

Systematic Evaluation of Managed Pressure Drilling Variants: A Framework-Based Comparative Review for Operational Decision Support

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ABSTRACT

MPD has evolved from a niche technique into a mainstream drilling capability over the last decade. It is now used in HPHT, deepwater, unconventional tight-gas, and sour-gas reservoirs. Despite this widespread adoption, the operational question of which MPD variant is best suited to a particular well profile has historically been addressed in the published literature on a case-by-case basis, without structured comparative synthesis. This paper addresses that gap through a systematic framework-based evaluation of fourteen MPD case-study publications sourced from the SPE and IADC literature between 2015 and 2025. A six-dimensional analytical framework, inductively developed from the recurring performance themes within the corpus, serves as the uniform evaluative instrument. The six dimensions encompass: well-control sensitivity and detection thresholds; narrow-margin pressure window navigation; non-productive time (NPT) and invisible lost-time reduction; rate-of-penetration (ROP) enhancement relative to conventional baselines; cementing and tripping operational reliability; and economic performance across deployment contexts. Synthesis findings confirm that MPD delivers well-control detection sensitivity approximately one to two orders of magnitude superior to conventional pit-volume methods; that variant selection materially affects operational outcomes; that NPT reduction is robustly demonstrated while ROP enhancement evidence remains comparatively sparse; and that economic viability is strongly contingent on multi-well campaign scale. A structured application-domain selection map, matching ten canonical operational situations to corpus-preferred MPD variants across three evidence-calibrated confidence tiers, is presented as the primary decision-support contribution of this review.

Keywords: Managed Pressure Drilling; Well Control; Narrow-Margin Drilling; Comparative Framework; CBHP; PMCD; ABP; CML; Selection Map; Drilling Engineering

INTRODUCTION

The global hydrocarbon industry has progressively migrated into operational settings of mounting geological complexity. Deepwater and ultra-deepwater development, ultra-HPHT exploration, naturally fractured sour-gas reservoirs, and unconventional tight-gas multi-well campaigns have each transitioned from exceptional to routine operational categories within the past decade. A defining geological characteristic shared across these settings is a narrow operating window between formation pore pressure and fracture gradient, a characteristic that directly challenges the fundamental assumptions underpinning conventional drilling practice.

Conventional drilling manages annular pressure primarily through hydrostatic mud-weight selection. This approach lacks the precision and rapid-response capability that narrow-margin operations demand. Influx detection relies on pit-volume monitoring at sensitivities typically in the range of 10–25 barrels, and the standard response to a detected influx proceeds through the multi-step shut-in-and-circulate-out kick-kill procedure — a process that requires hours to complete and substantial overbalance margin to execute safely. In narrow-margin environments, these limitations translate directly into elevated well-control risk, increased non-productive time, and reduced economic performance.

Managed Pressure Drilling (MPD) was engineered specifically to address these limitations. Its defining architectural innovation is the introduction of a controllable surface back-pressure as a fourth pressure-

management lever — supplementing the hydrostatic, friction, and bottom-hole-pressure contributions that conventional drilling employs. By dynamically modulating surface back-pressure through a controllable choke manifold, MPD enables the operator to position the annular pressure profile precisely along the narrow line between pore pressure and fracture gradient across the full well depth, rather than fixing the annular pressure at a constant overbalance that must be tolerable at every depth simultaneously. The closed-annulus architecture, incorporating a Rotating Control Device (RCD) at the wellhead, a Coriolis flow meter on the return line, and a real-time mass-balance computation comparing pump-in and return-flow rates, simultaneously delivers an order-of-magnitude improvement in influx detection sensitivity relative to conventional pit-volume monitoring.

Despite more than a decade of operational deployment across multiple continental settings, the published MPD literature has been characterised predominantly by individual case-study reporting rather than structured comparative synthesis. This reporting pattern has left operators, service providers, regulators, and academic researchers without a consolidated evidential basis for understanding how MPD variants compare in performance across differing operational settings — a gap with direct practical consequences for variant selection decisions. This paper addresses that gap through systematic framework-based comparative analysis of fourteen SPE and IADC case-study publications from 2015–2025, and presents a structured application-domain selection map as its principal decision-support output.

