INTRODUCTION

China's energy demand will be met by the use of coal for a long time to come.\textsuperscript{1-4} With the increase of coal mining intensity and the rapid growth of mining depth, the problems of coal and gas outburst are becoming more serious. Therefore, in coal mining, effective technical measures must be taken to reduce the outburst. At present, for a single outburst coal seam with no mining protection layer and low-permeability, pre-draining boreholes to extract gas often cause problems such as large drilling volume and low drainage efficiency.\textsuperscript{5-7}

Therefore, many coal mines have adopted hydraulic fracturing as a technical measure to increase coal seam permeability. Hydraulic fracturing enhancement technology is a main measure to increase production of conventional and unconventional oil and gas wells.\textsuperscript{8-12} Various hydraulic fracturing technologies are also used in underground coal mines for coal seam penetration enhancement.\textsuperscript{13-16} Coal seam hydraulic fracturing involves injecting high-pressure fluid into the coal seam through fracturing holes. During the fracturing process, as the primary fissures in the coal body crack and continue to extend, the damage variables of the fissures will continue to
increase. This causes the secondary fissures to crack, expand, and extend, and the fracturing water will enter the secondary fissures. Such development will eventually form a perforated network centered on fracturing boreholes, causing coal seams to crack and decompose, improve the permeability of the coal seams, and provide good conditions for gas drainage by boreholes.

Current research on hydraulic fracturing technology in coal mines includes theoretical research on the initiation and extension of hydraulic fractures, establishing hydraulic fracturing mathematical models for numerical calculation studies, and conducting hydraulic fracturing physical experiments in the laboratory. Our understanding of hydraulic fracturing initiation, extension law, and permeability characteristics of coal has developed from experimental research. Yin Shuaifeng studied the effect of hydraulic fracturing pulse frequency on pore volume.21

Jingna used a mercury intrusion method and liquid nitrogen adsorption method to quantitatively analyze the changes in coal porosity and pore-size distribution under pulse action and studied the effect of hydraulic fracturing pulse frequency on pore volume.21

Yulong Liu studied the crack propagation law of different macro-type coal samples during hydraulic fracturing and found that bright coal hydraulic fractures are mainly composed of open type, directional expansion type, and composite types that form a network of fractures. The density is large, and the hydraulic fractures have the characteristics of isolated fractures.23,24

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Tan Peng and Qianting Hu analyzed the initiation and development of fractures from two perspectives. The effect of hydraulic fracture cleats will change the extension path, causing hydraulic deformation of fractures, and more complex fractures near the holes. Geometric shape, and in the case of multi-layer fracturing, the cracks of thinner or softer coal seams will develop and expand first.25,26

Shuai Chen compared the coal sample fracturing method with liquid nitrogen injection with pure water, and liquid nitrogen can effectively promote the generation of macroscopic cracks in the coal and increase the degree of coal sample damage under constant confining pressure. As the injection pressure increases, the penetration rate is exponentially increasing.27

In summary, a lot of research has been reported on the law of hydraulic fracturing crack propagation and permeability. However, there are few studies on the large-scale stress transfer after hydraulic fracturing in low-permeability coal seams and the investigation of gas drainage effects. When hydraulic fracturing is implemented in coal mines, the selection of fracturing parameters usually relies on on-site experience, which leads to poor fracturing effects because of unreasonable parameters. Also, the combined effects of in situ stress and high-pressure water in the coal body may produce rapid deformation, displacement, and even induce coal and gas outbursts. In this study, we address some of the issues by conducting hydraulic fracturing simulations and field experiments to study the water pressure changes under the condition of repeated fracturing in coal seams, the changes in roof stress and the effect of coal seam permeability enhancement, so as to guide the high efficiency of underground hydraulic fracturing implementation.

## 2  REPEATED HYDRAULIC FRACTURING SIMULATIONS

Characteristics of the A1 coal seam of Lizuizi Coal Mine of Huainan Mining Group were used as the basis of hydraulic fracturing simulation. Similar materials were selected to represent the roof and floor rock layers of the coal seam, and hydraulic fracturing simulations were conducted to determine the initiation pressure and the fracture characteristics of the coal seam. The scope was then extended to investigate the influence of water pressure on the stress field of the coal roof during the fracturing process and observe the location and extension direction of the coal seam crack.

