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Experimental Investigation of Particle Deposition and Pipeline Plugging Mechanisms in Produced Fluids from High-Salinity Gas Reservoirs

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ABSTRACT: This study investigates the physicochemical characteristics, particle deposition behavior, and plugging mechanisms of produced fluids from drainage-gas recovery wells in high-salinity gas reservoirs, using a representative well from the Tarim Oilfield as a case study for a broad class of production systems affected by liquid-phase pipeline plugging. A comprehensive experimental methodology was adopted, combining physicochemical characterization, filtration and static sedimentation experiments, dynamic deposition tests, scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM-EDS), and X-ray diffraction (XRD). This combined experimental approach was employed to identify the dominant deposition mechanisms and determine the particle-size fractions most responsible for pipeline plugging. The produced fluid was identified as a high-salinity, weakly acidic CaCl₂-type aqueous system with potential scaling tendencies associated with BaSO₄, SrSO₄, and CaCO₃. Particle-size analysis revealed that particles were predominantly distributed within the 2–10 μm range, representing 58.89% of the total particle population and constituting the principal plugging-risk fraction. In particular, particles between 2 and 5 μm were found to play a dominant role in turbidity breakthrough, membrane bridging, and the initiation of deposit formation. Microscopic characterization further showed that the deposits consisted primarily of NaCl, CaCO₃, SiO₂, together with minor sulfate- and metal-containing phases, indicating a composite deposition mechanism involving both suspended particles and salt crystallization.

KEYWORDS: High-salinity produced fluid; pipeline plugging; particle-size distribution; dynamic deposition; composite deposition mechanism

1 Introduction

Pipeline plugging caused by high-salinity produced fluids is a common flow-assurance challenge in deep and ultra-deep gas reservoirs, particularly during drainage-gas recovery and long-term gas production [1]. The Tarim Oilfield provides a representative case for investigating such plugging problems because its produced fluids are characterized by high salinity, weak acidity, abundant suspended particles, and multiple scale-forming ions. With prolonged production from drainage-gas recovery wells, plugging in surface gathering

pipelines has become increasingly prominent, restricting continuous gas-well operation and reducing gas-field development efficiency. Wellbore plugging, sand-scale composite deposition, and targeted unplugging treatments have been reported in deep gas reservoirs in the Kuqa Piedmont, Dina area, and Keshen area of the Tarim Basin [2–4], indicating that plugging in deep high-salinity gas wells is technically complex and representative of block-scale flow-assurance problems. The produced fluids from the investigated block are characterized by high salinity and weak acidity, with Na^+ and Cl^- as the dominant ions. They also contain scale-forming ions such as Ca^{2+} , HCO_3^- , Sr^{2+} , and Ba^{2+} , together with suspended particles including formation debris, drilling residual solids, and corrosion products. When temperature, pressure, or flow conditions change, carbonate and sulfate precipitates may interact with suspended particles to form composite deposits with complex structures on pipe walls or filtration media. Such deposits reduce the effective flow area, increase pressure drop, and decrease transport efficiency [5–7]. Therefore, clarifying the composite deposition mechanism of high-salinity produced fluids and identifying the major plugging-risk particle-size range are important for pipeline plugging control and produced-fluid treatment.

Produced fluid from gas fields is typically composed of dissolved salts, dispersed oil, suspended solids, corrosion products, scale-forming ions, and production chemicals. Treatment processes must therefore be selected according to water chemistry, salinity, particle characteristics, and reuse or discharge requirements. For high-salinity gas-field produced fluid, membrane filtration, phase separation, adsorption, chemical treatment, and integrated treatment processes have received increasing attention. However, suspended-solid migration and inorganic scaling remain key factors affecting treatment stability and field operational reliability [8–12].

Suspended particles are important solid-phase constituents in the plugging process of high-salinity produced fluid. Their particle-size distribution, dispersion stability, and migration–deposition behavior directly affect filtration retention, bridging plugging, and wall attachment. Particle size determines the ability of particles to migrate in the flow system, settle, and pass through membranes or pore-throat structures. Fine particles generally have stronger mobility, whereas intermediate-sized particles are more likely to be retained, bridged, and accumulated in filtration media or on rough pipe-wall surfaces. During produced-fluid reinjection, reuse, and treatment, suspended-solid size and concentration are commonly used as important water-quality control indicators. Particle retention may induce filter-cake formation, pore-throat plugging, flow-channel narrowing, and reduced injectivity [13,14]. Meanwhile, zeta potential can be used to characterize the electrostatic stability of particles or dispersed systems. In high-salinity produced fluid, abundant electrolyte ions compress the electrical double layer on particle surfaces, reduce electrostatic repulsion between particles, and thereby promote destabilization, aggregation, and bridging of fine particles [15]. Thus, particles are not merely inert suspended matter transported by the fluid; rather, they provide an important material basis and structural framework for subsequent deposit formation.

On the basis of particle migration, retention, and aggregation, precipitation and crystallization of scale-forming ions can further enhance the stability and compactness of the deposit layer. High-salinity produced fluid commonly contains scale-related ions such as Ca^{2+} , Ba^{2+} , Sr^{2+} , HCO_3^- , and SO_4^{2-} . When temperature, pressure, pH, or flow conditions change, carbonate and sulfate minerals may undergo supersaturation, nucleation, crystal growth, aggregation, and surface deposition [16–19]. Previous studies have shown that the formation behavior of sulfate scales such as BaSO_4 under dynamic conditions may differ from that observed in static compatibility tests, indicating that flow disturbance can alter mass transfer, nucleation, and deposition of scale-forming ions [16,17]. In addition, particle and pipe-wall surfaces can both provide interfaces for salt-crystal nucleation and attachment, while pipe-wall material and surface properties also influence scale adhesion, deposition rate, and scale-inhibition performance [5,19,20]. Therefore, plugging

in high-salinity produced fluid should not be attributed solely to particle retention or inorganic salt precipitation. Instead, it should be understood as a composite deposition process involving suspended-particle migration and aggregation, salt-crystal nucleation and growth, particle–salt-crystal composite deposition, and wall attachment. Accordingly, particle-size distribution, zeta potential, staged filtration, scaling tendency, and dynamic deposition behavior should be considered together when evaluating plugging risk in such systems.