METHODOLOGY

Corpus Definition and Selection Criteria

The analytical corpus comprises fourteen technical papers drawn from the SPE and IADC published literature over the 2015–2025 decade, selected to represent the operational, geographical, and technical breadth of contemporary MPD practice. Papers were included on satisfaction of five explicit criteria: (i) inclusion in OnePetro or equivalent peer-review-screened technical-publication infrastructure; (ii) substantive operational reporting extending beyond procedural overview; (iii) representation of a distinct operational variant or operational context not duplicated elsewhere in the corpus; (iv) publication within the 2015–2025 window; and (v) sufficient analytical content to support uniform framework application across all six evaluation dimensions. The resulting corpus spans North America (three approaches), Asia-Pacific (five), the Middle East (two), Europe and South America (one each), and laboratory or test-rig controlled settings (two).

A publication-bias limitation inherent to this selection methodology warrants acknowledgement: papers reporting failed or aborted MPD deployments are less likely to appear in the peer-reviewed literature than successful applications, which may lead to a positive-outcome skew in the corpus. Future reviews should seek to incorporate service-company internal datasets and operator after-action reports to mitigate this bias.

Six-Dimensional Analytical Framework

The analytical framework was constructed inductively through iterative thematic analysis of the corpus prior to formal cross-case assessment. Six performance dimensions emerged as the recurring evaluative themes against which published cases report operational outcomes. To strengthen the credibility and generalisability of the inductively derived framework, the six dimensions were subsequently applied as a sanity check against two corpus-external case studies not included in the original fourteen (Approach A: a North Sea HPHT re-entry well; Approach B: a shallow unconventional well in North America). Both cases mapped coherently onto the framework without requiring dimensional modification, providing an initial cross-validation indication. Formal industry validation through a structured expert-panel review is recommended as a priority next step.

Dim.	Dimension Name	Description
D1	Well-Control Sensitivity	Detection thresholds, response latency, and robustness across operational modes.

D2	Narrow-Margin Navigation	Quantification of the operating-window width within which the MPD approach maintained successful drilling without fracturing or influx.
D3	NPT & Invisible Lost-Time Reduction	Measurable reductions in non-productive time and invisible lost time attributable to MPD deployment.
D4	ROP Enhancement	Rate-of-penetration improvement against a defined conventional baseline.
D5	Cementing & Tripping Reliability	Operational reliability of cementing and tripping operations conducted under MPD-managed pressure conditions.
D6	Economic Performance	Capital, mobilisation, and operational cost analysis across single-well and multi-well deployment contexts.

Table F1. Six-dimensional comparative analytical framework applied uniformly across fourteen corpus approaches. Dimensions D1 through D6 are inductively derived from recurring performance themes in the literature.

Data-Extraction Protocol

Each corpus paper was processed through a uniform five-section data-extraction template: (§1) operational context — geography, operator identity, well architecture, reservoir conditions, and operating window characteristics; (§2) MPD configuration — variant classification, equipment spread, operational procedures, and distinctive technical features; (§3) operational outcomes — well-control events, NPT quantification, ROP measurements, cementing results, and economic data; (§4) critical analysis — enabling factors, operational limitations, generalisability assessment, and evidential strength evaluation; and (§5) framework assessment — primary, secondary, or absent classification of the approach against each of the six framework dimensions D1 through D6. Uniform application of the protocol across all fourteen approaches produces commensurable per-approach outputs that directly support the cross-case synthesis reported in Section 3.

RESULTS: CROSS-CASE COMPARATIVE FINDINGS

Well-Control Effectiveness (D1)

The most robust cross-case finding from the structured review is the qualitatively superior influx detection sensitivity achieved by MPD-equipped drilling operations. Eleven of the fourteen corpus approaches provide specific detection-sensitivity evidence. Quantitative outcomes include the 53-well Saudi unconventional tight-gas CBHP campaign's Coriolis-derived detection threshold of 3 gallons per minute (Approach 13), the UK North Sea HPHT infill well's containment of a 0.06 m³ influx within a single circulation (Approach 11), and the West Canadian Dynamic Well Control deployment's sub-barrel simulation outcomes validated against field operations (Approach 1).