### 2.1  Similarity theory and phase material ratio

#### 2.1.1  Similarity theory

According to similarity theory, when studying the stress and strain of materials, the test model and material should be geometrically similar to the research object, and the bulk density and stress should be similar.28-31

1. Geometric similarity

When conducting simulation experiments, the geometric dimensions of the experimental model and the prototype should be similar:

\[
a_l = \frac{l_p}{l_m}.
\]
where $a_l$ is the geometric similarity ratio, usually 10-50 in the experiment, and 20 in this experiment; $l_p$ is the original rock size, the actual thickness of the A1 coal seam is 4 m; $l_m$ is the model size, that is, the simulated coal seam thickness.

2. Density similarity

When considering the self-weight of the surrounding rock within the elastic range, the model and the prototype need to have a similar density:

$$a_γ = \frac{γ_p}{γ_M},$$

(2)

where $a_γ$ is the density similarity ratio; $γ_p$ is the actual density of coal seams and rock layers, the coal seam is 1.25 g/cm³, and the overlying rock layer is 2.5 g/cm³; $γ_M$ is the density of the simulated coal seam material.

3. Stress similarity

When studying problems such as stress and strain, the stress similarity criterion should be met, and the stress conditions of the model and the prototype should meet the stress similarity:

$$a_σ = \frac{σ_p}{σ_M} = \frac{l_pγ_p}{l_mγ_m} = a_la_γ,$$

(3)

2.1.2 | Similar material ratio

Select the similar material ratios of multiple coal seams and roof and floor rock layers through literature 32,33 and made standard test pieces of similar materials with different ratios. The material ratio test is carried out to determine the ratio scheme similar to the actual coal and rock mechanical properties of the coal mine.

| Simulation type      | Serial number | Sand:Cement:Gypsum:Coal powder | Density ($γ$) g/cm³ | Compressive strength ($σ_c$) MPa | Tensile strength ($σ_t$) MPa |
|----------------------|---------------|-------------------------------|---------------------|----------------------------------|-----------------------------|
| Roof and floor rocks | S1            | 3:0.3:0.7:0                   | 2.18                | 4.42                             | 0.45                        |
|                      | S2            | 3:0.5:0.5:0                   | 2.16                | 5.39                             | 0.49                        |
|                      | S3            | 4:0.3:0.7:0                   | 2.13                | 3.25                             | 0.39                        |
|                      | S4            | 5:0.3:0.7:0                   | 2.11                | 3.00                             | 0.31                        |
|                      | S5            | 5:0.5:0.5:0                   | 2.10                | 2.77                             | 0.33                        |
|                      | S6            | 6:0.3:0.7:0                   | 2.11                | 2.23                             | 0.25                        |
| Coal seam            | C1            | 5:0.5:0.5:1                   | 1.68                | 1.28                             | 0.37                        |
|                      | C2            | 6:0.3:0.7:1                   | 1.48                | 0.68                             | 0.13                        |
|                      | C3            | 6:0.5:0.5:1                   | 1.52                | 1.02                             | 0.28                        |

| Simulation type      | Geometric size | Density ($γ$) g/cm³ | Stress ratio |
|----------------------|----------------|---------------------|--------------|
| A1 coal seam         | 4 m            | 1.25 g/cm³          | $a_γ = 17$   |
| Similarity model     | 200 mm         | 1.85 g/cm³          | $a_γ = 0.85$ |
| Similarity constant  | $a_l = 20$     |                     |              |

According to the characteristics of coal seams and roof and floor rocks, coal seams use river sand and coal powder as aggregates, cement, and gypsum as cementing materials, and similar materials for roofs and floors use river sand as aggregates and cement as cementing materials.

According to the literature, the coal seam and the roof and floor rock layers are optimized with similar material ratios, and standard specimens of similar materials with different ratios are made. After 14 days of curing under natural laboratory conditions, the mechanical parameters are tested. The ratio of similar materials and the test results of mechanical properties are shown in Table 1.

According to the measured data reported in Table 1, combined with the tensile strength, bulk density, and coal seam depth of A1 coal seam for model loading requirements, it is finally determined that the roof rock layer should be selected S5 proportioning plan, the bottom rock layer should be selected S4 proportioning plan, and A1 coal seam should be selected C2 proportioning plan. The calculated results for similar constants are shown in Table 2.

