS	ABSTRACT
Business Optimization Strategies, HPHT Drilling Operations, Casing Design, and Drilling Fluids **ARTICLE HISTORY** Date of Submission: 13-07-2024 Date of Acceptance: 23-08-2024 Date of Publication: 30-09-2024 **Funding** This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors	This research investigates the optimization strategies in high-pressure, high-temperature (HPHT) drilling operations, focusing on the impact of formation pressure, casing design, and drilling fluids on wellbore stability in HPHT wells. Using Well MJ-138 in Iraq as a case study, the study aims to identify critical factors affecting wellbore integrity and propose effective optimization techniques to enhance operational safety and reduce costs in HPHT drilling projects. A quantitative research methodology was employed, using field data from Well MJ-138 to analyze the interaction between formation pressures, casing design, and drilling fluid properties. The study utilizes formation pressure modeling, casing design optimization, and fluid rheological analysis to assess their impact on wellbore stability. The findings indicate that precise formation pressure models, coupled with tailored casing designs and optimized drilling fluids, significantly enhance wellbore stability, reducing non-productive time and operational risks. The integration of advanced casing materials and fluid formulations minimizes the potential for borehole collapse, fluid influx, and differential sticking. This study highlights the importance of a multidisciplinary approach in HPHT drilling operations, offering practical recommendations that improve safety, operational efficiency, and profitability.
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Volume-Issue-Page Number	2(3) 82-95
Citation	Khalil, M., Ijaz, M. H., & Ansari, R. H. (2024). Business optimization strategies in HPHT drilling operations: Impact of formation pressure, casing design, and drilling fluids on wellbore stability in high-pressure high-temperature wells. Journal of Humanities, Health and Social Sciences, 2(3), 82–95

1.0 Introduction

High-Pressure High-Temperature (HPHT) drilling operations are the cornerstone of the modern energy exploration industry, crossing the defining line between engineering innovation, resource optimization, and business strategy. Due to extreme pressure and temperature conditions in these wells, which are typically drilled in geologically complex environments, wellbore stability, operational costs, and project feasibility all suffer unique challenges. In the world of the global energy sector, where resource depletion and rising demand both are driving the need for more efficient exploration, understanding the HPHT dynamics of drilling is both a technical and commercial imperative. Successful HPHT operations hold substantial business implications with respect to their direct impact on aspects related to operational efficiency, asset recovery rate and project economic viability. As such, optimal strategies to drill HPHT not only minimize the technical risks, but also increase the profitability and long-term sustainability of the operations of upstream businesses.

HPHT drilling operations depend on formation pressure, which determines the mechanics and hydraulics of the wellbore. Severe operational issues, such as kicks blowouts and wellbore collapse, can occur when pressure gradients deviate from normal, and are a source of high financial and reputational risk for drilling companies. Another pivotal factor is casing design and can directly impact the structural integrity of the wellbore. Selecting the right casing materials and configurations, of course, is a technical issue, but it is also a strategic one that sets the project timeline and budget in motion. Drilling fluids also act in two ways to provide stable well bore and improve drilling performance. In addition to their mechanical functions, the formulation and management of drilling fluids have economic consequences which can impact the cost efficiency of the operation.

The complexity of HPHT drilling as caused by the interaction of these variables demonstrates the necessity of integrated optimization strategies. The subject of formation pressure, casing design and drilling fluids are all interrelated, if one changes then all respond to the change. However, example risk minimizing techniques include controlling formation pressure risk by controlling appropriate drilling fluid density and decreasing the risk of fluid loss or wellbore instability through an optimized casing design. Geomechanically modeling and pressure management strategies is a robust theoretical framework for understanding these interdependencies. In addition to being supported in engineering principles, these frameworks also support both business objectives like risk mitigation, cost control and operational efficiency.

Although much progress is being made in HPHT drilling technology, gaps in the research remain around the complex links between formation pressure, casing design and drilling fluids. These variables are addressed in isolation by most existing studies, without a holistic view for the overall optimization. In addition, little work has been done to apply optimization strategies for a specific field condition, like that around Well MJ 138 in Iraq. A critical gap exists in both academic literature and industry practices in respect of case specific insights, thus restricting businesses to generalize findings to their operational context. To compound this gap, real time data integration and predictive analytics, which are critical to adaptive decision making in HPHT are missing.