The detection-sensitivity advantage is consistent across all represented operational contexts, spanning onshore tight-gas horizontal wells, offshore HPHT infill wells, deepwater development campaigns, and naturally fractured sour-gas reservoirs. The underlying mechanism is consistent across approaches: the closed-loop annulus architecture, combined with Coriolis return-flow measurement and real-time mass-balance computation, enables detection of influxes substantially below the pit-volume threshold on which conventional drilling depends. The aggregate well-control finding extends beyond detection to encompass response latency reduction

and mode robustness, with MPD's well-control advantage demonstrated across drilling, connection, tripping, and cementing operational modes.

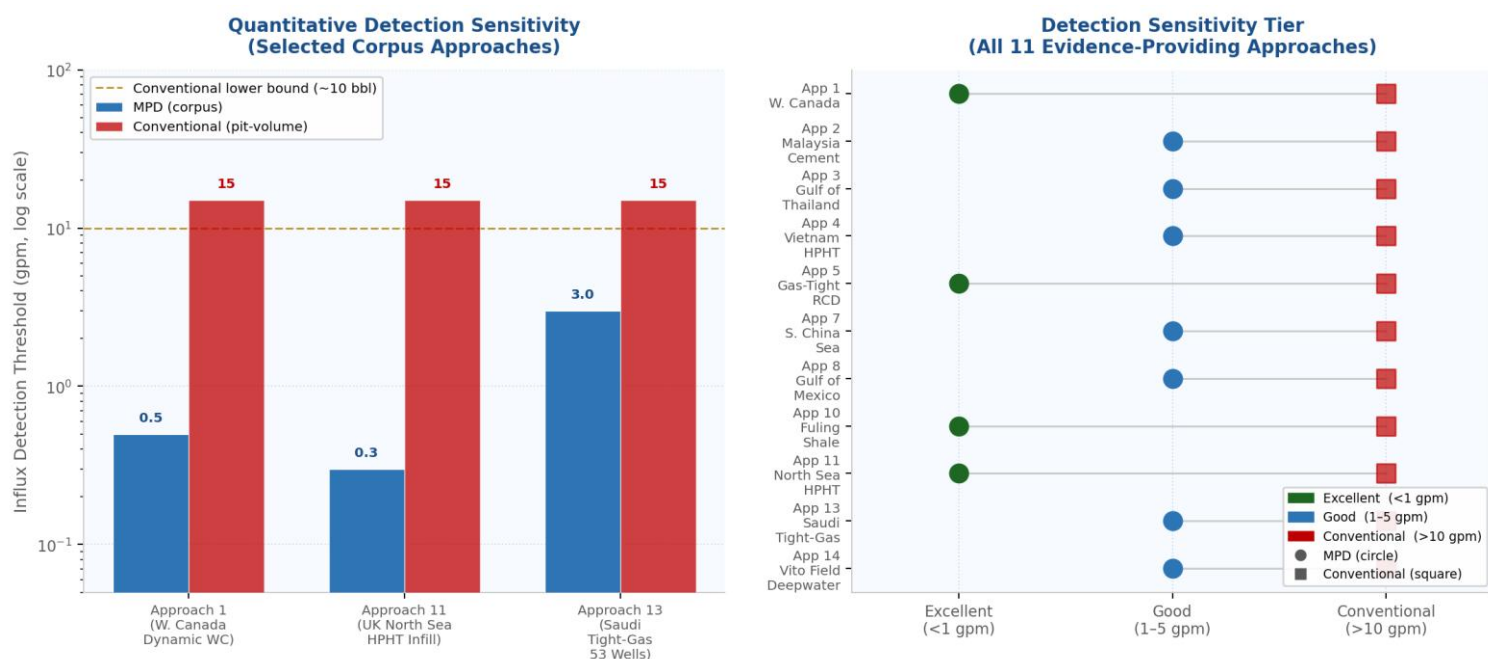


Figure 2. Detection-sensitivity comparison across corpus approaches. MPD configurations consistently achieve approximately one to two orders of magnitude superior minimum-detection performance relative to conventional pit-volume kick detection methods.