2.2 | Similarity simulation test of hydraulic fracturing

2.2.1 | Hydraulic fracturing test system

As shown in Figure 1, the hydraulic fracturing simulation system is mainly composed of a test model box, a ground
stress loading system, a stress data acquisition system, a water pressure acquisition system, a pump source device, and other auxiliary devices.

1. Test model box

The test model box is a rectangular parallelepiped, and the bottom and surroundings are welded by Q345 steel plates with a thickness of 10 mm; the internal space dimensions (length × width × height) are 500 mm × 500 mm × 600 mm.

2. Stress loading system

The stress loading system is composed of four hydraulic jacks and a return force frame. Among them, the range of the hydraulic jack is 0-10 MPa, and the maximum pushing force of the hydraulic cylinder is 10 t; the return force frame is supported by four cylindrical screws with a diameter of 300 mm. Since only the relative law of the change of the roof stress is considered, and the influence of the crack direction and confining pressure on the results is not considered, the test system does not set the confining pressure.

Corresponding to the target coal seam buried depth is −915 m, to simulate the vertical stress of the coal seam, the compensation load required by the model must meet the following formula:

\[
\sigma_b = \frac{\rho_p g (h_p - h_m)}{a_\sigma} \times 10^{-6}
\]

where \(\sigma_b\) is the model ground stress compensation load, MPa; \(\rho_p\) is the original rock density provided by the coal mine, taking 2500 kg/m³; \(h_p\) is the thickness of overlying strata of coal seam, that is, the buried depth of the coal seam, m; \(h_m\) is the model roof thickness, m; \(a_\sigma\) is the stress similarity constant of this simulation experiment, \(a_\sigma = 17\).

Using 915 m as the thickness of the overlying rock layer of the coal seam, the thickness of the upper rock layer simulated by the experiment is 4 m, and calculating with Equation (4), the required compensation load is 1.39 MPa.

3. Data collection system

As shown in Figure 2, with the fracturing hole as the center, a miniature pressure cell is arranged every 4.5 cm in the coal roof of the model, and a total of 30 miniature pressure cells are arranged in eight directions. The stress box data line is connected to the YE2539 high-speed static strain gauge, and data are collected during the hydraulic fracturing water injection process to observe the stress change trend of the coal roof and floor during the entire water injection process during the fracturing process.

4. Data collection system

This test uses an automatic water pressure data collector to automatically record the water pressure data during the test in real time to effectively monitor and record the changes in water injection pressure during the hydraulic fracturing process.

5. Pump source device

The model of the water pump used in this test is JZ1.6-4.0/40 plunger metering pump. The pump has a maximum rated flow of 4.0 L/h and can provide a maximum water pressure of 40 MPa.
2.2.2 | Test plan and model making method

1. Overall test plan

The main purpose of this test is to compare and analyze the water injection pressure, flow rate, crack initiation, and extension direction and range of the change of the coal roof stress during the repeated hydraulic fracturing process. During the test, the test model was fractured three times, with time intervals of 3 and 5 days.

2. Model making method

Considering the size of the test box and the actual situation of the coal seam in the field test, the test model is divided into three layers, namely, the roof rock layer, the coal seam and the floor rock layer, and the thickness of each layer is 200 mm; the test box is a confining device outside the specimen. After all layers are laid and solidified, the return force frame and jack are installed to load the model. The production process is shown in Figure 3.

2.2.3 | Experimental procedure

As shown in Figure 4, hydraulic fracturing is conducted in accordance with the procedures of debugging the system, data collection, starting fracturing, observing the condition of the specimen, and ending fracturing. The experiment was conducted 3 and 5 days after the first fracturing, respectively, and the box was disassembled to observe the condition of the specimen.

3 | TEST RESULTS AND DISCUSSION

3.1 | Water injection pressure changes during fracturing

Figure 5 shows the changes of water injection pressure during each hydraulic fracturing process. The entire fracturing process can be divided into hydraulic pressure accumulation stage, fracture initiation stage, and fracture expansion stage according to the change law of hydraulic pressure.