Despite these advances, several limitations remain when existing studies are applied to high-salinity, weakly acidic produced fluid from drainage-gas recovery wells. First, the particle-size ranges associated with filtration bridging and surface deposition have not been sufficiently quantified. Second, static compatibility, filtration, or sedimentation tests cannot fully represent particle aggregation and salt-crystal deposition under dynamic shear conditions. Third, particle deposition and salt crystallization are often discussed separately, and their coupling mechanism remains insufficiently clarified. Fourth, many dynamic deposition studies use metallic surfaces, whereas particle–salt-crystal composite deposition on flexible composite pipe surfaces has received limited attention.

Based on these considerations, this study investigates produced fluid from a drainage-gas recovery well in a block of the Tarim Oilfield. Water-quality analysis, apparent saturation index calculation, particle-size distribution measurement, zeta-potential characterization, multi-pore-size membrane filtration, static sedimentation, dynamic deposition on flexible composite pipe coupons, and microscopic structural and compositional characterization of deposits were conducted. The study focuses on identifying plugging-risk particle-size ranges associated with filtration bridging and deposition on flexible composite pipe surfaces and on elucidating the composite deposition mechanism driven by the synergistic interaction between suspended particles and inorganic salt crystallization.

2 Experimental Methods

2.1 Physicochemical Characteristics and Scaling Tendency of Produced Fluid

2.1.1 Water Chemistry Analysis

The produced-fluid sample was collected from the outlet of a three-phase separator connected to a drainage-gas recovery well in the studied block of the Tarim Oilfield. After sampling, the fluid was immediately sealed, protected from light, and transported to the laboratory. Water-quality analysis and particle characterization were completed within 24 h to minimize changes in ion speciation, particle aggregation, and natural sedimentation during storage.

The analysis of physical and chemical properties of produced fluid strictly follows the specification of “Oilfield Water Analysis Methods” (SY/T 5523-2016). Ion chromatography (Thermo Scientific ICS-2100) was used to determine the concentration of anions and cations with a test accuracy of 0.01 mg/L; laser particle size analyzer (Malvern Mastersizer 3000) was used to analyze the particle size distribution with a test range of 0.01–3000 μm ; zeta potential analyzer (Malvern Zetasizer Nano ZS90) was used to determine the particle zeta potential; pH value was measured on-site with a precision pH meter (METTLER Toledo FE28); salinity was measured by gravimetric method. Each sample was tested repeatedly 3 times, and the average value was taken as the result. Detailed information on sample collection, physicochemical property measurements, and particle characterization procedures is provided in Appendix A.1.

2.1.2 Apparent Saturation Index Calculation

To quantitatively evaluate the scaling tendency of the produced fluid, apparent saturation indices for CaCO_3 , BaSO_4 , and SrSO_4 were calculated from the measured ion composition according to Eq. (1).

$$SI_{\text{app}} = \log_{10} \left(\frac{IAP_{\text{app}}}{K_{sp}} \right) \quad (1)$$

where SI_{app} is the apparent saturation index, IAP_{app} is the apparent ion product calculated using measured ion concentrations, and K_{sp} is the solubility product of the corresponding mineral at the experimental temperature. When $SI_{\text{app}} > 0$, the system is supersaturated with respect to the corresponding mineral and has a tendency for precipitation. When $SI_{\text{app}} = 0$, the system is close to equilibrium. When $SI_{\text{app}} < 0$, the system is undersaturated and the precipitation tendency is weak. The K_{sp} values used in this study were common thermodynamic solubility-product parameters at room temperature.

2.2 Filtration–Static Sedimentation Tests

For the produced fluid of a well, five types of membranes with pore sizes (1.2 μm , 2 μm , 5 μm , 10 μm , and 30 μm) were customized. The produced fluid was statically filtered through membranes with different pore sizes and then settled; the suspended solid concentration of the produced fluid after filtration was tested by gravimetric method (sand core filtration device), the pH of the filtrate was tested by pH meter, and the turbidity of the filtrate after sedimentation for different times was measured by turbidity meter. Detailed information on the membrane filtration procedure and static sedimentation experimental conditions is provided in Appendix A.2.

2.2.1 Multi-Pore-Size Membrane Filtration

To clarify the causes of pipeline plugging and the key plugging particle size range of a well in a block of Tarim Oilfield, the experiment adopted a positive pressure filtration device (as shown in Fig. 1) to classify the full particle size range of the produced fluid. To cover the full particle size range of the produced fluid, five types of filter membranes with pore sizes of 1.2 μm , 2 μm , 5 μm , 10 μm , and 30 μm were selected for the suction filtration static experiment. The core structure of the positive pressure filtration device includes a 304/316 L stainless steel filter barrel (pressure resistance 0.2–0.5 MPa, corrosion resistance), a pressure gauge, an air inlet/exhaust control valve, a filter medium such as a microporous membrane/filter paper that can be replaced as needed, and an equipment support bracket.

The experimental operation process is as follows: first, the filter membrane was soaked in ultrapure water for 24 h to remove impurities, then dried to constant weight for later use; the pretreated filter membrane was placed flat in the filter cavity, and the upper and lower shells were fixed with bolts to ensure no leakage; then 500 mL of water sample was introduced, the inlet pressure was adjusted to 0.3 MPa, and the filtrate was collected for later use after filtration.



Figure 1: Positive pressure filtration device.

2.2.2 Suspended Solid Concentration and pH

To accurately quantify the suspended solid concentration in the produced fluid of a well, the experiment used a solid suspension determination device to carry out the determination by gravimetric method. The specific detection process is as follows: the microporous filter membrane was placed in a weighing bottle, dried at 105°C to constant weight (the difference between two final weighings ≤ 0.2 mg), then installed in the device and connected to a vacuum pump, and the negative pressure was controlled $\leq 6 \times 10^4$ Pa; 200 mL of mixed water sample was measured for suction filtration, the filter membrane was washed 3 times with distilled water and then continued to be suction-filtered to remove water, and then the filter membrane retaining the suspended solids was moved back to the original weighing bottle and dried again at 105°C to constant weight; the suspended solid concentration was calculated according to the mass difference of the filter membrane before and after and the volume of the water sample. Each group of measurements was set with 3 parallel experiments, and the average value was taken as the result.