Drilling Efficiency Outcomes (D3 and D4)

The corpus supports a strong and well-evidenced case for NPT reduction (D3) and a comparatively thinner evidentiary foundation for direct ROP enhancement (D4). NPT-reduction outcomes documented across the corpus include the Gulf of Thailand ultra-high-temperature CBHP campaign's approximately twenty-day operational saving against the conventional well baseline (Approach 3), the SINOPEC multi-mode gas-influx detection model's reported NPT reduction of sixty percent or greater across the monitored campaign (Approach 10), and the elimination of contingency casing strings demonstrated repeatedly across multiple corpus approaches (Approaches 2, 14, and others). These outcomes reflect both the direct well-control advantage of MPD and the secondary operational benefits of closed-annulus architecture.

ROP-enhancement evidence is more limited in both quantity and quality. Only the 53-well Saudi unconventional tight-gas campaign (Approach 13) provides a field-scale ROP comparison against a clearly defined conventional baseline. Even this strongest evidence is complicated by operational-team-learning effects across the campaign, which confound direct attribution of ROP improvements to the MPD configuration alone rather than to accumulated crew experience. The asymmetric evidence base between NPT reduction and ROP enhancement is identified as one of the principal evidence gaps requiring structured research attention. The scarcity of ROP-enhancement data is attributable to two compounding factors: inconsistent ROP reporting conventions across operators and service providers, and confounding of MPD-specific effects with contemporaneous bit design and drilling-parameter optimisation. Standardising ROP measurement and reporting protocols — including baseline-well specification and crew-learning correction methods — in future multi-well campaigns would substantially close this evidence gap.

Economic Performance (D6)

Cross-case evidence on economic performance is anchored by the operator-authored business-case analyses presented in the Shell deepwater Gulf of Mexico ABP study (Approach 8) and the Vito Phase-2 CML campaign (Approach 14). Both analyses demonstrate that MPD's economic justification depends critically on the multi-well-campaign versus single-well deployment distinction. Campaign-scale amortisation of mobilisation costs,

combined with operational-team learning accumulated across multiple wells, produces a strongly positive economic case in multi-well applications. As a practical threshold, corpus evidence suggests positive economic returns are consistently achieved in campaigns encompassing six or more wells or involving total drilling budgets exceeding approximately USD 30 million, where mobilisation cost amortisation and learning-curve efficiency gains combine to produce a net positive case. Single-well economic justification requires substantially larger per-well operational benefits — typically measurable NPT avoidance or well-count reduction through casing-string elimination — to overcome the fixed costs of MPD equipment mobilisation and specialist personnel.

Service-provider-authored economic reporting across the remainder of the corpus tends to understate the incremental ongoing operational costs that operator-authored analyses surface transparently. This systematic asymmetry between operator-authored and service-provider-authored economic reporting has direct implications for the strength and generalisability of economic conclusions drawn from the published literature and should be acknowledged explicitly in any deployment economic analysis.

Application-Domain Selection Map

The primary decision-support output of this review is the application-domain selection map, which systematically matches canonical operational situations identified from the corpus to corpus-preferred MPD variants, with explicit confidence-tier calibration reflecting the strength and consistency of the underlying evidence. Table 1 presents the selection map in abbreviated form.

Tier 1 entries are supported by multiple corpus approaches with consistent outcomes and can be adopted with high operational confidence. Tier 2 entries are supported by single approaches with substantive evidence and should be treated as working hypotheses requiring verification against specific operational context. Tier 3 entries are supported by foundational or prospective evidence and should be treated as directional indications rather than as direct deployment recommendations pending additional field validation.

Operational Situation	Preferred MPD Variant	Confidence Tier
HPHT Exploration Wells	CBHP	Tier 1
Ultra-HPHT (T > 200 °C)	CBHP + Advanced ECD Model	Tier 1
Tight-Gas Horizontal Multi-Well Campaign	CBHP + Continuous Casing System	Tier 1
Ultra-HPHT Liner Cementing	Managed Pressure Cementing (MPC)	Tier 2
Deepwater MODU Operations	ABP (Air/Light-Fluid Bypass)	Tier 2
Deepwater Curved PP/FG Profile	CML (Controlled Mud Level)	Tier 2
Sour-Gas Fractured Reservoir	CBHP + Gas-Tight RCD	Tier 2
Mature / Depleted Reservoir Zones	PMCD	Tier 3
Autonomous Well-Control Response	CBHP + Automated Well Control	Tier 3

Table 1. Application-Domain Selection Map: Canonical Operational Situations Matched to Corpus-Preferred MPD Variants across Three Evidence-Calibrated Confidence Tiers.

