Simulation-Based Well Control Technology for Oil and Gas Blowout Elimination Using the AMT-411 Work-Over Simulator

Jamshid Eshkobilov[1], Sanjar Khaydarov[1], Dilshod Sohibov[2], Akhrorjon Sirojiddinov[1], Sherali Ashurov[1] and Gulmira Kalesheva[3]
[1]Tashkent State Technical University, University Str. 2, 100000 Tashkent, Uzbekistan
[2]Center for Training of Employees of the Ministry of Poverty Reduction and Employment, Kamarniso Str. 37, 100109 Tashkent, Uzbekistan
[3]West Kazakhstan University of Innovation and Technology, Ikhsanova Str. 44, 090000 Uralsk, Kazakhstan
jamshideshqobilov883@gmail.com, sanjarxaydarov86@gmail.com, ahror.sirojiddinov9095@mail.ru, asherali@gmail.com, sohibovd082@gmail.com, Kalesheva~gulmira_29_69@mail.ru

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Abstract: Gas, oil, and water influxes (GOWI) represent critical well control complications posing substantial operational, environmental, and economic risks during drilling, completion, and work-over operations. This study integrates digital technologies, including real-time process modeling, predictive analytics, and automated parameter adjustment, to enhance well control operations. Timely detection, accurate diagnosis, and technologically justified mitigation of such influxes are essential to ensure well integrity, operational safety, and sustainable hydrocarbon production. Failure to properly manage GOWI may result in blowouts, formation damage, non-productive time (NPT), and significant financial losses. Therefore, the development of digitally supported, scientifically grounded well control strategies remains a priority for modern petroleum engineering. This study systematically analyzes the classification, underlying mechanisms, and early diagnostic indicators of gas, oil, and water influxes, emphasizing pressure imbalance, kick tolerance limits, and transient flow behavior. Advanced well control techniques, including soft shut-in procedures, are critically evaluated in terms of pressure stabilization efficiency and reduction of dynamic loading on surface and down-hole equipment. Digital simulation using the AMT-411 work-over simulator provides scenario-based training, real-time monitoring, and predictive decision support for operators. Based on simulation outputs and engineering calculations, optimized well killing strategies are proposed, demonstrating improved.

1 INTRODUCTION

GOWI represent the uncontrolled entry of gas, oil, or water from a productive formation into the wellbore and to the surface as a result of an imbalance between formation pressure and bottom-hole pressure. GOWI most frequently occur during drilling, well completion, routine maintenance, and work-over operations and require the immediate implementation of control measures [1]-[3].

Here, digital monitoring tools, automated alerts, and integrated well control dashboards are suggested to detect GOWI at early stages, reducing response time and human error.

The problem of GOWI becomes particularly critical under conditions of abnormally high formation pressures, significant depths of productive horizons, and in cases of insufficient personnel qualification or violation of technological discipline [4].

The primary objective of engineering and operational personnel in the oil and gas industry is the prevention of GOWI. In the event of occurrence, it is essential to promptly identify indicators of influx, accurately assess the situation, and eliminate the complication while minimizing risks to equipment, personnel, and the reservoir. The integration of predictive analytics and decision-support software enhances the accuracy of influx detection and assists operators in real-time decision-making.

2 MATERIALS AND METHODS

2.1 Gas, Oil and Water Influx Control Methods

The control of gas, oil, and water influxes involves the removal of invading formation fluids from the well bore while maintaining the bottom-hole pressure within a safe operating window. Gas influxes are the most hazardous due to the high compressibility of gas and its rapid expansion during upward migration toward the wellhead.

In drilling and work-over operations, influx control methods are conventionally classified into two groups:

- constant bottomhole pressure methods (soft shut-in well control methods);
- variable bottomhole pressure methods.

Constant bottom-hole pressure methods are the most widely applied, as they minimize the risk of secondary complications, including lost circulation and formation fracture initiation. Digital well control platforms now allow real-time adjustment of bottom-hole pressure using automated choke systems controlled via software algorithms. The principal constant bottom-hole pressure methods include:

- the driller's method (two-circulation method);
- the wait-and-weight method (single-circulation method);
- the continuous circulation method.