2.2.3 Static Sedimentation

The filtrates filtered through five types of filter membranes with pore sizes of 1.2 μm , 2 μm , 5 μm , 10 μm , and 30 μm were collected into 5 groups (3 parallel samples in each group) of 50 mL stoppered transparent sedimentation bottles respectively, and the on-site static working conditions were simulated in a room temperature, dark, and vibration-free environment. After 0 min, 10 min, 30 min, 1 h, 2 h, 4 h, 6 h, 8 h, 24 h, and 48 h, photos were taken to record the turbidity state, stratification, precipitation generation, and accumulation characteristics of each filtrate, so as to comprehensively reveal the sedimentation evolution law of particles of different sizes.

2.2.4 Turbidity Test

To characterize the turbidity of suspended particles in the produced fluid and indirectly reflect the particle content and dispersion state, a turbidity meter was used to determine the turbidity of the produced fluid after sedimentation for 10 min, 30 min, 1 h, 2 h, 4 h, 6 h, 8 h, 24 h, and 48 h. Before the experiment, the produced fluid was allowed to stand to remove large particles, eliminate air bubbles, and stabilize the temperature; the instrument was calibrated with a standard turbidity solution matching the measuring range, the pretreated sample was injected into a special cuvette, the cuvette wall was wiped clean, and the

instrument was placed to record after the reading was stable. Each group was measured 3 times, and the average value was taken as the result; after the determination, the sample cell was rinsed and dried.

2.3 Dynamic Deposition

To reveal the contribution of different particle-size fractions to dynamic pipeline deposition in high-salinity produced fluid and to identify the priority-control particle-size range, a dynamic shear device was used to simulate the effect of pipe-flow shear on the attachment and accumulation of suspended particles, salt crystals, and their composites on flexible composite pipe surfaces. Because of laboratory limitations in temperature, pressure, and pipe-flow geometry, the test was designed to compare the relative deposition tendencies of filtrates obtained with different membrane pore sizes under the same hydrodynamic conditions. Detailed information on the dynamic deposition experimental setup and operating conditions is provided in Appendix A.3.

The flexible composite pipe section used in the experiment was taken from the gathering pipeline of the studied well. After pretreatment, the pipe wall was cut into 20 mm × 10 mm × 2 mm coupons. The dynamic shear device (Fig. 2) consisted of a 500 mL beaker, an IKA RW20 magnetic stirrer, a 30 mm magnetic stirring bar, and the flexible composite pipe coupon. Based on the field pipeline dimensions and flow conditions, the apparent shear rate in the field pipeline was estimated using an engineering approach [21]. The Metzner–Otto equivalent shear-rate method for stirred systems was then used as a reference [22,23], and the stirring speed during the experiment was set to 300 r/min.



Figure 2: Dynamic shear experimental device.

Before the test, the coupons were ultrasonically cleaned in acetone and ethanol for 15 min each, dried to constant mass, and weighed. Filtrates obtained through the 1.2 μm , 2 μm , 5 μm , 10 μm , and 30 μm membranes were added separately to beakers, and one pretreated coupon was placed in each beaker. The tests were conducted at room temperature and atmospheric pressure with continuous stirring at 300 r/min. After 7 d, a stable stage of deposition was observed on the coupon surfaces. The coupons were then gently rinsed with ultrapure water to remove loosely attached particles, dried at low temperature to constant

mass, and weighed. Deposit mass was calculated from the mass difference before and after the test. Each condition was tested in triplicate.

2.4 Microscopic Characterization of Deposits

To analyze the microscopic morphology, elemental composition, and mineral phases of deposits formed on flexible composite pipe surfaces during dynamic deposition, representative deposits after dynamic deposition were characterized by SEM-EDS and XRD. After the test, the coupons were removed, gently rinsed with ultrapure water to remove loosely attached material, and dried at low temperature to constant mass. Representative deposited regions or detached deposits on the coupon surface were selected as test samples. The SEM-EDS and XRD samples were both taken from deposits formed on the coupon exposed to the 5 μm filtrate. The 5 μm condition was selected because it lies in the key transition interval between effective retention by the 2 μm membrane and turbidity breakthrough at 5 μm , and therefore can represent the typical deposits formed after 2–5 μm particles entered the dynamic deposition system.

A scanning electron microscope (SEM, MA15, Carl Zeiss Microscopy Co., Ltd.) was used to observe the microscopic morphology, particle aggregation, and crystal morphology of the deposits. An energy-dispersive spectrometer (EDS, JED-2300, JEOL, Japan) was used to analyze elemental enrichment in the deposits. An X-ray diffractometer (XRD, D8 Advance, Bruker, Germany) was used to identify the major crystalline phases. These characterization results were used to assess suspended-particle deposition, inorganic salt crystallization, and their coupled effects on flexible composite pipe surfaces.

3 Results and Discussion

3.1 Physicochemical Properties of the Produced Fluid

3.1.1 Water Chemistry

The test results of anion and cation concentrations and physical and chemical indicators of the produced fluid from a well in a block of Tarim Oilfield are shown in Tables 1 and 2.

Table 1: Ion concentrations of produced fluid.

Ion Type	Ion	Concentration (mg/L)	Ion Type	Ion	Concentration (mg/L)
Cation	Na ⁺	72,724.45	Anion	Cl ⁻	239,441
Cation	K ⁺	5660.55	Anion	PO ₄ ³⁻	84.85
Cation	Ca ²⁺	6671.2	Anion	HCO ₃ ⁻	105.71
Cation	Ba ²⁺	8.65	Anion	SO ₄ ²⁻	442.75
Cation	Sr ²⁺	364.2	Anion	NO ₃ ⁻	26.05
Cation	Mg ²⁺	170.7	Anion		
Cation	Total Fe	10	Anion		

Table 2: pH, dissolved oxygen, total major ions, and salinity of produced fluid.

pH	Dissolved Oxygen (mg/L)	Total Major Ions (g/L)	Salinity (mg/L)
6.72	0.6	325.67	325,674.4

As shown in Tables 1 and 2, the produced fluid was dominated by Na⁺ (72,724.45 mg/L) and Cl⁻ (239,441 mg/L). The Ca²⁺ concentration reached 6671.2 mg/L, and Sr²⁺ (364.2 mg/L), Ba²⁺ (8.65 mg/L), SO₄²⁻ (442.75 mg/L), and HCO₃⁻ (105.71 mg/L) were also present, providing the chemical basis for carbonate and sulfate precipitation. The pH was 6.72, indicating weakly acidic conditions, and the dissolved oxygen

concentration was 0.6 mg/L. The total major-ion concentration calculated from ion chromatography was approximately 325.67 g/L, consistent with the salinity of 325,674.4 mg/L. Therefore, the produced fluid can be classified as a CaCl_2 -type high-salinity weakly acidic water. The major ion composition and salinity were used to characterize the dissolved-solid properties, and these values are internally consistent and directly relevant to scaling tendency and particle stability analysis.