DISCUSSION

Three principal observations from the cross-case synthesis merit extended discussion.

Variant-Choice Consequentiality. The finding that MPD variant choice materially affects operational outcomes carries direct practical implications for the two-stage decision framework that operators contemplating MPD adoption should employ. The Vito Phase-2 deepwater campaign (Approach 14) provides the corpus's most instructive single illustration through its explicit CML-versus-ABP-versus-conventional comparison conducted on a common operational substrate. Operators should approach the adoption decision in two distinct stages: a first-stage assessment of whether to adopt MPD at all, resting primarily on the well-control and narrow-margin-navigation evidence; and a second-stage assessment of which MPD variant to adopt, resting on the operational-situation-to-variant matching that the selection map supports. Operators treating the decision as a single stage may achieve acceptable outcomes but will not capture the full operational and economic value available from rigorous variant selection.

Evidence Asymmetry in Drilling Efficiency. The asymmetry between the strong NPT-reduction evidence base and the thinner ROP-enhancement evidence base reflects the structure of the published literature rather than any inherent technological limitation of MPD. Operators report NPT-reduction outcomes more readily because NPT reduction carries transparent cost implications that directly motivate publication. ROP enhancement, by contrast, requires careful counterfactual construction against a conventional baseline that is not always available in single-well deployments and is subject to learning-curve confounding in multi-well campaigns. The practical implication is that systematic ROP-comparison studies — ideally structured through joint-industry-project mechanisms with pre-specified conventional baselines and controlled for crew-learning effects — represent the highest-value incremental research investment for closing this evidence gap.

Foundational Technology Maturation. The foundational contributions represented in the corpus — particularly the gas-tight RCD qualification to API 16RCD documented in Approach 5 and the autonomous-response test-rig demonstration of Approach 12 — represent technological investments whose full operational value remains to be captured. Both establish capabilities whose field-operational deployment is more recent and less comprehensively documented than the underlying technologies themselves. Service providers investing in field-validation and commercial deployment of these foundational capabilities are positioning themselves to capture disproportionate operational-value share as the MPD market continues to mature and as autonomous well-control requirements become increasingly mainstream.

CONCLUSIONS

Systematic framework-based comparative analysis of fourteen SPE and IADC MPD case-study publications from 2015–2025 supports the following principal conclusions:

- (1) MPD achieves qualitatively superior influx detection sensitivity across all operational contexts represented in the corpus, approximately one to two orders of magnitude better than conventional pit-volume kick detection. This is the most robust and consistently supported cross-case finding.
- (2) MPD variant choice is consequential to operational outcomes, and the corpus supports defensible variant-to-situation matching across three confidence tiers. The application-domain selection map (Table 1) is the primary decision-support contribution of this review.
- (3) NPT-reduction evidence is well-demonstrated and consistent across the corpus, while direct ROP-enhancement evidence is asymmetrically sparse. This asymmetry reflects the reporting structure of the published literature and defines a specific priority research gap.
- (4) Economic performance is critically dependent on the multi-well-campaign versus single-well deployment distinction. Operator-authored economic analyses carry disproportionate evidential weight relative to service-provider-authored reporting and should be preferentially weighted in deployment economic assessments.

(5) Specific evidence gaps — autonomous-response field validation, regional economic calibration across international cost environments, and dedicated PMCD case coverage — constitute a structured research agenda for the continuing development of MPD practice. Field validation of autonomous well control across multi-well campaigns is identified as the highest-priority unresolved research question.

The methodological contribution — the petroleum-engineering-specific adaptation of the structured comparative review research tradition — is offered as a replicable template for adjacent comparative questions in drilling engineering, including wellbore-strengthening technique evaluation, drilling-automation-system comparison, and completion-technology comparative analysis.

Ethical Considerations

This study is a secondary analytical review of publicly available technical publications and does not involve human participants, animal subjects, or primary data collection. No ethical approval was required. The authors declare no conflict of interest. This research received no specific funding from public, commercial, or not-for-profit funding agencies.

Data Availability

All primary data supporting this review are drawn from the fourteen technical papers cited in the References section, each publicly accessible through the OnePetro technical publication database (www.onepetro.org). No proprietary datasets were generated or analysed in the course of this study.

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