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DRILLING, COMPLETIONS & PRODUCTION CONFERENCE

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Precise ECD Control Led to Successful Ultra Deep HTHP Sour Gas Well Cementing Operations

– A Case History in Tarim Basin

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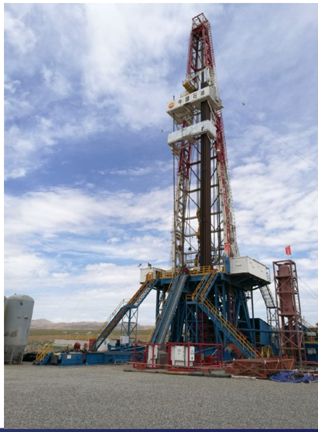

Oil and Gas Reservoir Geology and Exploitation

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Outline

- Introduction to the Team
- Challenges in Deep Wells in Tarim Basin
- Plug Flow Displacement Technique
- Field Applications
- Conclusions

Introduction to the Team

History

- Main cementing engineering R&D center in CNPC.
- Built in 1977, located in Chengdu, China.

People

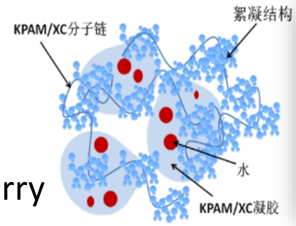
- 9 researchers, 45 postgraduate students.
- Academic leader Prof. *Xiaoyang Guo* has 40 years experience in cementing engineering and is vice-director of Cementing Group of Chinese Petroleum Society.

Laboratories and equipment

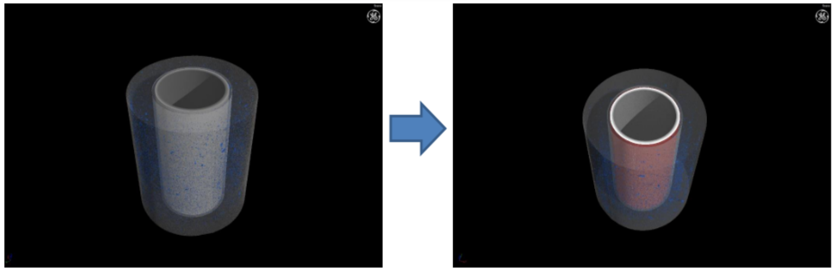
- API equipment (HTHP consistometers, HTHP curing vessels, etc.)
- Special self-developed equipment :
  - HTHP Slurry Volume Shrinkage/Expansion Tester
  - Slurry Weight-Loss Simulation Tester
  - HTHP Cement Sheath Mechanical Integrity Tester
  - HTPT Plugging Simulation Tester

Introduction to the Team

Focused Areas



- **Fundamental research** (corrosion, downhole mechanical analysis, slurry rheology, wellbore integrity, etc.)
- **Cementing materials** (basic cement, additive, admixture, slurry systems, pre-flush, etc.)
- **Cementing technologies** (anti-pollution safety cementing, technical standard, etc.)
- **Technology consulting and service**



Achievements

- **Low density slurry technology for long isolation interval with high temperature difference**

  This technology is widely used in Tarim Basin and can generate cost savings of four millions CNY for a well by simplifying casing program. The deepest isolation interval is 7,000 m.

- **Anti-pollution safety cementing theory and highly effective spacer technology**

  Through contamination mechanism research and molecular design, a highly effective spacer was designed and used in > 100 ultra deep wells (>5,000 m) in Sichuan Basin.

- **Non-silicate cement technology for heavy oil thermal recovery**

  With innovative mineral and design, this cement can sustain long-term 300 ~ 400 °C and maintain good performances, and has been widely used in Liaohe oilfield thermal recovery wells.

- **> 30 patents and > 100 articles**

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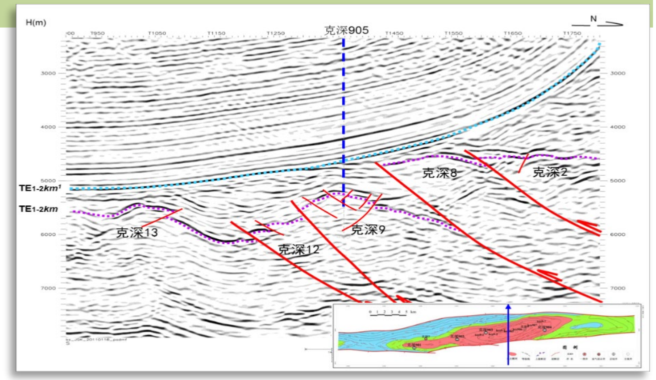
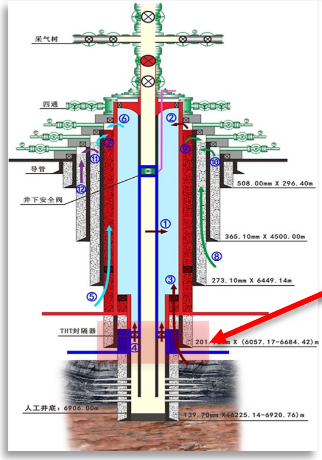
Challenges in Deep Wells in Tarim Basin
– Special Geological Characteristics



Kuqa foreland thrust belt of Tarim Basin is one of the most important natural gas producing region in China, the starting point of " West-to-East natural gas transportation project" (0.5~1.5 million m^3 per well per day).

It is an internationally recognized extremely complex reservoir with complex geological conditions, deep burial depth, high pressure and high temperature.

- **Depth:** 6000 ~ 8038 m;
- **Steep Structure:** Dip angle 15° ~ 87°;
- **High Temperature:** SBHT ≥ 180 ° C;
- **High Pressure:** ≥ 180 MPa.