Based on the measured ion concentrations in Table 1, the ionic strength of the produced fluid was estimated to be approximately 5.40 mol/L [24]. Such a high ionic strength can markedly compress the electrical double layer on suspended-particle surfaces, weaken electrostatic repulsion, promote fine-particle aggregation, and facilitate particle bridging and composite deposition. However, the presence of scale-forming ions alone is insufficient for quantitative scaling-risk assessment. Therefore, apparent saturation indices for CaCO_3 , BaSO_4 , and SrSO_4 were further calculated from the measured ion composition to evaluate the relative thermodynamic precipitation tendency of the major scale-forming minerals. The results are listed in Table 3.

Table 3: Apparent saturation indices of major scale-forming minerals.

Mineral Phase	Major Ions	IAPapp	Ksp	Apparent SI	Scaling Tendency
CaCO_3	Ca^{2+} , CO_3^{2-}	7.09×10^{-8}	3.31×10^{-9}	1.33	Supersaturated
BaSO_4	Ba^{2+} , SO_4^{2-}	2.90×10^{-7}	1.10×10^{-10}	3.42	Strongly supersaturated
SrSO_4	Sr^{2+} , SO_4^{2-}	1.92×10^{-5}	3.44×10^{-7}	1.75	Supersaturated

Table 3 shows that the apparent SI values of CaCO_3 , BaSO_4 , and SrSO_4 were all positive, indicating that the produced fluid was supersaturated with respect to these minerals under the calculation conditions based on the apparent ion product (IAPapp). BaSO_4 had the highest apparent saturation index, indicating the strongest sulfate-scaling tendency. Because of the high salinity and ionic strength of this produced fluid, ion activity may differ substantially from concentration. Thus, the calculated SI values are apparent saturation indices used mainly to compare the relative scaling tendency of different mineral phases and should not be interpreted as rigorous thermodynamic equilibrium predictions.

3.1.2 Zeta Potential and Particle-Size Distribution

Zeta potential and particle-size distribution were used to evaluate particle stability and potential plugging capacity. The apparent zeta potential of the produced fluid was 4.25 mV, indicating weak electrostatic repulsion between suspended particles. Under high-salinity conditions, electrolyte ions compress the electrical double layer on particle surfaces, reduce interparticle repulsion, and promote aggregation. Because of the high conductivity of the sample, this value should be interpreted as an apparent zeta potential reflecting particle stability in the produced-fluid system.

Particle-size analysis showed that the produced fluid was dominated by intermediate-sized particles. As shown in Fig. 3, particles in the 2–5 μm and 5–10 μm ranges accounted for 28.41% and 30.48%, respectively, giving a cumulative proportion of 58.89%. Particles smaller than 2 μm accounted for 19.05%, and particles larger than 10 μm accounted for 22.08%. These results indicate that 2–10 μm was the main suspended-particle range in the produced fluid.

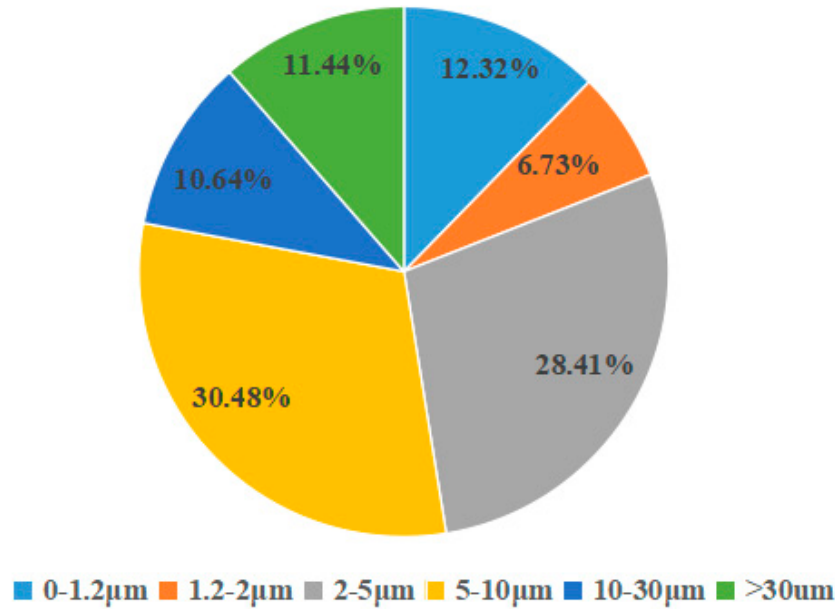


Figure 3: Particle-size distribution of the produced fluid.

Particles in the 2–10 μm range have a certain capacity for suspended migration while also being susceptible to retention, bridging, or deposition. Particles smaller than 2 μm have strong mobility but limited direct retention ability, whereas particles larger than 10 μm are more prone to settling under static conditions. The high proportion of 2–10 μm particles, together with the low apparent zeta potential, indicates that this interval represents the main plugging-risk particle-size range. Among these particles, 2–5 μm particles can pass through relatively coarse filtration media and participate in turbidity increase, membrane bridging, and subsequent deposition under shear conditions; therefore, they should be regarded as the priority-control particle-size range for this water-quality and experimental system.

3.2 Filtration–Static Sedimentation Results

3.2.1 Identification of Plugging-Risk Particle-Size Ranges Using Multidimensional Data

To identify the major plugging-risk particle-size range, membrane retention, suspended-solid concentration, and pH variation were analyzed together. The filter-cake morphology after filtration through membranes of different pore sizes is shown in Fig. 4, and the corresponding filtrates are shown in Fig. 5.