Simulation-based training with AMT-411 integrates these methods, allowing trainees to experiment with digital choke regulation, automated pump control, and real-time visualization of pressure trends (Fig. 1).

Simulation modeling allows the evaluation of well-control responses under various operational conditions and provides a basis for selecting optimal technological parameters for safe and effective well killing.

Figure 1: General view of the AMT-411 well work-over simulator.

2.2 Driller's Method FOR Well Kick Control

The elimination of a well kick using the driller's method consists of six stages.

2.2.1 Stage 1 - Well Closure

The first stage involves closing the well. During closure and afterward, continuous monitoring of the wellhead pressure P_e is required to ensure it does not exceed the allowable limit $P_{e,max.}$ In digital-assisted systems, pressure sensors feed data into predictive models to warn operators before reaching critical limits.

After closure, the well is kept at rest for 5-10 minutes to stabilize pressures within the shut-in well. Subsequently, the pressures at the well inlet $P_{n,shut-in}$ and at the wellhead $P_{e,shut-in}$ are measured. The target bottom-hole pressure is calculated as:

$$P_{target} = P_{res} + \Delta P_{bh}, \quad (1)$$
$$P_{res} = P_{n,shut-in} + P_{hyd,DP} \quad , \quad (2)$$
$$P_{hyd,DP} = 0.1 \rho_n H_0, \quad (3)$$

where:

- P_{res} - reservoir pressure (kg/cm²);
- ΔP_{bh} - safety margin for reducing bottom-hole pressure (kg/cm²);
- $P_{hyd,DP}$ - hydro static pressure in the drill string (kg/cm²);
- H_0 - well depth (m).

The AMT-411 simulator calculates these parameters automatically and displays recommended fluid densities, enabling trainees to apply real-time corrections digitally:

$$\rho_{target} = P_{target} / (0.1\, H_0). \quad (4)$$

The pump pressure required to maintain the bottom-hole pressure at the target value is:

$$P_{n,target} = P_{n,shut-in} + \Delta P_{dc} + \Delta P_{bh}, \quad (5)$$
$$\Delta P_{dc} = \Delta P_{DP} + \Delta P_{bit} + \Delta P_d, \quad (6)$$
$$\Delta P_{DP} = 10 - 8\, K_h\, \rho_{DP}\, Q_n^2\, L_i, \quad (7)$$

where:

- ΔP_{dc} - pressure losses in the drill string (kg/cm²);
- ΔP_{DP} - pressure losses in drill pipes (DP and HWDP) (kg/cm²);
- K_h - hydraulic resistance coefficient in DP and HWDP (m⁻⁵);
- ρ_{DP} - fluid density in DP and HWDP (g/cm³);
- Q_n - flow rate at the well inlet (L/s);
- L_i - length of the tool in the well (m);

- ΔP_{bi} - pressure losses in the turbine drill bit (kg/cm²);
- i - additional pressure losses (kg/cm²).

For rotary drilling, $\Delta P_{bit} = 0$. For turbine drilling, it is computed using standard turbine-specific formulas.

The wellhead pressure required to maintain the target bottom-hole pressure is:

$$P_{e,target} = P_{e,shut\text{-}in} + \Delta P_{bh}. \quad (8)$$

2.2.2 Stage 2 - Flushing the Well

The well is flushed with drilling fluid of the original density. The pump flow rate and drill pipe pressure are kept constant using choke regulation. Once the fluid is displaced, the pump is turned on, and the well is closed. The shut-in wellhead pressure should equal the inlet pressure.

2.2.3 Stage 3 - Preparing Weighted Drilling Fluid

The drilling fluid in surface tanks is weighted to the target density.

2.2.4 Stage 4 - Circulating Weighted Drilling Fluid

Weighted drilling fluid is pumped into the well at the target density. Pump flow rate and casing pressure are maintained constant by choke regulation.

When the fluid reaches the drill bit, the drill string pressure is recorded, and constant pressure is maintained via choke adjustment. When the fluid reaches the surface, the well is closed. In a properly executed operation, the inlet and outlet pressures in the shut-in well should be zero.