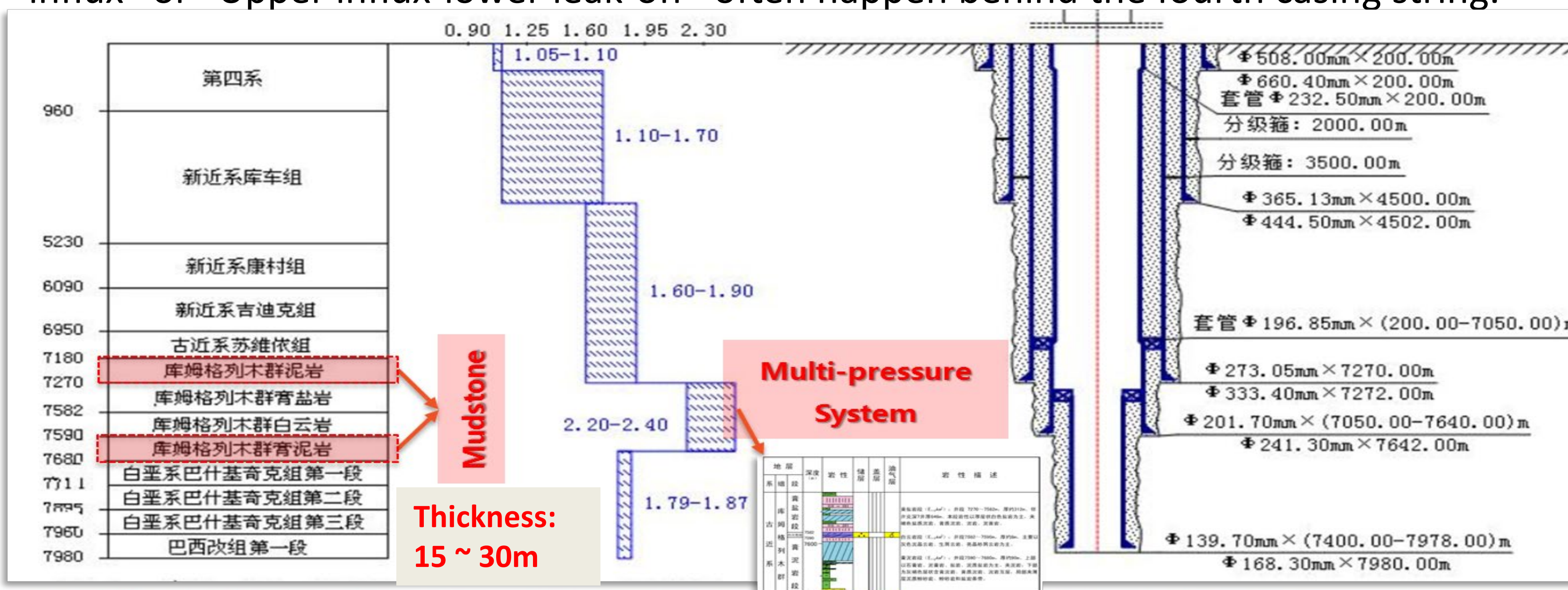
Well	Depth	Density	Pressure
KS901	7857 m	2.45 g/cm^3	188.84 MPa
KS902	7766 m	2.48 g/cm^3	188.94 MPa
KS903	7559 m	2.59 g/cm^3	192.06 MPa

Challenges in Deep Wells in Tarim Basin

– Special Geological Characteristics

- **The composite gypsum-salt formation is complex behind fourth casing string .**

- **Composite gypsum-salt formation:** Deep burial depth, uncertain thickness, high pressure with multi-pressure system, strong water sensitivity separated by the mudstone.
- **Mudstone:** Deep burial depth, thin layers. It is easy to drill out. “Upper leak-off - lower influx” or “Upper influx-lower leak-off” often happen behind the fourth casing string.

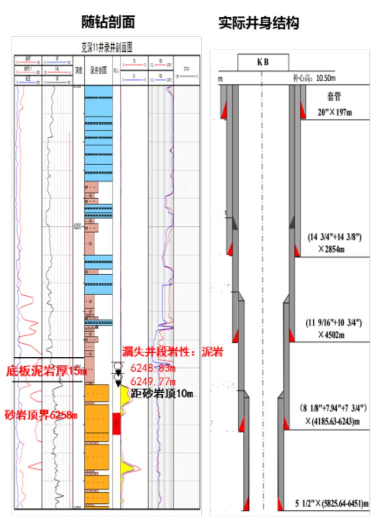


Challenges in Deep Wells in Tarim Basin

– Special Geological Characteristics

- **Serious leak-off (lost circulation) often occurs, increasing operation cost.**

Well name	Mud	Density (g/cm³)	Leak-off volume (m³)	Time Lost (days)	Money Lost ($)	Cementing
KS904	Oil-based mud	2.57	436	6	2.85 million	Squeeze cementing
KS11	Oil-based mud	2.32	645.7	19	2.5 million	Squeeze cementing
KS24	Oil-based mud	2.32	79.1	29	1.75 million	Drill pipe sticking, Sidetrack drilling



- 完钻井深：6451
- 井漏位置：6248.33m、6249.77m（距砂岩顶9.23m）
- 泥浆密度：2.32（油基）
- 井底层位/岩性：库姆格列木群膏盐岩段/泥岩
- 底板泥岩厚度：15m（6244-6259m）
- 上层管鞋：4502m（11 9/16″）
- 井眼尺寸：9 1/2″（四开）

发生经过：密度2.32钻进至6248.83m，扭矩由7↗21kN.m，憋停顶驱，出口失返

压力折算1：环空液面最低350m，当量密度2.19，压差7.96MPa

处理过程：

1、静止候堵，起钻更换6 5/8″小钻头卡层，漏失72.5m3；

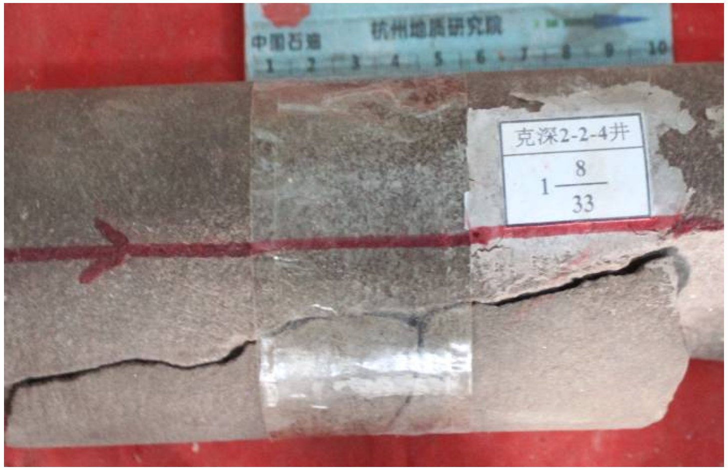
2、小钻头钻井至6249.77m再次井漏失返，反复堵漏施工

3、下套管封固，固井井漏失返，正注反挤。

压力折算2：环空液面最低960m，当量密度1.96，压差21.84MPa

周期及费用小计：

- 钻进漏失：164m3，堵漏漏失：164.3m3，固井漏失：317.2m3，合计645.7m3；
- 损失周期：18.25天
- 费用共计约：1692万（油基泥浆+工期）



KS2-2-4, (K1bs2 6674.85-6675.05m)

Challenges in Deep Wells in Tarim Basin

– Cementing Challenges

■ **Complex pressure system, ultra high pressure**

- ➢ Variation of burial depth and thickness of composite gypsum-salt formation is large.
- ➢ High Pressure and complex pressure system.
- ➢ The pressure difference between neighboring wells is large.