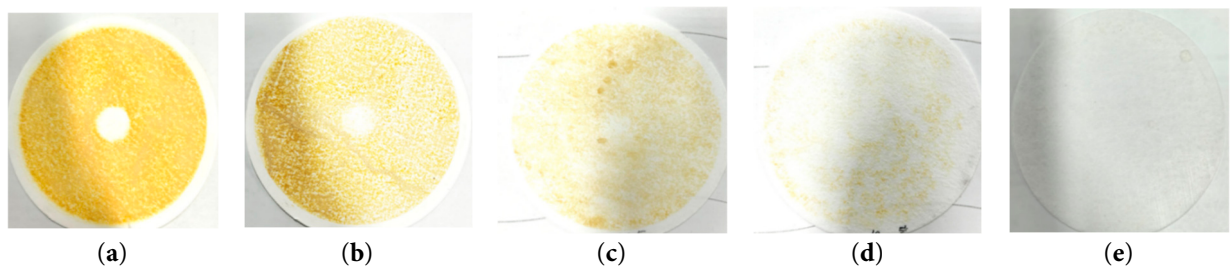


Figure 4: Filter cakes formed after filtration through membranes with different pore sizes: (a) 1.2 μm , (b) 2 μm , (c) 5 μm , (d) 10 μm , and (e) 30 μm .



Figure 5: Filtrates obtained using membranes with different pore sizes.

Figs. 4 and 5 show that both filter-cake morphology and filtrate appearance exhibited clear pore-size dependence. The 1.2 μm and 2 μm membranes formed relatively dense retention layers, indicating that they effectively retained most particles responsible for turbidity increase. In contrast, the 5 μm , 10 μm , and 30 μm membranes retained fewer solids, and the corresponding filtrates became progressively more turbid. This trend is consistent with the particle-size distribution, indicating that a large proportion of particles was concentrated in the 2–10 μm range and that particles passing through larger-pore membranes could still migrate and deposit in subsequent processes.

The difference between the 2 μm and 5 μm filtrates was particularly important. The 2 μm membrane retained most particles in the dominant 2–10 μm size interval, resulting in a relatively clear filtrate. When the membrane pore size increased to 5 μm , 2–5 μm particles could pass through, leading to a marked increase in filtrate turbidity and a decrease in solid accumulation on the membrane surface. This indicates that 2–5 μm particles are important contributors to turbidity increase and membrane-bridging risk.

As shown in Fig. 6, when the membrane pore size increased from 1.2 μm to 30 μm , the concentration of retained suspended solids decreased from 1137 mg/L to 305.5 mg/L, corresponding to a decrease of approximately 73.2%. Within the 1.2–10 μm pore-size range, the retained suspended-solid concentration remained relatively high, indicating that the dominant 2–10 μm particles were effectively retained to different extents. When the pore size increased to 30 μm , the retention ability decreased markedly, and most particles could pass through the membrane. The pH values of the filtrates remained essentially stable at 6.55–6.60, indicating that staged membrane filtration mainly changed the suspended-particle content and had little effect on the acid–base state of the produced-fluid samples.

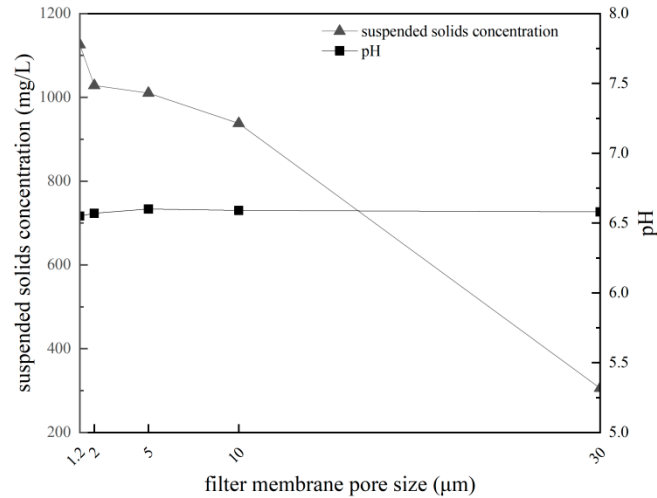


Figure 6: Changes of suspended solid concentration and pH with filter membrane pore size.

3.2.2 Multi-Level Particle Size Static Sedimentation

Static sedimentation tests were conducted on filtrates obtained through membranes of different pore sizes to evaluate particle settling, stratification, and deposition potential under quiescent conditions. The sedimentation states at different time points are shown in Fig. 7.

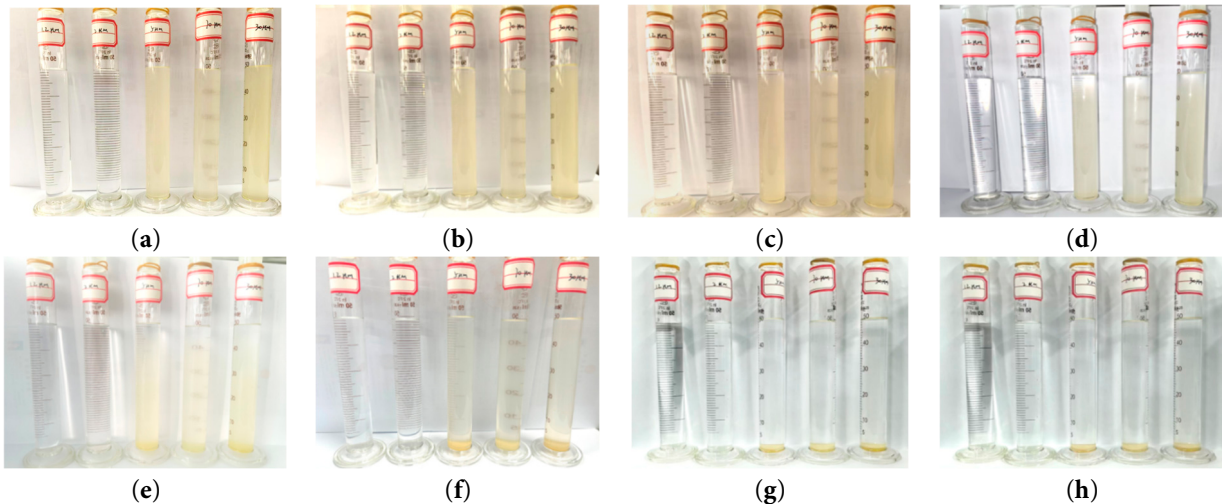


Figure 7: Static sedimentation states of filtrates obtained using membranes with different pore sizes at different settling times: (a) 0 min, (b) 10 min, (c) 30 min, (d) 1 h, (e) 4 h, (f) 6 h, (g) 18 h, and (h) 24 h. In each subfigure, the filtrates correspond to membrane pore sizes of 1.2, 2, 5, 10, and 30 μm from left to right.