2.2.5 Stage 5 - Well Reopening and Equilibrium Control

The well is reopened, and the restoration of equilibrium between the reservoir pressure and the hydro static column of weighted drilling fluid is monitored. The fluid level in surface tanks should not rise. If it does, kick control continues by increasing the fluid density.

2.2.6 Stage 6 - Confirmation of Kick Elimination

If the reservoir pressure is balanced by the hydro static column (i.e., no rise in tank levels), the gas-oil-water shows are considered successfully eliminated.

3 SIMULATION OF GAS-OIL-WATER SHOWS ELIMINATION DURING DRILLING

The task "Simulation of GOWS Elimination during Drilling" simulates gas-oil-water shows and is designed to develop trainees' skills in eliminating GOWS using any method, including smooth kill techniques such as the driller's method and the wait-and-weight method.

In the simulation, the correct sequence of actions for a specific method, the target bottom-hole and pump pressures, and the specified density of the weighted drilling fluid are not monitored. Only general emergency situations common to all methods-such as kicks, fluid losses, and gas influx-are monitored. No performance grade is assigned after completion.

3.3 Trainee Actions Sequence

3.3.1 Setting Initial Conditions

The initial parameters correspond to the starting conditions of the drilling task. The initial fluid density at the well inlet is recommended to be calculated as:

$$\rho_{n0} = (P_{res} - \Delta P_{bh}) / 0.1\, H_0. \quad (9)$$

where:

- P_{res} - reservoir pressure (kg/cm²);
- ΔP_{bh} - safety margin for bottom-hole pressure reduction (kg/cm²);
- H_0 - well depth (m).

3.3.2 Kick Appearance

A kick occurs when the reservoir pressure at the productive formation depth exceeds the bottom-hole pressure. This typically happens due to an incorrect choice of circulating fluid density or encountering a formation with abnormally high reservoir pressure.

3.3.3 Simulator Response

An error signal, outlet flow rate exceeding inlet flow, gradual rise of the fluid level in the receiving tank, and decreasing inlet pressure.

In real drilling, the kick hazard is assessed, after which either drilling continues or remedial actions, such as increasing fluid density, are taken. In the simulator, resolving the kick requires switching to the

GOWS elimination task, a one-way transition from drilling simulation to kick control simulation [5], [6].

3.4 Well Sealing

To seal the well, set the required values on the driller panel, circulation system, blowout preventer (BOP), wellhead equipment, manifold, and choke block [7], [8]. After sealing, wait 5-7 minutes for pressure stabilization and measure pressures at the well inlet and outlet.

3.5 Process Parameter Calculation

After sealing, the following parameters must be calculated to perform kick elimination:

- Volume of fluid entering the well and height of the fluid column in the annulus (L_{fl});
- Density of the incoming fluid (ρ_{fl});
- Reservoir pressure (2);
- Drilling fluid density required for kill (4);
- Fluid type based on the inequality:

$\rho_{fl} \leq 0.5\ g/cm^3 \Rightarrow$ gas, otherwise liquid

- Inlet pressure required to maintain bottom-hole pressure during fluid displacement (5).

3.5.1 Circulation Initiation

Partially open the choke and start the pump at half maximum capacity. Fluid displacement can be performed with the original density fluid or simultaneously with weighted fluid injection. Weighted fluid preparation is simulated by setting the new density on the density controller. In the visualization, the new-density fluid is shown in a different color. If the color does not change, the density is outside the allowable range:

$$\rho target - \Delta\rho n < \rho w < \rho target + \Delta\rho n \quad (10)$$

where:

- ρ_w - weighted fluid density *(g/cm³)*;
- $\Delta\rho_n$ - density control tolerance *(0.01 g/cm³)*.

During fluid displacement and weighted fluid injection, pump pressure should maintain bottom-hole pressure within the safety range:

$$P_{res} < P_{bh} < P_{kick-start}, \quad (11)$$

where $P_{kick-start}$ is the fluid loss threshold specified in the scenario.

Emergency conditions:

- Fluid loss: $P_{bh} > P_{kick-start} \rightarrow$ slightly open the choke;
- Kick: $P_{bh} < P_{res} \rightarrow$ kick appearance.