→

- ➢ Difficult to accurately determine the pressurization ability of the stratum;
- ➢ Serious leak-off (lost circulation);
- ➢ Apply upset casing, small annular clearance;
- ➢ Narrow window of safe density and ECD.

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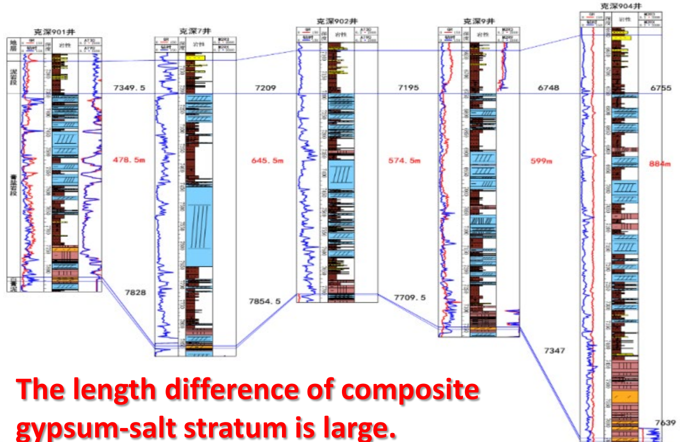
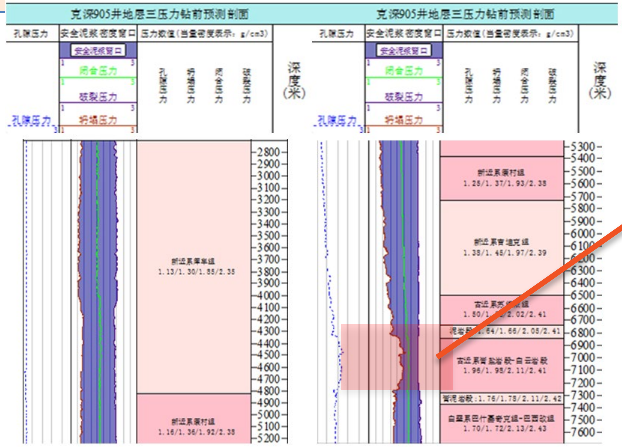
- •Serious leak-off in cementing;
- •Squeeze cementing often required



The length difference of composite gypsum-salt stratum is large.



Pressure sensitivity

Challenges in Deep Wells in Tarim Basin

– Cementing Challenges

- **Oil based mud with ultra high density:** Strong water sensitivity of the mudstone and gypsum-salt formation.

> Poor compatibility between oil-based mud and cement slurry.

> Oil-based mud has a poor wettability.

→

> Reduce the displacement efficiency;
> Difficult to bond between cement sheath and formation.

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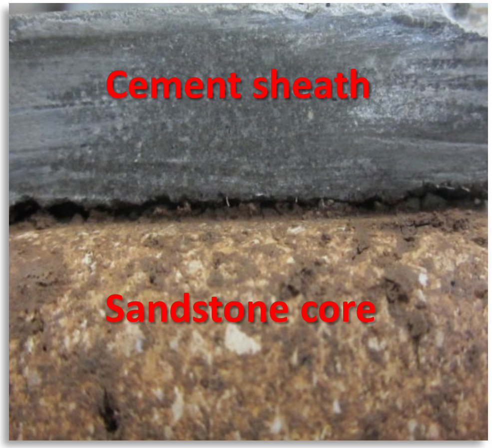
- High pump rate, Turbulence displacement;
- Further cause serious leak-off (lost circulation)