The sedimentation results reflect the combined effects of particle-size composition, high ionic strength, and particle aggregation. Filtrates containing particles smaller than 1.2 μm or 2 μm were relatively stable. Fine particles were strongly affected by Brownian motion and showed limited direct settling, but they could still act as aggregation precursors under high-salinity conditions. Particles in the 2–10 μm range showed stronger settling and stratification tendencies because they could migrate with the fluid and also form aggregates or bridging structures under charge screening and cation-bridging effects. Particles larger than 10 μm were more prone to settling, but their proportion in the produced fluid was relatively limited.

Therefore, the intermediate particle-size range, especially 2–10 μm , is more closely associated with sustained plugging risk in wellbores and surface pipelines. Among these particles, 2–5 μm particles can pass through relatively coarse filtration barriers and participate in secondary aggregation and deposition and should therefore be preferentially controlled.

3.2.3 Turbidity Change Law with Time

The turbidity variation of filtrates obtained using membranes with different pore sizes is shown in Fig. 8.

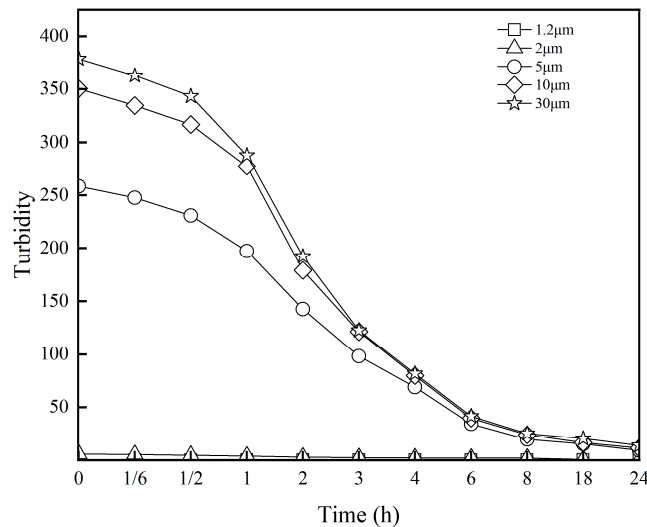


Figure 8: Turbidity variation of filtrates with different particle-size fractions over time.

The turbidity of all filtrates decreased with sedimentation time, indicating gradual settling or aggregation of suspended particles. The 1.2 μm filtrate remained essentially clear throughout the test, suggesting that most particles contributing to turbidity had been retained by the membrane. For the 2 μm filtrate, turbidity decreased from 5.67 to 0.20 after 24 h, corresponding to a reduction of approximately 96.47%. For the 5 μm filtrate, turbidity decreased from 258.47 to 9.11 after 24 h, also corresponding to approximately 96.47%. Therefore, the same rounded value of 96.5% for these two groups resulted from numerical approximation rather than data duplication. After 24 h, turbidity in the 10 μm and 30 μm filtrates decreased from 350.24 to 11.34 and from 378.60 to 13.57, corresponding to reduction rates of 96.76% and 96.42%, respectively.

Although the turbidity reduction rates after 24 h were similar among the groups, the initial and residual turbidity levels differed substantially with membrane pore size. The initial turbidity of the 5 μm , 10 μm , and 30 μm filtrates was much higher than that of the 1.2 μm and 2 μm filtrates, indicating that particles passing through membranes larger than 2 μm made a major contribution to turbidity. Therefore, absolute turbidity level is more suitable than reduction rate alone for evaluating the plugging contribution of different particle-size fractions. The sharp increase in turbidity when the membrane pore size increased from 2 μm to 5 μm further indicates that 2–5 μm particles are key contributors to turbidity breakthrough and membrane-bridging risk.

Together, the membrane filtration, static sedimentation, suspended-solid concentration, pH, and turbidity results indicate that 2–10 μm can be regarded as the main plugging-risk particle-size range for this produced fluid. Within this interval, 2–5 μm particles can pass through relatively coarse filtration media while still being sufficiently large to participate in bridging, aggregation, and deposition. They therefore represent the priority-control particle-size range in this system.

3.3 Dynamic Deposition Behavior

3.3.1 Microscopic Morphology

To compare the relative deposition tendencies of filtrates with different membrane pore sizes under the same shear disturbance and to further reveal the microstructural features of deposits on flexible composite pipe surfaces, macroscopic morphology observation and SEM characterization were combined to analyze coupon surfaces after dynamic deposition tests.

As shown in Fig. 9, the deposition degree on flexible composite pipe coupons varied markedly among filtrates obtained using different membrane pore sizes. For the 1.2 μm and 2 μm filtrates, only small amounts of deposits were observed on the coupon surfaces, mainly as local point-like or thin-layer deposits. When the membrane pore size increased to 5 μm and above, the amount of attached material increased markedly and gradually showed flaky or continuous coverage. This indicates that smaller-pore membranes effectively retained most particle components prone to deposition, whereas migratable particles retained in filtrates of 5 μm and larger were more likely to aggregate, bridge, and attach to the surface under shear disturbance and high-salinity conditions.

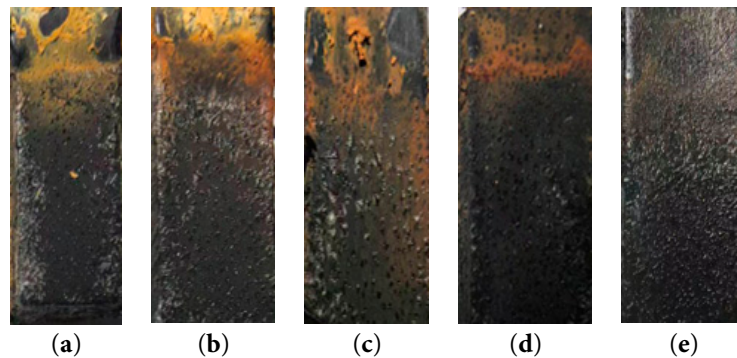


Figure 9: Macroscopic surface morphology of flexible composite pipe coupons after dynamic deposition tests using filtrates obtained with different membrane pore sizes: (a) 1.2 μm , (b) 2 μm , (c) 5 μm , (d) 10 μm , and (e) 30 μm .