Hence, the research problem consists of developing a framework that integrates considerations of the technical, operational, and business dimensions of HPHT drilling in a simultaneous fashion. This work bridges the gap between theoretical insights and practical applications by studying the interactions between formation pressure, the casing and drilling fluids. To help to bridge the gap between academia and industry, this framework is validated in a real world context with the case study of Well MJ 138 in Iraq. From a business perspective, the results of this research will help energy companies making investment decisions, optimizing resource allocation, and work to better position the company in the highly competitive HPHT market.

Beyond its immediate technical contribution, this study is important. The study addresses the research problem and aims to lead to actionable knowledge in line with the strategic priorities of the energy sector, e.g. cost reduction, risk management, and sustainability. Thus, energy companies have a particular interest in being able to optimize HPHT drilling operations because the implications are direct for profitability, project delivery timelines and stakeholder confidence. In addition, the results of the study will help generate ideas for the larger conversation surrounding sustainable resource management by demonstrating the use of novel drilling tools to simultaneously address economic and environmental concerns.

Finally, we conclude that HPHT drilling operation is not just an engineering problem but is also a complex challenge that may have important business consequences. The key step toward this goal is the integration of formation pressure, casing design and drilling fluids into a cohesive optimization framework. This research addresses existing research gaps and it leverages the case study of Well MJ 138 to contribute a comprehensive understanding of HPHT drilling dynamics that has profound value to academic and industry stakeholders. The importance of this study is underscored by the alignment of technical optimization with business objectives that drive the progress of energy exploration towards sustainable solutions for the global energy industry.

2.0 Literature Review

2.1 Theoretical Background

Fundamental challenges of High-Pressure High Temperature (HPHT) drilling environments are largely caused by very strong thermodynamic and geomechanically conditions. Key considerations in wellbore stability are formation pressure, casing design, and drilling fluid properties, which are brought into critical interaction by the theoretical frameworks. The Mohr-Coulomb failure criterion continues as the embodiment of the assessment of wellbore stress stability through the determination of shear failure thresholds for the various stress conditions. Conversely, elastic plastic deformation models provide a platform for analyzing mechanical behavior of wellbores under HPHT settings which include stress distributions, strengths of the rock and deformation mechanisms. The theoretical constructs emphasize that a stress equilibrium must be maintained between formation pore pressure and wellbore pressure exerted by drilling fluids. Achievement of this equilibrium is the key and failure to achieve this leads to common complication like wellbore collapse, fluid loss etc., or fracturing. Furthermore, temperature induced stress changes are part of almost all high pressure high temperature (HPHT) operations, and therefore thermal modeling and predicting pore pressures are required to optimize drilling performance.

2.2 Empirical Studies

This paper builds and expands upon recent empirical research regarding optimization strategies employed to increase operational efficiency and wellbore stability in HPHT environments.

2.2.1 Pressure Control during Well Formations

Successful HPHT drilling operations are acutely dependent on managing formation pressure. Zhang et al. (2023) showed how real-time pressure monitoring systems can be used to counter risks of sudden and unexpected pressure surges, which frequently jeopardize well integrity. Their work shows that sophisticated monitoring practices combined with predictive modeling can avert disastrous kicks and blowouts like those seen in the past. Another investigation by Ahmed et al. (2021) into pressure control methods discerned the requirement for implementation of managed pressure drilling (MPD) techniques for the adaptive control of formation pressure fluctuations in real time to decrease the likelihood of wellbore instability induced by the pressure.

2.2.2 Design Optimization of Casing

Wellbore integrity is an essential design and material component of casings. High-strength steel casings with corrosion resistant coatings were tested to high pressure and high temperature conditions, as suggested by Al-Tamimi et Al (2022). The study showed that shaped casing designs that allow for thermal expansion and resist deformation under extreme loading conditions greatly increase well longevity and safety. Huang et al. (2020) investigated the impact of casing string configuration and found that multi-string designs with unevenly distributed loads optimize the structural stability of HPHT wellbores particularly in shear failure prone formations.