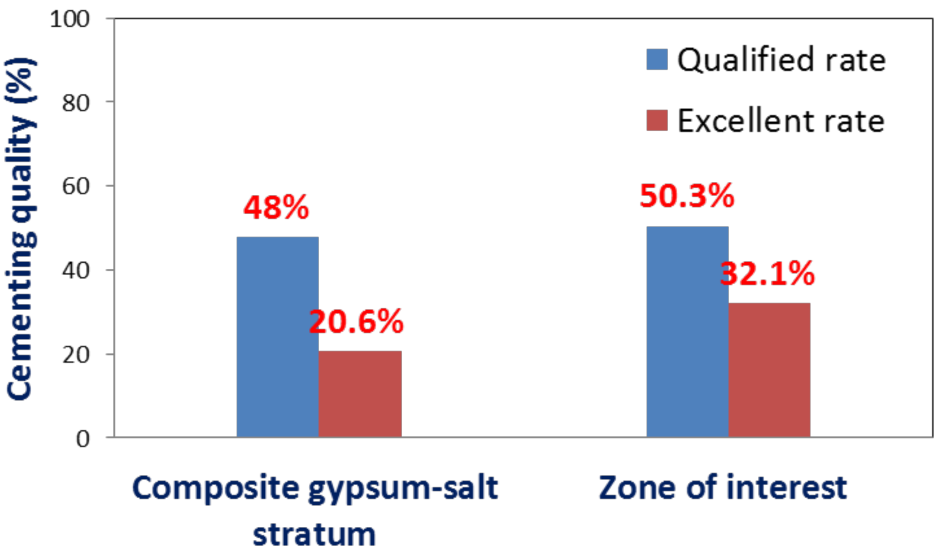
•Serious leakage in cementing

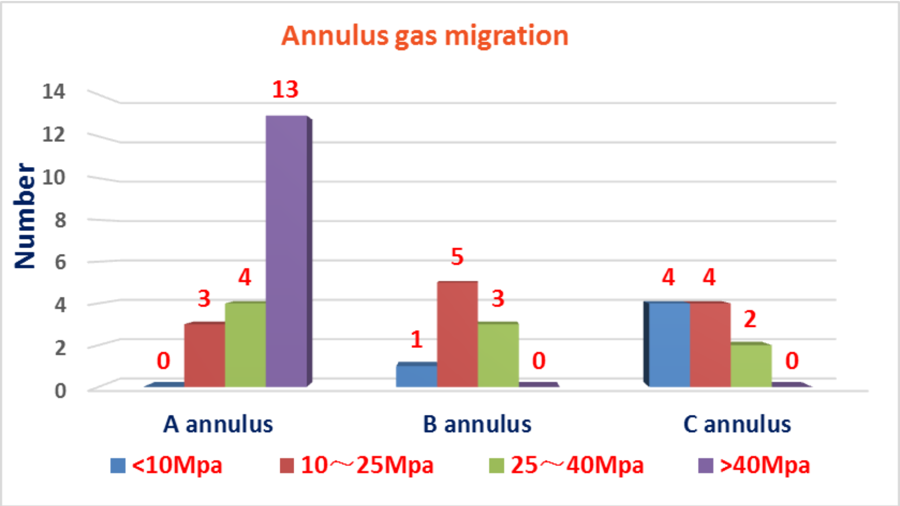


Challenges in Deep Wells in Tarim Basin

– Cementing Challenges

- Easy to form channels and low quality cementing - Severe gas migration.





Cementing quality is an urgent problem to be resolved to ensure operation safety and natural gas production of Kuqa foreland thrust belt.

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Plug Flow Displacement Technique - Design Concept

Problem

- Complex geological condition;
- Ultra high pressure, high temperature;
- Narrow safe density and ECD window;
- Oil-based mud.

Concept

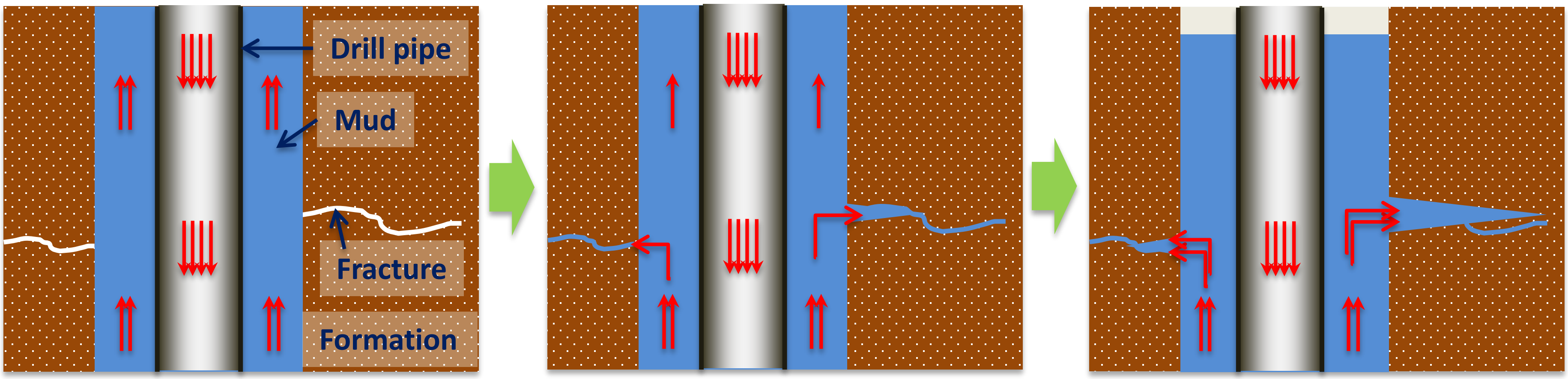
First: Avoid leak-off during cementing to ensure cement slurry return to designed position;
Second: Increase displacement efficiency to improve cementing quality.

Key Technology

1. Accurately determine formation leak-off pressure, (from wells with leak-off);
2. High efficiency spacer that can sustain at ultra high temperature;
3. Ultra high temperature cement slurry with desired performance.

Plug Flow Displacement Technique - Designing Workflow

1. Determining Formation Leak-off Pressure and ECD



Case 1: Normal circulation

Case 2: Partial mud loss

Case 3: Total mud loss

Formation leak-off pressure

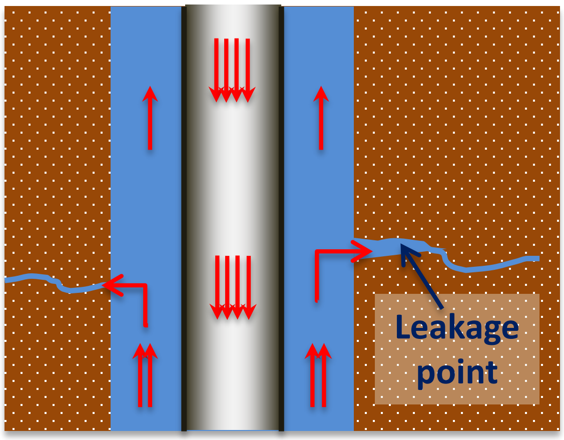
- ①Formation breakdown experiment
- ②Geological report, and offset well files
- ③Calculate the pressure when the well is leaking-off using the mud pumping rate, borehole size and mud properties.

The ultra deep wells are very pressure sensitive and pressure system is complex. Traditional procedures are not applicable.