The 5 μm condition represented an important threshold for the enhancement of deposition behavior. Compared with the 2 μm filtrate, the 5 μm filtrate produced a clear increase in surface deposition on the coupon, indicating that 2–5 μm particles could pass through the membrane and participate in the formation of an initial deposition layer on the flexible composite pipe surface. This result is consistent with the previously observed turbidity increase and suggests that 2–5 μm particles are not only important contributors to turbidity breakthrough but also key particle fractions enhancing dynamic deposition.

Macroscopic morphology reflects only the degree of deposit coverage and cannot distinguish the contributions of particle deposition and salt crystallization. Because the 5 μm condition represents the deposition response after breakthrough of 2–5 μm particles, representative deposited regions on the coupon exposed to the 5 μm filtrate were selected for SEM observation.

As shown in Fig. 10, the deposits on the coupon exposed to the 5 μm filtrate were not a uniform, dense, single-crystal layer. Instead, they exhibited particle accumulation, flaky or blocky attachment, local pores, and irregularly distributed crystals. Some fine particles were aggregated and embedded within the deposit layer, and relatively regular crystal morphologies were observed locally. These features indicate that particle migration and aggregation, salt precipitation, and wall attachment occurred simultaneously during deposit formation under the 5 μm condition.

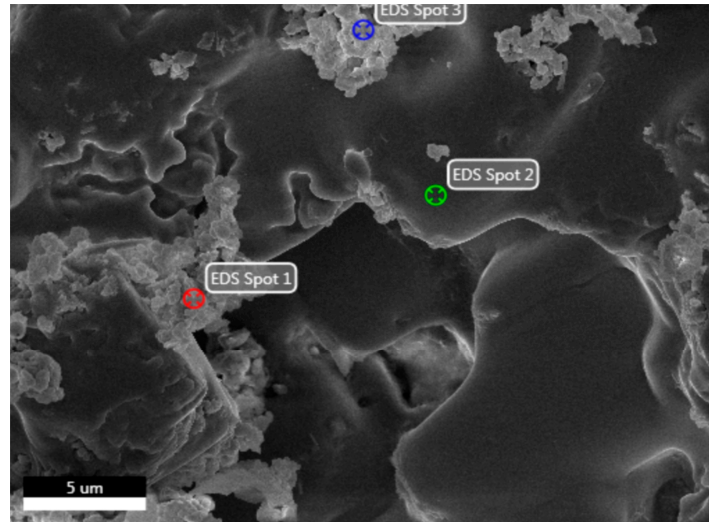


Figure 10: SEM-EDS characterization of representative deposits.

3.3.2 Compositional Analysis

To further clarify the elemental composition and mineral/compositional characteristics of the deposits on the flexible composite pipe surface, representative deposits from the coupon exposed to the 5 μm filtrate were analyzed by SEM-EDS and XRD based on SEM observations. The representative elemental compositions are listed in Table 4, and the XRD/compositional analysis results are shown in Table 5.

Table 4: Representative SEM-EDS elemental compositions of surface deposits.

Analysis Spot	Major Elemental Composition (Mass Fraction/%)
Spot 1	O 41.73, Si 36.19, Au 17.28, Cl 2.75, Cu 2.06
Spot 2	Cl 48.57, Na 40.39, Au 11.04
Spot 3	O 39.99, Si 36.06, Au 15.78, Na 3.57, Cl 3.36, Al 1.21, S 0.03

Note: Au mainly originated from gold sputter coating or conductive coating before SEM testing and was not considered an intrinsic component of the deposits.

Spots 1 and 3 showed clear Si and O enrichment, indicating the presence of SiO_2 or silicate suspended particles in the deposits. Spot 2 showed strong Na and Cl enrichment, indicating a NaCl crystal or high-salinity crystallization region. Spot 3 also contained small amounts of Na, Cl, Al, and S, suggesting that siliceous particles and salt crystals coexisted or were locally encapsulated at the microscale. Local Cu may be associated with corrosion products, equipment-derived metal-related particles, or localized metallic residues. These results indicate that the deposits on the flexible composite pipe surface were not a single inorganic scale or a single suspended-particle deposit but showed a siliceous-particle–salt-crystal composite deposition feature.

Table 5: XRD/compositional analysis results of surface deposits.

Major Phase/Component	NaCl, CaCl_2 , etc.	CaCO_3	SiO_2 , Elemental Cu, etc.	Alcohols, Condensate, etc.
Relative content	45.60%	20.60%	24.80%	8.50%

As shown in Table 5, the deposits on the coupon exposed to the 5 μm filtrate were mainly composed of soluble salts, carbonate scale, residual suspended solids, and a small amount of organic components. XRD

analysis indicated a relatively high proportion of soluble salts such as NaCl and CaCl₂, showing that salt enrichment and crystallization occurred during dynamic deposition of the high-salinity produced fluid. The presence of CaCO₃ was consistent with the apparent saturation-index calculation, indicating that carbonate precipitation was also an important source of the deposit layer. SiO₂ and elemental Cu indicate that formation debris, siliceous particles, and minor metal-related particles participated in deposition. A small amount of organic components such as alcohols and condensate may enhance adhesion and cementation between particles and salt crystals.

3.3.3 Deposit Mass

The relationship between membrane pore size and deposit mass on flexible composite pipe coupons is shown in Fig. 11.

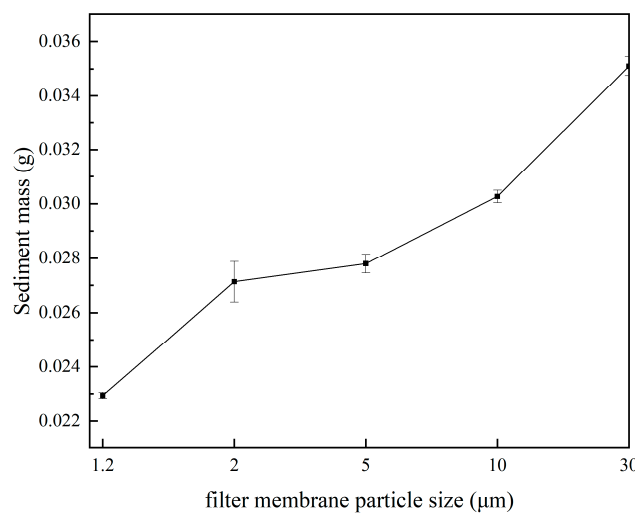


Figure 11: Effect of membrane pore size on deposit mass.