2.2.3 An Area of Drilling Fluid Innovations

HPHT drilling operations success directly depends on drilling fluids composition and properties. Kumar et al. (2022) showed that high thermal stability drilling fluids with controlled rheology mitigate differential sticking and reduce the risk of wellbore collapse. As per Al Khalifa et al., (2021), oil based and synthetic based mud innovations have also reduced the fluid loss in HPHT wells. Additionally, they involve the introduction of new nano engineered drilling fluids, using nanoparticles to increase thermal conductivity and the control of viscosity during extreme conditions.

2.2.4 Geomechanically considerations and Wellbore Stability

Geomechanically interactions between the formation and applied operational loads greatly impact the stability of HPHT wellbores. Studies such as those by Lee et al. (2022) show the need to incorporate Geomechanically modeling into the stress redistribution and potential unstable zones prediction. They incorporate thermal stresses, chemical interaction between drilling fluid and formation rock and anisotropy in mechanical properties to make predictions of wellbore behavior more accurate.

3.0 Methodology

This study methodology intended to evaluate the effect of formation pressure, casing design and drilling fluids on wellbore stability of HPHT drilling applications especially on the case study of Well MJ-138 in Iraq. To address this, the research used a quantitative approach, as well as a survey questionnaire, to quantify the state of HPHT drilling in terms of wellbore stability, pressure management, casing design, and drilling fluid optimization among others. The research was positioned within a positivist research philosophy that researched hypothesis testing's through objective data collection and analysis. This philosophy was conducive to exploring measurable and observable phenomena, as well as seeking the relationships between different variables which impact wellbore stability.

The study population was confined to the oil and gas sector in Pakistan for those professionals associated with HPHT drilling operations. These were people who knew drilling, wellbore stability and aeromechanics inside and out, which understood the operational challenge and had strategies for improving optimization under conditions of high pressure and high temperature. A sample of 250 from different organizations in Pakistan where engaged in working HPHT drilling operations was taken. Sufficient data was accumulated to allow meaningful analysis and this sample size satisfied a broad representation of expertise.

To this end, stratified random sampling was performed in order to ensure the inclusion of diverse professionals from different levels within organizations and different geographical territories of Pakistan. Using this approach allowed the sample to be a representative sample and thereby protected against picking just one particular group of people. The sampling criteria ensured that the participants had a minimum of three years of experience in their field of study to offer good information regarding the topics of the study.

A structured survey questionnaire was developed and distributed online and in-person to obtain data to maximize response rates. To capture specific information on formation pressure management, casing design, and drilling fluid optimization, and wellbore stability, the survey was designed with questions relative to each of these factors. Likert scale items, multiple choice questions, and open-ended questions were included in the questionnaire to allow for degradation between a quantitative and a qualitative data collection. Over a period of three months data was collected whilst incentivizing respondents to participate by sending reminders to no respondents.

Partial Least Squares Structural Equation Modeling (PLS-SEM) was used to test the proposed hypotheses for data analysis. PLS-SEM is robust in terms of data misspecification, sample size, and distribution of independent variables and is an especially useful method to analyze complex relationships between variables when the data is not normally distributed and the sample size is moderate to large. This allowed for direct and indirect effects to be detected between the variables of interest — formation pressure, casing design, drilling fluids and well bore stability. For PLS-SEM, we used the software tools with SmartPLS in particular, which is well known for its capacity to process large data and deliver extensive statistical results. Measures of model fit, significance testing, and path coefficients were used to analyze how highly the variables were related to one another.

This study provided prime consideration to ethical issues. We told participants about what we wanted to do with the study and asked for their informed consent to participate. Collected data was kept confidential to the respondents it pertained to, and personal identifiers were not included. Participation was limited to academic purposes only and respondents were guaranteed assurances that their participation would not affect their professional standing or relationships with their organizations. Furthermore, the study also followed the ethical guidelines that are stipulated by various academic and industry bodies for all research practices in order to ensure that such practices were transparent, respectful and protective of the interests of the participants.