Plug Flow Displacement Technique - Designing Workflow

1. Determining Formation Leak-off Pressure and ECD

Case 2: Partial mud loss



Circulating friction pressure above leak-off point (P_{ci})

Hydrostatic pressure above leak-off point (P_h)

Additional pressure (P_1)

Formation leak-off pressure (P_f)

- Determine formation leak-off pressure with Fanning-Darcy formula:

$$P_f = P_h + \sum_{i=1}^{m} P_{ci}$$

$$= P_h + \sum_{i=1}^{m} \frac{2\rho_m v_i^2 f_i L_i}{D_{hi} - D_{ci}}$$

$$= P_h + \sum_{i=1}^{m} \frac{32\rho_m f_i L_i Q_d^2}{\pi^2 (D_{hi} - D_{ci})^3 (D_{hi} + D_{ci})^2}$$

Q_d : pump rate during drilling process (L/s)
D_{ci} : outer diameter of casing or drilling pipe in annular section i (mm)
D_{hi} : inner diameter of annular section i (mm)
P_f :lost-circulation pressure (MPa)
P_{ci} : circulating friction pressure in annular section i (MPa)
P_h: hydrostatic pressure (MPa)
f_i : friction resistance coefficient of fluid in annular section i
L_i : length of annular section i (m)
ρ_m : density of mud (g/cm^3)

Plug Flow Displacement Technique - Designing Workflow

1. Determining Formation Leak-off Pressure and ECD

Example:

KS905: The well is drilled to 7148.58 m, mud density is 2.58 g/cm^3.
Case 1: Pump rate is 17 L/s, leak-off rate is 2.4 m^3/h;
Case 2: Pump rate decreased to 8 L/s, there is no leak-off.
ECD and mud properties can be calculated with these parameters:

External diameter of drill pipe/m	Internal diameter of hole / m	Length /m	Circulating friction pressure (MPa)	
			8 L/s	17 L/s
0.1397	0.24537	2317	0.92	1.22
0.127	0.24537	4345	1.50	1.91
0.127	0.253365	296	0.10	0.14
0.1778	0.253365	190	0.16	0.28
Circulating friction pressure total			2.68	3.55
ECD			2.62 g/cm^3	2.63 g/cm^3

The formation is very sensitive to pressure, < 1 MPa.

Plug Flow Displacement Technique - Designing Workflow

2. Design Cementing Operation Procedure Based on Formation Leak-off Pressure

– Casing Running Speed Determination

Control running speed to prevent excessive surge pressure in order not to exceed critical ECD. The speed (v_c) calculation:

$$v_c = av_{cm} = aP_f^{0.5}\left(\sum_{i=1}^{m}\frac{2\rho_m f_i L_i\left(K_c + \frac{D_{ci}^2}{D_{hi}^2 - D_{ci}^2}\right)^2}{D_{hi} - D_{ci}}\right)^{-0.5}$$

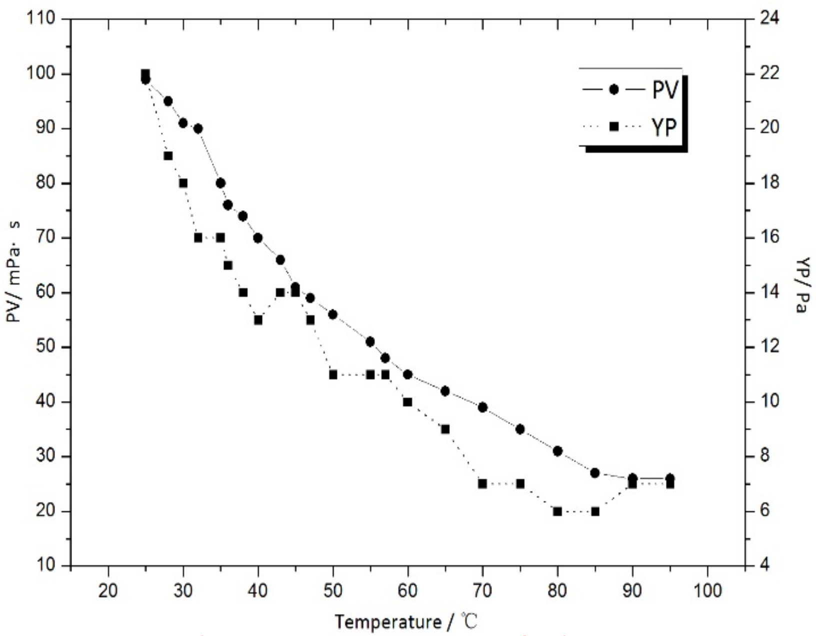
P_f = formation leakage pressure (MPa)
v_c = allowable casing running speed (m/s)
v_{cm} = critical casing running speed (m/s)
a = safety coefficient (0.5-0.75)
ρ_m = density of mud (g/cm^3)
f_i = friction resistance coefficient of fluid in annular section i
ρ_m = density of mud (g/cm^3)
L_i = length of annular section i (m)
$K_{c\,=}$ adhesion coefficient (0.4-0.5)
D_{ci} = outer diameter of casing or drilling pipe in annular section i (mm)
D_{hi} = inner diameter of annular section i (mm)
i = number of different annular sections (1.2.3…m)

Example:

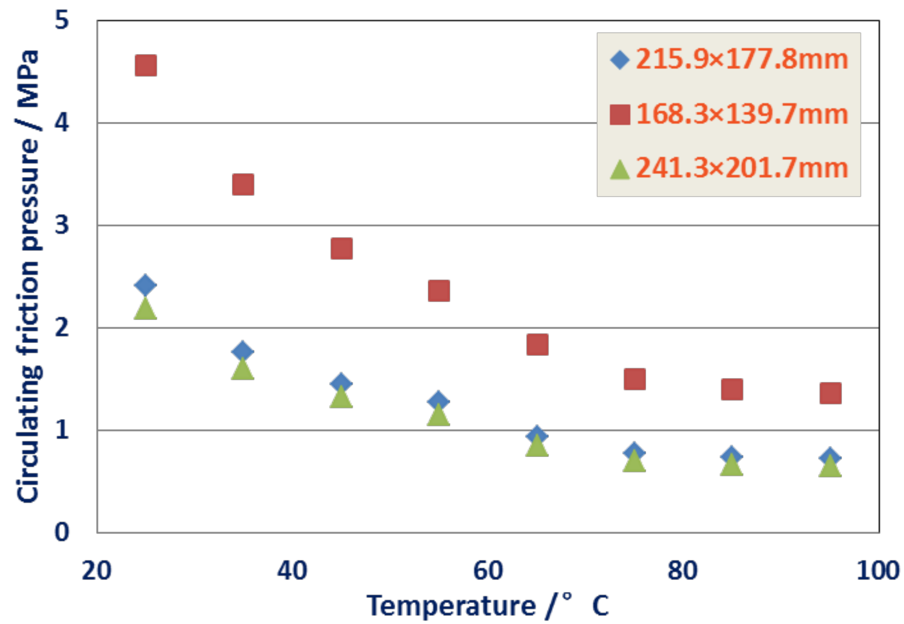
Considering the surge pressure during casing running, the running time of a casing (11m) usually takes about 90~130 seconds.