Pump, bottom-hole, and outlet pressures are controlled via the choke.

If the pump pressure exceeds the maximum allowable value:

$$Pn > Pn, max, \quad (12)$$

an overload occurs, and the pump stops. To reset, turn the pump off and on again.

Circulation continues until the entire well-bore is flushed. If flushing used original-density fluid, stop the pump and close the well. Inlet and outlet pressures should then equal the original shut-in pressure.

3.5.2 Weighted Fluid Injection

Prepare and inject the weighted drilling fluid. During injection, maintain bottom-hole pressure within the safety range (11) by adjusting the outlet pressure. Record pump pressure when weighted fluid reaches the drill bit and maintain it until the fluid appears at the surface.

3.5.3 Well Sealing and Verification

After the well bore is filled with weighted fluid, seal the well. Inlet and outlet pressures in a closed well should be zero.

- Outlet pressure > 0, inlet = 0 → residual fluid in the annulus; continue circulation to remove fluid.
- Inlet pressure > 0 → weighted fluid density insufficient; prepare new fluid and circulate.

Finally, open the BOP and verify that hydro static pressure in the open well satisfies:

$$P_{res} < P_{hyd,kill} < P_{res} + \Delta P_{bh}. \quad (13)$$

The GOWS elimination process is considered complete. The initial well, reservoir, drilling-fluid, and equipment parameters used for the AMT-411 simulation are summarized in Table 1.

Stage 1: On the Capital Well Work-over simulator, after drilling through the sand plug, a kick occurs. The well is immediately secured by closing the drill pipe and annular valves (Fig. 2).

After closure, pressures at the well inlet and wellhead are allowed to stabilize, after which the shut-in pressures are measured. These readings are essential for calculating the target bottom-hole pressure and the required density of the weighted drilling fluid for the subsequent stage of the kick elimination process [9]-[11].

Table 1: The following input parameters were used for the simulation of the two-stage driller's method.

Parameter	Value	Unit	Notes
Well depth	2045	m	Measured depth from surface
Interval of sand plugs	1984-1985	m	Depth interval of formation obstruction
Depth of artificial bottom-hole	1984.0	m	Target depth for fluid control
Tool depth	1984.0	m	Drill string tip depth
Reservoir pressure	270	kgf/cm²	Formation pressure at target depth
Fracture pressure	350	kgf/cm²	Maximum allowable formation pressure
Fluid loss onset pressure	310	kgf/cm²	Pressure at which absorption begins
Current drilling fluid density	1.18	g/cm³	Circulating fluid density at the time
Casing diameter	168.3	mm	Outer diameter of casing string
Drill pipe	89 × 7	mm	1914 m, drill pipe length and dimensions
Heavy-weight drill pipe (HWDP)	120 × 35	mm	66 m, HWDP section
Method of kick elimination	Driller's method, two-stage	-	Simulation scenario

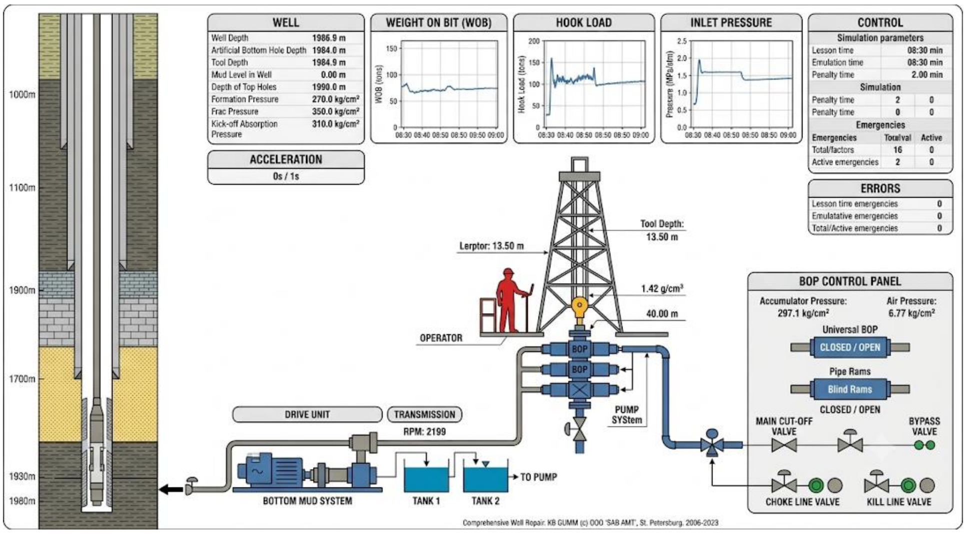

Figure 2: Drilling process of sand plugs.