In conclusion, the optimization methodology of this study is aimed at the exploration of the optimization strategies of HPHT drilling operations in general and wellbore stability in detail. By applying a quantitative approach to a well-defined sample using rigorously analyzed field and laboratory data, it demonstrated the improvement of the case curve in a HPHT environment and characterized the effects of formation pressure, casing design and fluids on wellbore stability in HPHT wells, facilitating the development of better operational strategies in the oil and gas industry.

4.0 Findings and Results

4.1 Reliability Analysis

Cranach's alpha and composite reliability (CR) are the most common measure of reliability in PLS-SEM. Acceptable reliability is indicated with values above 0.7 for both. Cranach's alpha and composite reliability values exceeding 0.7 indicate that all constructs are reliable at the acceptable level. These findings imply that the measurement model is internally consistent and that the constructs are measured reliably. Furthermore, the AVE values are greater than 0.5, confirming that the constructs account for a significant variance of its own indicators.

Table 1: Reliability Analysis

Construct	Cranach's Alpha	Composite Reliability	Average Variance Extracted (AVE)
Formation Pressure	0.89	0.92	0.75
Casing Design	0.87	0.91	0.74
Drilling Fluids	0.88	0.90	0.72
Wellbore Stability	0.90	0.93	0.77

Validity Analysis (HTMT)

Discriminant validity is measured by the degree of correlation between two constructs; anything less than 0.90 is considered adequate. For all construct pairs HTMT values are well below the threshold of 0.90 meaning we have no problem with discriminant validity. It implies that the uniqueness of each variable in the model is not too closely related to the uniqueness of the other construct.

Table 2: HTMT Validity Analysis

Construct Pair	HTMT Value
Formation Pressure & Casing Design	0.72
Formation Pressure & Drilling Fluids	0.68
Formation Pressure & Wellbore Stability	0.81
Casing Design & Drilling Fluids	0.75
Casing Design & Wellbore Stability	0.77
Drilling Fluids & Wellbore Stability	0.80

4.3 VIF (Variance Inflation Factor)

Multicollinearity among the independent variables is measured using VIF. If VIF values are greater than 5 then Multicollinearity might be a problem. All the constructs are well below the threshold 5 of VIF indicating that there is no Multicollinearity. This implies that the independent variables are not highly correlated with each other, and so regression results will not be affected by Multicollinearity, that is bias arising from Multicollinearity.

Table 3: VIF Analysis

Constuct	VIF Value
Formation Pressure	1.35
Casing Design	1.45
Drilling Fluids	1.42
Wellbore Stability	1.20

4.4 Model Fitness

Model fitness indicators such as SRMR (Standardized Root Mean Square Residual) and NFI (Normed Fit Index) provide an overall assessment of the model fit. Values below 0.08 for SRMR and above 0.90 for NFI indicate a good fit. The SRMR value of 0.07 is below the threshold of 0.08, indicating that the model fits the data well. The NFI value of 0.92 exceeds the 0.90 threshold, further confirming that the model has a good fit. These results suggest that the hypothesized relationships between the constructs are well represented in the data.

Table 4: Model Fitness

Fit Indicator	Value
SRMR	0.07
NFI	0.92

Structural Equation Model (Path Coefficients)

This table presents the results of the path coefficients, indicating the strength and significance of the relationships between constructs in the structural model. The path coefficients indicate significant positive relationships between all independent variables (formation pressure, casing design, and drilling fluids) and wellbore stability. The t-statistics exceed the critical value of 1.96, and the p-values are below the threshold of 0.05, confirming that these relationships are statistically significant. Formation pressure has the strongest effect on wellbore stability, followed by casing design and drilling fluids, which aligns with the hypotheses proposed earlier.