Plug Flow Displacement Technique - Designing Workflow

2. Design Cementing Operation Based on the Formation Leak-Off Pressure – Mud Circulation and Conditioning (Rheology)



Rheological parameters of oil-based mud



Circulating friction pressure

Sufficient mud circulation and appropriate conditioning after running casing is to improve displacement efficiency (PV and YP decreasing). Low rheology mud could reduce ECD.

Plug Flow Displacement Technique - Designing Workflow

3. Increase the Displacement Efficiency – Mud Circulation and Conditioning (Circulation Rate)

To decrease lost circulation risk, the calculation of circulating rate is to prevent friction pressure from exceeding critical ECD. Calculation includes actual mud rheology, casing string and wellbore parameters and formation leak-off pressure before cementing. Maximum allowable circulating rate is calculated as:

$$P_f = \sum_{i=1}^{m} \frac{32\rho_m f_i L_i Q_{cm}^2}{\pi^2 (D_{hi} - D_{ci})^3 (D_{hi} + D_{ci})^2} + P_t$$

Choke pressure caused by liner hanger in annulus (MPa)

$$Q_{cm} = (P_f - P_t)^{0.5} \left(\sum_{i=1}^{m} \frac{32\rho_m f_i L_i}{\pi^2 (D_{hi} - D_{ci})^3 (D_{hi} + D_{ci})^2} \right)^{-0.5}$$

***Q_{cm}* is maximum allowable circulating rate (L/s)**

Example: In Φ177.8mm+Φ182mm liner cementing operation of well QT-1 in Kuqa field, the maximum allowable circulating rate calculated according to the method is 7 L/s. During mud circulating, lost circulation was occurred when the rate over 6.9 L/s and stopped when it decreased to 6.3 L/s.
It is a preliminary proof of the feasibility of the method.

Plug Flow Displacement Technique - Designing Workflow

3. Increase the Displacement Efficiency - Plug Flow Displacement Rate Design

Calculating the critical annular velocity of plug flow V_{pm}:

$$v_{pm} = \left\{\frac{12^{n-1}[(2n+1)/(3n)]^n kRe}{\rho_c(D_h - D_c)^n}\right\}^{[1/(2-n)]}$$

The critical pump rate of plug flow cementing Q_{pm}:

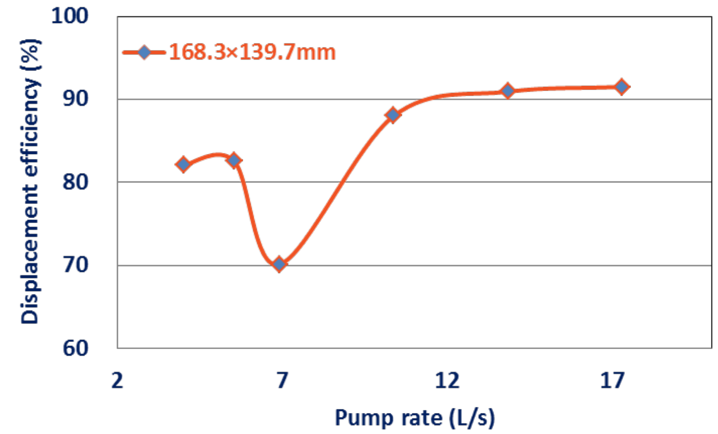
$$Q_{pm} = \frac{\pi\left(D_h^2 - D_c^2\right)}{4000}\left\{\frac{12^{n-1}[(2n+1)/(3n)]^n 100k}{\rho_c(D_h - D_c)^n}\right\}^{[1/(2-n)]}$$

The critical pump rate of leakage during cementing Q_{sm}:

$$Q_{sm} = (P_f - P_t - \Delta P_h)^{0.5}\left(\sum_{i=1}^{m}\frac{32\rho_i f_i L_i}{\pi^2(D_{hi} - D_{ci})^3(D_{hi} + D_{ci})^2}\right)^{-0.5}$$

The actual pump rate of cementing operation Q_p:

$$Q_P = \begin{cases} Q_{pm}, & Q_{pm} < Q_{sm} \\ Q_{sm}, & Q_{pm} > Q_{sm} \end{cases}$$



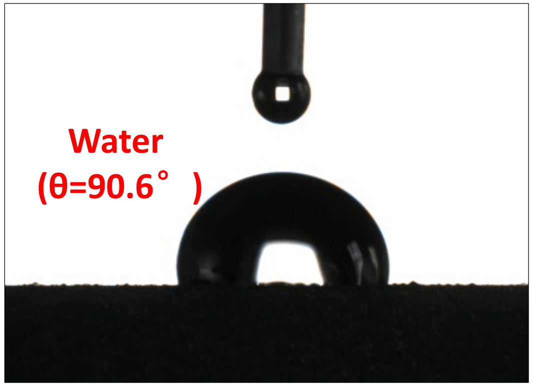
Q_p is determined by selecting Q_{sm} or Q_{pm}, to meet both the requirement of plug flow and lost circulation control.

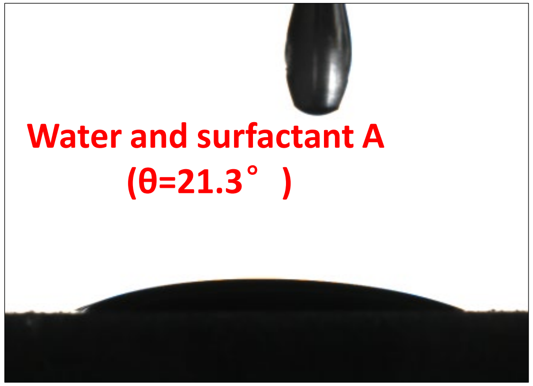
Plug Flow Displacement Technique - Designing Workflow

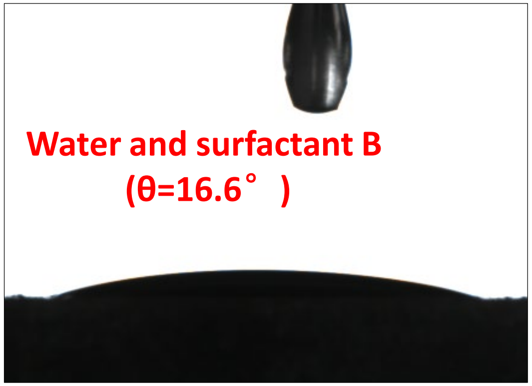
3. Increase the Displacement Efficiency – High Performance Spacer (Surfactant)

Compared to turbulent flow, at plug flow rate, the shear stress at wall is low. Oil-based mud and mud cake removal is an issue. Interfacial wettability and oil-based mud removal efficiency should be remedied and enhanced by better surfactant.