Water pressure accumulation stage: After the water injection is started, the injected high-pressure water gradually wets the simulated coal seam and fills the primary fissures of the coal seam. When the pores are filled with water and then continue to inject water, the water in the pores will gradually generate internal water pressure and exert pressure on the pore walls and surrounding fissures. As the amount of water continues to be injected, the internal water pressure in the pores increases. During this process, the water pressure changed little in the early stage, but increased in the later stage.

Crack initiation stage: When the water pressure accumulates, the water injection pressure rapidly increases and
reaches the peak. At this time, the tensile stress generated by the water pressure on the weak surface of the fracture is greater than the tensile strength of the simulated coal seam, and the tip of the fracture begins to crack, and the space of the fracture increases accordingly. The potential energy of water is converted into kinetic energy, and the water injection pressure is reduced. At this stage, the water pressure first rapidly increases to reach a peak, and then decreases.

Fracture expansion stage: As the high-pressure water fills the fissure space again, the kinetic energy of the water is transformed into pressure potential energy, and the water pressure also increases, causing the fissures to continue to extend under the action of the high-pressure water until the high-pressure water seeps from the surface cracks of the model or around the box. In the crack propagation stage, the internal pore pressure is an alternating process of increasing and decreasing, and the increase of internal pore pressure will reflect the increase of system pressure. At this stage, the water pressure is in a process of continuously increasing and decreasing the reciprocating shock, and the water pressure is reduced in the later stage.

The pressure change process can be simplified to the model shown in Figure 6. It can also be found from Figure 5 that in repeated fracturing, with the continuous implementation of fracturing, lower initiation pressure is required. In the first fracturing,
the peak water injection pressure is 2.7 MPa, and the second is 2.3 MPa, the third time is only 2.1 MPa, which is mainly because the coal seam is fatigued and damaged by repeated fracturing. After each fracturing, the degree of coal seam fracture gradually increases, so lower initiation pressure is required.

3.2 | Analysis of stress change of coal roof

Figure 7 is a picture of multiple azimuth shapes of the specimen after hydraulic fracturing. In the figure, it can be seen that the roof layer has obvious water seepage and large cracks. Figure 8 shows the seam roof stress cloud diagram of water injection for 200 seconds, 800 seconds, 1000 seconds, and 2000 seconds during the first hydraulic fracturing, and the stress accumulation and stress transfer of the coal roof during the entire fracturing process. At the beginning of fracturing, the coal seam is still in the stage of water pressure accumulation, and the roof is less affected by water injection, and only the stress around the water injection hole increases. As the fracturing progresses, the stress rapidly increases in the area centered on the water injection hole and results in a stress concentration zone. At this time, the water injection pressure also reaches its peak, the coal seam begins to crack, and the stress decreases in the area near the water injection hole. This is mainly because after the coal seam cracks open and expand, the crack space increases, and the potential energy of the water in the crack is converted into kinetic energy. The water injection pressure is also reduced at this time because the fracturing cracks gradually expand into the surroundings, the stress concentration area also shifts to the surroundings, and the stress increases. This is because the coal seam around the water injection hole has already relieved pressure and stress transfers to the depths of the coal seam.

In general, the change in roof stress is consistent with the change in water injection pressure. First, the area around the water injection hole is affected by continuous water injection, and the stress gradually increases. The coal body ruptures when stress exceeds strength, pressure is relieved, and the stress transfers to the surroundings. After fracturing, the pressure relief zone and stress concentration zone are formed.

Figure 9 shows the stress change curve in different directions at 2000 seconds. The pressure value shows a decaying trend at greater distances from the center of the test piece. Based on the stress cloud diagram of Figure 6, the stress concentration area generally shifts upward with an initial upward stress followed by a decay.

**FIGURE 6** Variation of water injection pressure during fracturing

**FIGURE 7** Images of multiple positions of the specimen after hydraulic fracturing
Figure 10 shows the stress change process over time at three typical positions with a distance of 4.5 cm, 9 cm, and 13.5 cm from the center of the specimen. The stress at different positions increases first and then decreases with the increase of fracturing time, and finally basically stabilizes. This is similar to the change process of water injection pressure in Figure 5, but with the increase of distance, the crack resistance increases, and the micro-crack space forms a buffer that gradually weakens, and the overall pressure gradually decreases.