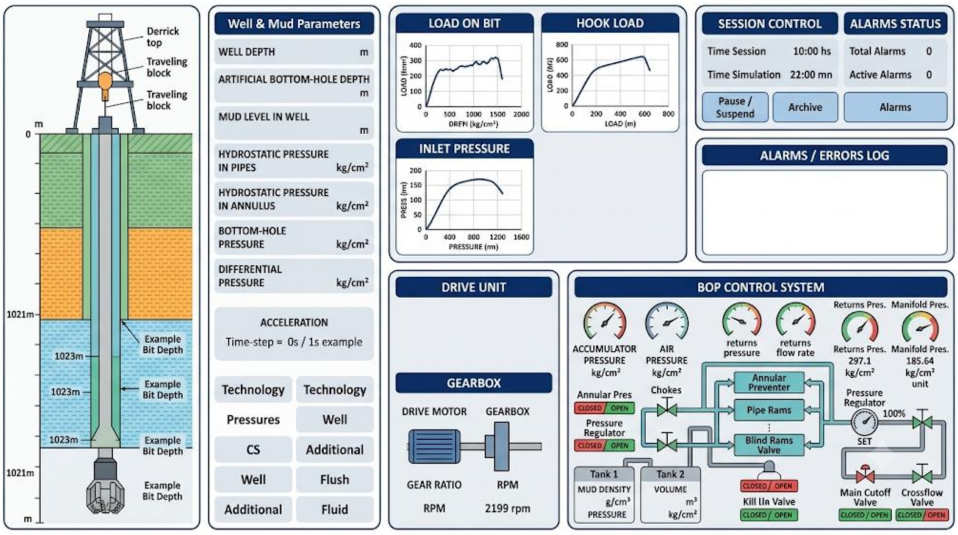

Figure 3: Injection of weighted kill mud with a density of $\rho = 1.42$ *g/c.m.*^{3}

The pressure in the drill pipes is $P_{dp} = 34.8\ kgf/cm^2$. The pressure in the annular space is $35.9\ kgf/cm^2$. The influx volume is $1.29\ m^3$. The formation pressure is calculated as:

$$P_f = \rho gh + P_{initial,\ dp} = 1.18\times0.1\times2045+34.8=276\ kgf/cm^2.$$

A 5% safety margin is applied:

$$276\times5\% = 14\ kgf/cm^2.$$

The kill mud density is then calculated as:

$$\rho_{kill} = 1.18 + (34.8 + 14) / (0.1 \times 2045) = 1.18 + 48.8 / 204.5 = 1.18 + 0.2386 = 1.4186 \approx 1.42\ g/cm^3.$$

Washing out the fluid pocket with the mud of current density under static conditions:

We will maintain a constant pressure in the drill pipes.

$$P_{dp} - P_{initial} = 34.8 + 23.5 + 14 = 72.3\ kgf/cm^2.$$

The fluid pocket is displaced using a drilling fluid with a density of $\rho = 1.18\ g/cm^3$, while maintaining a constant drill pipe pressure of $P_{DP} = P_{initial} = 72.3\ kgf/cm^2$.

Stage 2: Injection of the weighted kill mud with a density of $\rho = 1.42\ g/cm^3$, initially into the drill pipes (*DP*) and subsequently into the casing (*Csg)*.

The mud is weighted to $\rho = 1.42\ g/cm^3$, and the pump volume counter is reset (Fig. 3).

A) Injection of kill fluid into the blowout preventer (BOP) in static conditions.