Contact angle θ is a critical performance indicator of surfactant wettability. The lower the contact angle, the better wettability the rock surface will be. Surfactant B has much better wetting ability than other products.



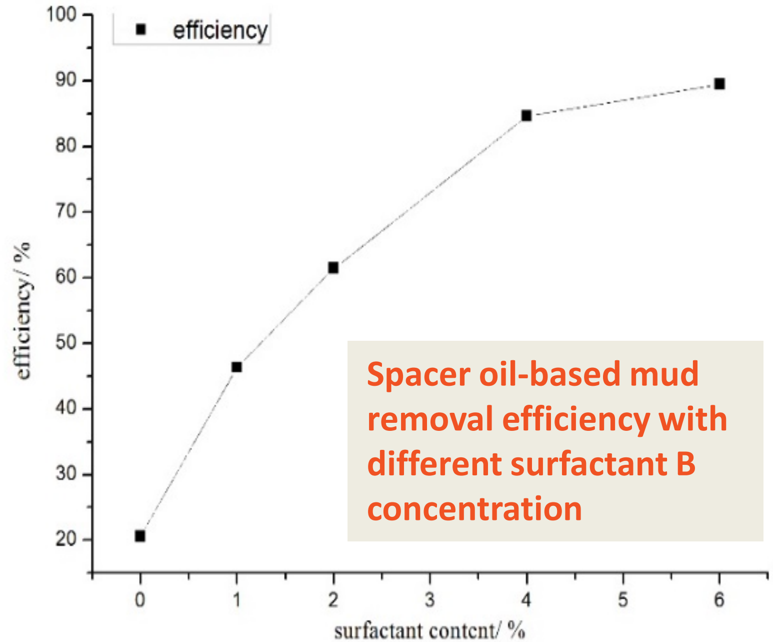




Plug Flow Displacement Technique - Designing Workflow

3. Increase the Displacement Efficiency – High Performance Spacer (Surfactant)

Flushing time: 20min
Rotation speed: 200rpm



Spacer oil-based mud removal efficiency with different surfactant B concentration

Higher oil-based mud removal efficiency could be obtained if surfactant B concentration is higher than 4% BWOW.

Plug Flow Displacement Technique - Designing Workflow

3. Increase the Displacement Efficiency – Weighting Material for High Density Spacer (Rheology improvement)

Mn_3O_4-based weighting material (4.80g/cm^3) - *MicroMAX,* was used to partially substitute magnetite powder due to its characteristics of much smaller particle size (0.1 ~ 10µm) and more spherical (1 ~ 100µm).

Stability and rheological parameters of spacers at 93℃

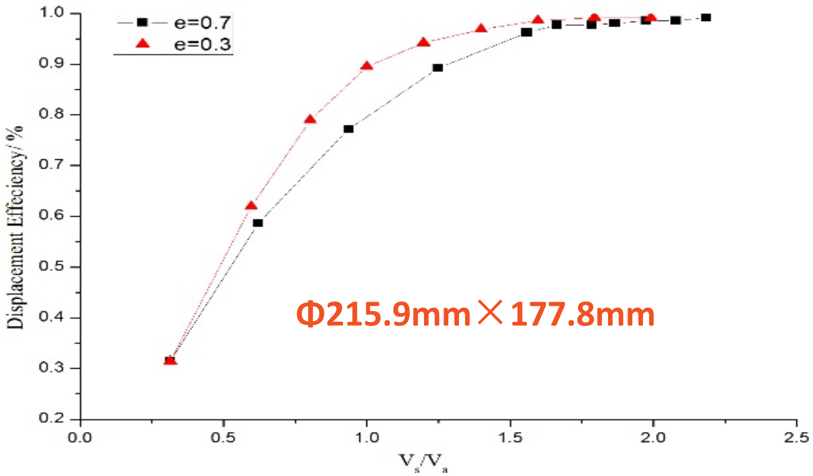
Spacer (g/cm^3)		Rheological parameters		Top Density (g/cm^3)	Bottom Density (g/cm^3)	Density difference (g/cm^3)
		n	k (Pa·s^n)			
2.30	With magnetite	0.603	1.636	2.273	2.331	0.058
	With MicroMAX	0.640	1.005	2.291	2.318	0.027
2.50	With magnetite	0.567	2.714	2.465	2.536	0.071
	With MicroMAX	0.604	1.182	2.486	2.519	0.033

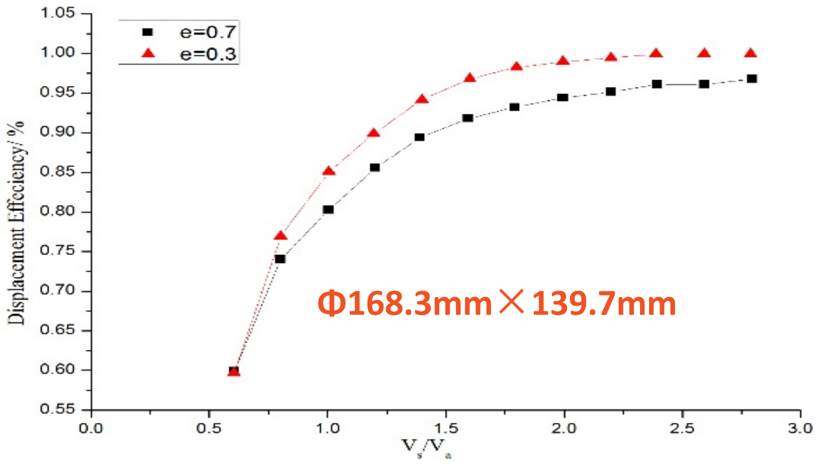
MicroMAX can provide high density spacer with good stability and rheological properties at high temperature.

Plug Flow Displacement Technique - Designing Workflow

3. Increase the Displacement Efficiency – High Performance Spacer (Volume)

The influence of volume ratio of spacer to open hole annulus on mud removal efficiency in eccentric condition (e), (e=0.3; e=0.7).