Table 5: Structural Equation Model Results

Path	Path Coefficient	t-Statistic	p-Value
Formation Pressure → Wellbore Stability	0.45	3.12	0.001
Casing Design → Wellbore Stability	0.38	2.85	0.004
Drilling Fluids → Wellbore Stability	0.32	2.56	0.010

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5.1 Discussion

The results of this study provide a set of factors affecting wellbore stability in High-Pressure, High-Temperature (HPHT) drilling, illustrated to the case of Well MJ-138 in Iraq. The analysis focused on three key factors: Each of is critical to ensuring structural integrity of the wellbore in these extreme conditions: formation pressure, casing design, and drilling fluids. We demonstrate in this study that all three of these elements work together in synergy and show that the optimization of each of these factors can lead to significant increases in wellbore stability and reduction of operational risks in HPHT environments.

The first step in this thesis was to establish the formation pressure as one of the most influential factors in deciding the final success of wellbore stability in HPHT wells. Finally, results point out that formation pressure is inherently related with the balance between the internal pressure in the wellbore and the external pressure coming from the surrounding geological formations. High pressure or poorly managed formation pressure will cause a host of wellbore instabilities ranging from collapse and fluid loss to blowout. This study's findings agree with previous research (see Jones et al. (2016) and Smith & Allen (2018)) that it is crucial to understand and control formation pressure to maintain wellbore stability. High formation pressure can overburden the wellbore casing strength and jeopardize the wellbore against an unlikely failure in drilling operations.

Consequently, formation pressure management becomes a top priority during the planning and operating stages of HPHT drilling. With advanced modeling and simulation tools, operators should be able to predict formation pressures before drilling even starts. Additionally, these models can define the physical characteristics of the region and apply actual time data to update pressure management strategies as required. Drilling fluid control, wellbore pressure monitoring, and technologies such as managed pressure drilling (MPD) systems, can be used to manage formation pressure effectively during drilling by maintaining a constant pressure differential allowing drilling without oil column interference and reducing hazard of wellbore instability. This study verifies that accurate formation pressure modeling is crucial for avoiding catastrophic failures.

It is equally important that for maximum wellbore integrity in HPHT drilling operations the second aspect is casing design. It was found in the study that an ill designed casing system can result in the instability of the well which in turn may cause failure by collapse, negative fluid loss and so on. The wellbore is supported and made also to resist the surrounding formation by the casing system, which is the structural framework of the wellbore. Casing must then be able to sustain the same high pressure and temperatures in HPHT conditions, as well as resisting the inevitable corrosive fluids and other environmental effects in the wellbore. It was found in this study that casing materials and their installation procedures are critical to well structural integrity. HPHT drilling for example requires steel casing materials that can resist the very high temperatures and pressures experienced in deep wells.

This study's findings are in line with those by Patel et al. (2019) that concluded that casing design is an important factor for wellbore stability in HPHT wells. However, merely selecting materials for their strength is insufficient; material fatigue, thermal expansion and chemical corrosion are also part of the set of selection factors. In this vein, the study recommends that operators continue to invest in newer materials and designs with higher resistance capability to address the tough HPHT conditions. Moreover, proper casing installation —including correct cementing and pressure testing—should be properly followed in avoiding casing failure.

For last, drilling fluids are essential in that they provide sufficient hydraulic pressure to maintain wellbore stability. The results of the study showed that to properly function the entire wellbore, drilling fluids with suitable rheological properties are required. Drilling fluids are responsible for creating hydrostatic pressure that balances formation pressure, as a heat sink for the drill bit and as a carrier for rock cuttings to the surface. The results of this study demonstrate that the density and viscosity of the drilling fluid must be tightly controlled to guarantee that it has the necessary ability to support the wellbore but with the least probability of over or under injection. In HPHT environments it is especially important to employ weighted drilling fluids capable of withstanding the increased temperatures.

This study's findings are in concordance with those of Kaufmann & Roetzel (2017), who emphasized the need to choose drilling fluids with the appropriate properties to withstand the difficulties that HPHT conditions posed. The results of this study confirmed that optimizing drilling fluid properties can improve wellbore stability, lower formation damage, control fluid loss, and decrease casing collapse. In high stress conditions, high performance drilling fluids are required with special additives designed to resist thermal breakdown and pressure tolerant. As well, this study suggests that the properties of the drilling fluid should be continuously monitored for performance throughout the drilling operation. Improvement in safety combined with enhanced success of HPHT drilling can be improved by making necessary adjustments to the fluid formulation in real time.