Figure 11 is a comparison diagram of the stress distribution of the coal roof during each hydraulic fracturing process. It can be seen from the figure that with the re-implementation of fracturing, the area of increased stress continues to expand, and this also shows that the cracks in the model coal seam are expanding farther and farther. The scope of influence of hydraulic fracturing gradually increases with the continuous implementation of fracturing. The influence of the first fracturing is centered within a 100 cm radius of the water injection hole. In the second fracturing, the influence radius is expanded to 150 cm; and in the third fracturing, the affected radius expanded to about 250 cm. Therefore, by implementing repeated fracturing, the extension range of coal seam cracks can be expanded, and the affected area of fracturing can be enlarged, so as to achieve the purpose of increasing production and efficiency.

Figure 12 shows the stress change curves of 4.5 cm, 9 cm, and 13.5 cm from the center under different fracturing times. Different positions showed the hydraulic pressure accumulation stage, the fracture initiation stage, and the fracture
expansion during the three fracturing cycles. However, the stress change was less dramatic with each successive fracturing and the distance from the center. Later, fracturing required lower initiation pressure and expansion pressure. At 4.5 cm and 9 cm, the accumulative rate of rise of water pressure during the second fracturing exceeded that of the first, it shows that a large number of cracks in this area are closed, and the filling resistance of water to the cracks in this range increases, so the stress rises faster. However, there is no such phenomenon at 13.5 cm, indicating that the distance factor has a greater influence in this range. The increase in the number of fracturing results in an increase in the overall fracture volume of the specimen, and the rate of water filling the fracture is slower and slower.

4 | APPLICATION

Field tests were conducted in Lizuizi Coal Mine in Huainan, Anhui to verify and compare the difference between repeated hydraulic fracturing and single hydraulic fracturing in the scope of influence and gas drainage effect.

4.1 | Introduction of the coal mine and test method

Lizuizi Coal Mine is a coal and gas outburst mine located in Huainan, Anhui (as shown in Figure 13), and the test target coal seam is A1 coal seam, with an average thickness of 3.9 m, an average inclination of 8 degrees, a vertical stress of 21.71 MPa, and horizontal stress coefficients of 1.1 and 0.8. In this experiment, a total of six interlayer hydraulic fracturing boreholes with a spacing of 20 m were designed, three of them are used for single hydraulic fracturing, and the other three boreholes are used for repeated hydraulic fracturing. Construction of 4 m × 4 m gas drainage borehole after fracturing and confluence metering devices are installed in different regions to calculate the drainage concentration and average single-hole measurement.
After drilling through hydraulic fracturing, the holes are sealed with a cement slurry. Small-hole screens are placed in the coal seam section, seamless steel pipes are placed in the rock section, and orifice devices (including pressure gauges and check valves) are installed at the orifices. The high-pressure hose is connected to the hydraulic fracturing pump set (as shown in Figure 14). A pump set with a flow rate of 400 L/min and a rated pressure of 56 MPa is used for fracturing. Because the target coal seam is soft and has no specific initiation pressure, 28 MPa constant pressure fracturing is set. Under this pressure condition, the flow rate of the whole fracturing process varies from 145 L/min to 315 L/min, and the orifice device is automatically set during any fracturing to maintain pressure and prevent drainage after fracturing.

4.2 | Analysis of results

The average time of a single fracturing is 11 hours and 30 minutes (the average water injection volume is 136 m³), and the total control time for repeated hydraulic fracturing is equal to that of a single fracturing. The first fracturing
FIGURE 12 The stress curve of different positions in the specimen under repeated hydraulic fracturing conditions

(a) The right side of the specimen is 4.5 cm from the center

(b) The right side of the specimen is 9 cm from the center

(c) The right side of the specimen is 13.5 cm from the center
is 3 hours and 50 minutes (average indentation is 44 m³), the interval is 3 days and then fracturing for 3 hours and 50 minutes (average indentation is 63 m³), and the final interval is 5 days after fracturing for 3 hours and 50 minutes (average indentation is 76 m³); the average indentation amount is 183 m³, which is 35% higher than the average indentation amount in a single fracturing at the same time (Figure 15).

During the construction of gas drainage boreholes, the water content of the coal sample discharged from each borehole is measured, and the sampling location where the water content of the coal sample is higher than the original area is regarded as the fracturing affected area. After measurement, the affected area after repeated fracturing is compared with a single hydraulic fracturing, it is increased by 31% (Figure 16), and the increase of injected water promoted the increase of the scope of fracturing.