The bottom-hole pressure is determined by:

$$P_{bh} = P_{mud,BOP} + P_{BOP} = P_{mud,KP} + P_{KP} = 290\ kgf/cm^2.$$

The pressure will be maintained according to the gauge on the choke manifold, with the pump operating at $n = 1310\ rpm$:

$$P_{KP} = P_{init,BOP} + \Delta P = 34.8+14 = 48.8\ kgf/cm^2.$$

B) Injection of kill fluid into the choke manifold in static conditions

The bottom-hole pressure is expressed as:

$$P_{bh} = P_{mud,BOP} + P_{BOP} = P_{mud,KP} + P_{KP}.$$

The transition of fluid from the BOP to the choke manifold is recorded based on the injected fluid volume:

$$V_{inj} = V_{BOP} = 8.58\ m^3.$$

The pressure will be maintained according to the gauge on the choke manifold:

$$P_{KP} = P_K = 28.2\ kgf/cm^2.$$

The hydro static pressure is calculated as:

$$P_{hyd} = \rho gh + P_{excess} = 1.18\times0.1\times2045+34.8=276\ kgf/cm^2.$$

Considering a 5% safety margin:

$$P_{bh} = 276+5\%\cdot P_{hyd}=276+14=290\ kgf/cm^2.$$

Wait-and-weight method (single-stage procedure).

The single-stage method involves simultaneous injection of a weighted kill fluid with density $\rho = 1.42\ g/cm^3$ and displacement of the well bore fluids. The kill fluid is weighted to $\rho = 1.42\ g/cm^3$. The injection counter is reset to zero. Pump speed is $N = 1310\ rpm$, with second gear choke pressure:

$$P_{choke} = 23.5\ kgf/cm^2.$$

The initial and final bottom-hole pressures are:

$$P_{initial} = P_{init,BOP} + P_{choke} + \Delta = 72.3\ kgf/cm^2$$
$$P_{final} = \rho_{well} / \rho_{kill} * P_{choke} = 1.42 / 1.18 * 23.5 = 28.2\ kgf/cm^2.$$

The gradient of pressure reduction per cubic meter of injected fluid is calculated as:

$$G_{rad} = \Delta P / V = (72.3-28.2) / 8.58 = 5.14\ kgf/cm^2/m^3.$$

After the weighted kill fluid with a density of $\rho = 1.42\ g/cm^3$ is transferred from the drill pipe (*DP*) into the annular space (choke manifold, *CM*), with the injected volume equal to the volume of the drill pipe *($V_{inj} = V_{DP}$),* the pressure in the drill pipe is maintained constant at the final value:

$$P_{final} = 28.2\ kgf/cm^2.$$

This is maintained until the kill fluid ($\rho=1.42\ g/cm^3$) has completely returned to the surface. Once the well kill is completed:

- The pump is stopped.
- The choke is closed.
- The pressures in the drill pipe and choke manifold are monitored to ensure the absence of well bore fluids:

$$P_{DP} = P_{CM} = 0.$$

4 RESULTS AND DISCUSSION

Well control operations were simulated using the AMT-411 training simulator to evaluate the performance of the Driller's Method and the Wait-and-Weight (single-stage) Method. Key parameters, including formation pressure, kill fluid density, and circulation regimes, were analyzed to ensure safe and effective well kill operations. The simulations demonstrated that maintaining the bottom-hole pressure (BHP) within the safe operating window-bounded by formation pressure and the pressure at which fluid loss begins-is critical for successful well control.

The integrated simulation results are summarized in Figure 4, which presents the dynamic behavior of mechanical and hydraulic parameters during the kill operations:

- Figure 4a - Hook and bit load dynamics: Peaks in hook load correspond to pressure surges observed when the heavier kill fluid was introduced, reflecting the mechanical response of the drill string. These transient variations highlight the need for real-time monitoring to prevent mechanical overstress.
- Figure 4b - Inlet and outlet mud density trends: The convergence of inlet and outlet mud densities demonstrates the efficient displacement of wellbore fluids, confirming successful bottom-hole pressure management.
- Figure 4c - Pressure comparison**:** Comparison of loss, fracture, formation, and bottom-hole pressures within the safe operating window shows that both methods maintained BHP without exceeding critical limits.
- Figure 4d - Drill pipe and annular pressure profiles: The profiles indicate hydraulic stability throughout the circulation and well kill operations.