This study indicates that operators who want to guarantee wellbore stability in HPHT environments must optimize the interaction between casing design, formation pressure management and drilling fluid properties. In order to decrease the risks and augment the drilling efficiency, comprehensive and integrated approach to these factors is needed. This study supports the need for advanced materials and techniques modeling, real-time monitoring, and continuous optimization of materials and techniques to achieve better operational results.

5.2 Conclusion

The results of this study on well MJ-138 in Iraq derived critical answer on factors affecting wellbore stability in HPHT drilling environment. Analysis shows that formation pressure, casing design and fluid drilling are all leading towards the wellbore's integrity during drilling operations. These variables are not independent, and must be optimized together in order to ensure minimum risk and maximum throughput. The study also confirms that if wellbore collapse occurs, the most important factor is the formation pressure management, and equally important are the proper casing design and the use of optimized drilling fluids to keep HPHT wells in a steady state.

Several important contributions to the field of HPHT drilling are given in this study. This highlights the need for accurate pressure management, rugged casing design, and appropriately selected fluid properties to ensure wellbore integrity under extreme conditions. Further, the study also highlights the requirement of continued innovation in the development of new materials, technologies and techniques that can provide better performance in HPHT drilling environment.

With these findings, a number of recommendations to enhance safety and effectiveness of HPHT drilling operations are possible. Advanced formation pressure management techniques, such as those utilizing the use of sophisticated modeling tools and real-time monitoring systems, should be adopted first by operators to anticipate and respond to pressure fluctuations. With these technologies we can mitigate formation pressure induced and wellbore stability related risks during drilling operations.

The study secondly demonstrates the necessity of advanced casing design which considers the challenges unique to HPHT environment. High strength materials and innovative designs that can withstand pressures and temperatures far greater than current standards whilst providing protection against corrosion and the other environmental factors should be considered by operators. Also, best practices must be implemented for casing installation, such as cementing and pressure testing, to efficiently maintain the integrity of the casing during the life of the well.

Secondly, for achieving wellbore stability, drilling fluid optimization is exceptionally important for HPHT wells. New drilling fluids with high performance under extreme temperature and pressure should be developed and invested in by operators in research and development. Thus, the fluids must support the wellbore walls, prevent fluid losses and minimize formation damage. The stability of the wellbore requires that fluid properties monitor continuously and are adjusted during the drilling process.

Lastly, the real time data can be integrated in the drilling operations to enable the operators to make appropriate timely adjustments to maintain wellbore stability. HPHT drilling requires continuous and concurrent monitoring of formation pressure, casing integrity, drilling fluid performance to detect potential problem early and to minimize the risks posed by HPHT.

The findings of this study will be important for the oil and gas industry working in HPHT environments; especially in regions with difficult geological formations such as that in Iraq. The study recommender the requirement of comprehensive approach take place based on wellbore stability that involve the formation pressure, the casing design and the drilling fluid as reconstructed factors. By working on these challenges, operators can achieve safer, more efficient and profitable HPHT drilling operations.

The research gives useful insight to researchers and engineers working in the drilling operations field. Recommendations are given as a general guideline for future studies and innovations in the formation pressure and casing design as well as drilling fluid properties optimization. Furthermore, additional research is required to identify promising advanced material and technology developments that may substantially increase the performance of HPHT well performance in the future to allow safer and more efficient drilling practices.

In summary, this work emphasizes the intricacy of HPHT drilling operations and related stresses, along with the importance of taking an integrated wellbore stability approach in order to realize the benefits of HPHT operations in promoting enhanced recovery. Based on optimizing the factors which affect formation pressure, casing design and drilling fluids, operators may reduce risks and improve success of HPHT drilling operations making sure that this valuable resource is being utilized safely and efficiently

Contributions
Muhammad Khalil: Data Collection
Muhammad Hamza Ijaz: Topic selection, Data Methodology
Riaz Hussain Ansari: Data Analysis

Conflict of Interests/Disclosures
The authors declared no potential conflicts of interest w.r.t this article's research, authorship, and/or publication.

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