According to the 33-day gas drainage statistics, as shown in Figures 17 and 18, the gas drainage concentration and the average single-hole gas drainage pure flow in the two hydraulic fracturing areas are higher than those in the original area.
Both the extraction concentration and the extraction pure flow rate decay are faster with time, and the gas extraction effect is poor. The gas drainage concentration in the hydraulic fracturing area shows a trend of first increasing and then stabilizing, and the pure gas drainage flow shows a trend of first increasing, then decreasing and then stabilizing. The reason for the low previous extraction data is that the water in the coal body blocks the cracked channels for gas flow, and the gas could not be quickly drawn out. When part of the water is drained by negative pressure, the cracked channel for gas flow is opened, and then the gas drainage concentration and drainage net flow are maintained at a high level and last for a long time, while the original area was reduced to a very low value.

In addition, after about 15 days, the repeated fracturing area and the single fracturing area gradually showed a difference. Compared with the single fracturing, the gas drainage concentration of repeated fracturing increased by about 36%, and the gas drainage scalar volume increased about 1.3 times. The gas content per ton of coal in the area is 12.8 m³/t, the coal seam gas reserves in the single fracturing zone and the repeated fracturing zone are both 191,693 m³, the gas drainage volume in the repeated fracturing zone is 111,757 m³, and the gas drainage volume in

**FIGURE 16** Comparison of the influence range of single hydraulic fracturing and repeated hydraulic fracturing

**FIGURE 17** Concentration change curve of collecting pipe
the single fracturing zone is 74,760 m³. According to the statistics of total regional drainage, the repeated fracturing area reached a coal seam gas drainage rate of 58.3% within 33 days, while the coal seam gas drainage rate of a single fracturing area was only 39%, so it can be enhanced through repeated fracturing. Gas drainage reduces the gas content of the coal seam faster and more quickly ensures the safety of coal mining faces.

4.3 | Advantages

The effect of increasing permeability produced by the implementation of repeated hydraulic fracturing technology in underground coal mines is mainly reflected in the following aspects.

1. Flush fissures: The internal space of the initial fissure may affect the flow of gas in the fissure because of blockage of coal and rock residues that reduce the efficiency of gas drainage. Through the re-implementation of fracturing, the inside of the fracture can be effectively cleaned to dredge the gas flow channel.

2. Open the closed cracks: The fissures generated by the initial fracturing may reclose under the action of high ground stress, resulting in an unsatisfactory anti-reflection effect. During repeated fracturing, the water injection rate and pressure can be strengthened to increase the fracture degree of the coal seam, which will effectively prevent the compressed fractures from closing again.

3. Open new cracks: Repeated fracturing can generate and extend new fractures, communicate with the original fractures, expand the fracture network of the coal seam, increase the density of fractures, and ultimately improve the effect of anti-reflection.

5 | CONCLUSIONS

The following conclusions can be drawn from this study.

1. The hydraulic fracturing process is divided into hydraulic pressure accumulation, fracture expansion, and fracture stable expansion stages. During repeated fracturing, because of increases in the total volume of the fractures, lower initiation pressure is required for later fracturing, and less time is required for water pressure accumulation before initiation.

2. The change of roof stress is consistent with the change of water injection pressure. First, the area around the water injection hole is affected by continuous water injection, and the stress gradually increases. At a threshold value, the coal body ruptures and relieves pressure, and the stress transfers to the surroundings, and the cracks also transfer to the surroundings with the stress. After fracturing, the pressure relief zone and stress concentration zone are formed. With the re-implementation of fracturing, the area of increased stress continues to expand, and the scope of influence gradually expands. Therefore, by implementing repeated fracturing, the extension range of coal seam cracks can be expanded, and the affected area of fracturing can be enlarged.

3. For the same total fracturing time, the total amount of indentation of repeated fracturing is 35% higher than that of single fracturing, and the affected area after repeated fracturing is 31% higher than that of single hydraulic fracturing. The increase in the amount of press-in water promotes the expansion of the impact of fracturing.

4. After repeated hydraulic fracturing, the concentration of gas drainage and the pure flow rate of gas drainage are substantially increased, the concentration is increased by about 36%, and the pure flow rate of gas drainage is increased by about 1.3 times.
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