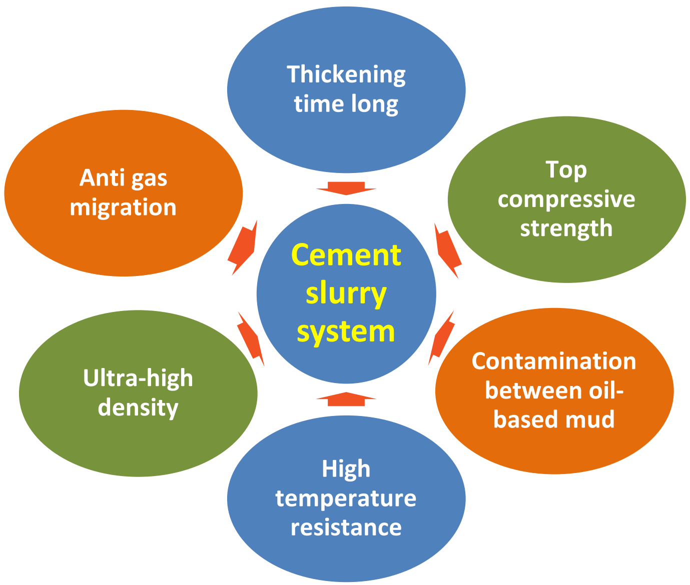




The more the eccentric is the casing, the more spacer volume is needed. Spacer volume should be more than 1.5-2 times of open hole annulus volume (greater than 30 m^3 /190 bbl) to achieve high mud removal efficiency.

Plug Flow Displacement Technique - Designing Workflow

3. Increase the Displacement Efficiency – High Performance Cement Slurry System



BHCT, °C	123	123	131
Pressure, MPa	140	140	120
Density, g/cm³	2.50	2.35	2.00
Thickening time, min	457	310	803
Density differential, g/cm³	0.030	0.027	0.012
Fluid loss, mL	48	46	44
Free water, %	0	0	0
48hr compressive strength (Top), MPa	16.1 (92°C)	18.2 (97°C)	14.5 (117°C)

- **Special experiment**
  - **Anti gas migration capability:** static gel transition time, volume shrinkage within the time, permeability within the time
  - **Temperature sensitivity experiment** (Fluctuation: ±5°C)
  - **Density sensitivity experiment** (Fluctuation: ± 0.03 g/cm³)
  - **Contamination experiment** (cement : spacer : mud = 7:3:0, 7:1:2, 1:1:1)

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Field Applications

Stage 1: Three Pilot Wells

Well code	KS603 (first)	KS10 (second)	KS603 (third)
Liner string	Φ177.8mm+Φ182mm	Φ177.8mm+Φ182mm	Φ127mm
Drill bit	Φ215.9mm	Φ215.9mm	Φ149.2mm
Section range	3957-5891m	4600-6160m	5600-6060m
OBM density	2.13 g/cm³	2.30 g/cm³	1.90 g/cm³
Cement density	2.35 g/cm³+2.30 g/cm³	2.50 g/cm³+2.30 g/cm³	2.10 g/cm³+2.10 g/cm³
Complications	✓ Three leakage zone, one salt water layer in 5872-5880m ✓ Severe lost circulation happened after liner hanger setting (choking pressure at hanger was underestimated)	✓ Four leakage zone ✓ Lost circulation happened after a 16 hours mud circulation (LCMs might be washed off)	✓ Active gas layer and water layer
Circulation pump rate	3~5L/s	2~6L/s	3L/s
Cementing pump rate	4.5~5L/s (Re=92-104)	4.5~5L/s (Re=82~101）	2L/s（Re=49~86）
Results	✓ Cement slurry returned to 5710 m in annulus ✓ One heavy leakage zone and salt water layer were isolated	✓ Cement slurry returned to 5750 m in annulus ✓ Two heavy leakage zone and salt water layer were isolated ✓ Qualification rate of cementing quality in plug flow cementing section was 86.6% (excellence rate was54.6%) (CBL/VDL)	✓ Cement slurry returned according to design ✓ No gas or water channeling happened ✓ Qualification rate of cementing quality in open hole section was 76% (excellence rate was 50%)
Remedial measures	Squeeze cement from annulus	Squeeze cement from annulus	None

Field Applications

Stage 2: Technique Improving and Promoting

Well Name	KS905	KS907
Liner string	Φ196.85mm+Φ206.38mm	Φ206.38mm
Section range	6553-7368m	6326-7440m
OBM density	2.50 g/cm^3	2.45 g/cm^3
Cement density	2.58 g/cm^3+2.51 g/cm^3	2.57 g/cm^3+2.51 g/cm^3
Complications	✓ Two leakage zone in 7148m and 7226m	✓ One leakage zone in 7357.3m ✓ One salt water layer in 7339-7405m
Circulation pump rate	4~6L/s	4~6L/s
Cementing pump rate	5~6L/s (Re=87-100)	5~6L/s (Re=82~97）
Results	✓ None lost-circulation happened ✓ Cement slurry returned according to designing ✓ None gas or water channeling happened ✓ Qualification rate of cementing quality in open hole section was 98% (excellence rate was 39%)	✓ None lost-circulation happened ✓ Cement slurry returned according to designing ✓ None gas or water channeling happened ✓ Qualification rate of cementing quality in open hole section was 85.2% (excellence rate was 75.1%)
Remedial measures	None. The best two wells in Kuqa Field. No wellhead gas channeling occurred after fracturing.	

Results: No gas channeling was found in these wells.

Outline

- Introduction to Our Team
- Challenges in Deep Wells in Tarim Basin
- Plug Flow Displacement Technique
- Field Applications
- Conclusions

Conclusions

- A complete success was achieved in cementing ultra deep HTHP complex wells in Tarim Basin by adopting a precise ECD control cementing methodology.
- It is an integrated process that includes:
  - Accurate ECD window determination
  - Selecting plug flow regime to work within the narrow ECD window
  - Mud conditioning and circulation, casing running speed control
  - Spacer with adequate surfactant and volume
  - Proper design of cement slurry system
  - Precise control of operation parameters to ensure within ECD window
- The procedure has been adopted by all ultra deep wells in Tarim Basin.

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Thank Your!