The quantitative comparison of the Driller's Method and the Wait-and-Weight Method is presented in Table 2, highlighting maximum casing and drill-pipe pressures, time-to-kill, pressure overshoot relative to the safe window, injected volume, and final surface pressures. Both methods successfully displaced wellbore fluids, achieving zero drill-pipe and choke-manifold pressures at the end of the operation.

The results indicate that the Wait-and-Weight Method provides a smoother pressure control profile with lower maximum drill-pipe pressure, reducing the risk of exceeding the safe operating window. Conversely, the Driller's Method requires more careful monitoring to avoid bottom-hole overpressure, although it remains effective for well kill operations.

Overall, the simulations demonstrate that both methods are capable of maintaining bottom-hole pressure within the calculated safe range, preventing fluid loss or formation fracture, and ensuring hydraulic stability during circulation and kill operations. These findings underscore the importance of integrated monitoring of mechanical and hydraulic parameters in achieving safe, efficient, and controlled well interventions.

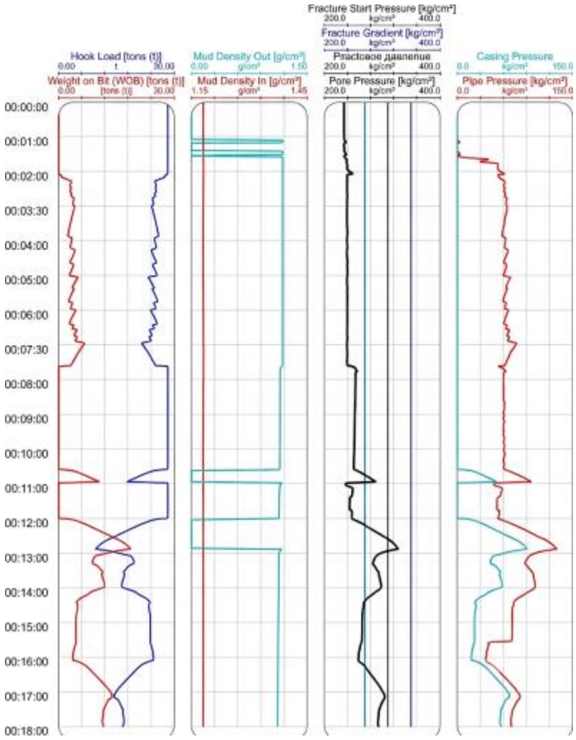

Figure 4: Integrated simulation results from the AMT-411 well control platform.

Table 2: Comparison of driller's method and wait-and-weight method.

Parameter	Driller's Method	Wait-and-Weight Method
Max casing pressure (kgf/cm²)	290	72.3
Max drill-pipe pressure (kgf/cm²)	48.8	28.2
Time-to-kill (min)	- (based on pump speed n=1310 rpm)	- (based on pump speed n=1310 rpm)
Pressure overshoot relative to safe window (kgf/cm²)	0	0
Volume of kill fluid injected (m³)	8.58	8.58
Initial bottom-hole pressure (kgf/cm²)	290	72.3
Final bottom-hole pressure (kgf/cm²)	290	28.2
Final drill-pipe / choke-manifold pressure (kgf/cm²)	0	0

5 CONCLUSIONS

Gas-oil-water shows represent one of the most hazardous complications encountered during drilling and well maintenance operations, requiring immediate technical and analytical response to prevent escalation into blowouts and severe operational losses. The results of this study demonstrate that controlled well-kill methods, particularly those based on maintaining constant bottom-hole pressure, provide a safe and technically effective approach to GOWS mitigation when combined with accurate hydraulic calculations and continuous real-time monitoring of well parameters. The application of the AMT-411 simulator proved to be an effective tool for practical training in well-control operations and kick management, enabling the reproduction of complex emergency scenarios under controlled and repeatable digital conditions. Furthermore, the simulation results confirmed the engineering applicability and reliability of both the driller's method and the wait-and-weight method under complex geological and operational conditions, ensuring pressure stabilization within safe operating limits and supporting their use in practical well-control procedures.

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