As shown in Fig. 11, when the membrane pore size increased from 1.2 μm to 30 μm, the 7 d endpoint deposit mass on the flexible composite pipe surface increased from 0.0230 ± 0.0003 g to 0.0350 ± 0.0004 g, corresponding to an increase of approximately 52.1%. The deposit masses corresponding to the 1.2 μm, 2 μm, 5 μm, 10 μm, and 30 μm filtrates were 0.0230 ± 0.0003 g, 0.0271 ± 0.0008 g, 0.0280 ± 0.0003 g, 0.0307 ± 0.0009 g, and 0.0350 ± 0.0004 g, respectively. These results indicate that larger-pore membranes allowed more suspended particles and potentially precipitable dissolved components to enter the dynamic deposition system, thereby enhancing deposition on the flexible composite pipe surface. The relatively small standard deviations of the triplicate tests indicate good repeatability.

Overall, the dynamic deposition results demonstrate clear differences in deposition behavior among filtrates obtained with different membrane pore sizes. As the membrane pore size increased, surface coverage and endpoint deposit mass increased simultaneously, indicating that migratable particles and precipitable inorganic components in the filtrates jointly promoted surface deposition. SEM-EDS and XRD analyses showed that the deposits were mainly composed of siliceous particles, NaCl, CaCO₃, and minor metal-related and organic components, exhibiting particle–salt-crystal composite deposition. Based on deposit mass, surface morphology, and compositional analysis, particles in the 2–10 μm range contributed strongly to dynamic deposition. Among them, 2–5 μm particles were prone to aggregation, bridging, and

salt-crystal encapsulation after passing through relatively coarse membranes, and should be regarded as the priority-control particle-size range in this produced-fluid system.

4 Conclusions

- (1) The produced fluid from the studied well was a CaCl_2 -type high-salinity weakly acidic water, with a salinity of 325,674.4 mg/L and a pH of 6.72. It was dominated by Na^+ and Cl^- and contained scale-forming ions such as Ca^{2+} , Ba^{2+} , Sr^{2+} , SO_4^{2-} , and HCO_3^- . The apparent saturation indices of CaCO_3 , BaSO_4 , and SrSO_4 were 1.33, 3.42, and 1.75, respectively, indicating supersaturation and a tendency for carbonate and sulfate precipitation.
- (2) The ionic strength of the produced fluid was approximately 5.40 mol/L, and the apparent zeta potential was 4.25 mV. These results indicate that the electrical double layer on particle surfaces was strongly compressed under high-salinity conditions, resulting in weak dispersion stability and a tendency for aggregation and bridging. Particle-size analysis showed that 2–5 μm and 5–10 μm particles accounted for 28.41% and 30.48%, respectively, with a cumulative proportion of 58.89%. Thus, 2–10 μm was the main suspended-particle range and main plugging-risk particle-size range in this produced fluid.
- (3) The filtration–static sedimentation results showed that membrane pore size significantly affected filtrate turbidity, suspended-solid retention, and sedimentation behavior. When the membrane pore size increased from 2 μm to 5 μm , filtrate turbidity increased markedly, indicating that 2–5 μm particles could pass through relatively coarse filtration media and contribute substantially to turbidity breakthrough, membrane bridging, and subsequent deposition. Therefore, 2–5 μm particles can be regarded as the priority-control particle-size range in this produced-fluid system.
- (4) Dynamic deposition tests showed that when the membrane pore size increased from 1.2 μm to 30 μm , the 7 d endpoint deposit mass on the flexible composite pipe surface increased from 0.0230 ± 0.0003 g to 0.0350 ± 0.0004 g, corresponding to an increase of approximately 52.1%. SEM-EDS and XRD results showed that the deposits were mainly composed of siliceous particles, NaCl, CaCO_3 , and minor metal-related and organic components. These results indicate that deposition on the flexible composite pipe surface was not a single-particle deposition process or a single inorganic-scaling process but a composite deposition process driven by the synergistic action of particles, salt crystals, and organic matter.
- (5) From an engineering perspective, plugging control for this type of high-salinity produced fluid should combine particle control with scale inhibition. Field filtration design should focus on the 2–10 μm particle range, with priority given to controlling 2–5 μm particles. Scale inhibition, corrosion inhibition, flushing, or pigging measures should also be combined to reduce pipeline plugging risks caused by particle–salt-crystal composite deposition. The results provide a basis for fine filtration of produced fluids from high-salinity drainage-gas recovery wells and for plugging control in flexible composite pipes.

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Ethics Approval: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation	Full Name
PSD	Particle Size Distribution
SEM	Scanning Electron Microscopy
EDS	Energy Dispersive Spectroscopy
XRD	X-ray Diffraction
Zeta potential	Zeta Potential
CaCl ₂	Calcium Chloride
BaSO ₄	Barium Sulfate
SrSO ₄	Strontium Sulfate
CaCO ₃	Calcium Carbonate

Appendix A

Appendix A.1 Produced Fluid Properties Measurement

The produced fluid samples were collected from a typical drainage gas production well in the Tarim Oilfield. The salinity, pH, and ionic composition were measured using standard analytical methods. The particle size distribution and Zeta potential were analyzed using a particle size analyzer.

Appendix A.2 Static Filtration Experiments

Multi-pore-size filter membranes (e.g., 1.2 μm , 2 μm , 5 μm , and 10 μm) were used to investigate particle retention behavior. The filtration process was conducted under controlled laboratory conditions, and the filtrate turbidity and membrane blockage characteristics were recorded.

Appendix A.3 Dynamic Deposition Experiments

Dynamic deposition experiments were carried out using flexible composite pipe specimens to simulate field pipeline conditions. The shear conditions were adjusted to match actual production scenarios, and particle deposition behavior was observed and analyzed.

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