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CO_2-enriched brine injection's impact on mechanical properties of a sandstone specimen

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Abstract. CO_2 capture and geological sequestration is one of the most practical and efficient methods of mitigating anthropogenic CO_2 emissions. Due to the uncertainties associated with CO_2 injection into deep saline reservoirs, the interaction between the host rock and the injected CO_2 needs to be better understood as it can lead to considerable pore-structure changes. The geochemical reactions, especially mineral dissolution, can compromise the mechanical properties of the reservoir rock, which consequently threatens the reservoir stability and integrity. Therefore, it is crucial to capture the variation of mechanical properties of the reservoir rock upon CO_2 injection. In this study the variation of elastic properties (e.g. Young's modulus, shear modulus, bulk modulus, and Poisson's ratio) of a brine-saturated sandstone specimen upon injecting CO_2-enriched brine is investigated. The elastic properties of the specimen were initially characterized through multi-stage elastic (MSE) test before injecting the CO_2-enriched brine. Then, the synthetic brine solution was enriched with CO_2 and injected into the brine saturated sandstone specimen. The mechanical test results revealed that a significant mechanical weakening occurred upon injecting CO_2-enriched brine into the sandstone specimen. This mechanical degradation can be attributed to the dissolution of calcite and clay minerals. The results from this study indicated that the mechanical deterioration of reservoir rock during CO_2 injection should be considered through the entire CO_2 sequestration process (i.e. site selection, injection operation, and post-injection monitoring).

1 Introduction

Carbon capture and sequestration (CCS) is among the most practical approaches that can reduce the amount of anthropogenic CO_2 emission [1-3]. Deep unmineable coal seams, available oil shales and cavities, enhanced oil recovery systems (EOR), depleted oil and gas reservoir, and deep saline aquifers are considered as the most popular alternatives for CO_2 sequestration [4-7]. However, due to availability and abundance, the latter option (i.e. deep saline aquifer) is more favourable compared to the rest [8]. Saline aquifers usually consist of sedimentary rocks, such as sandstone, and are usually located between the depths of 800 m to 2 Km [9].

The Injection of CO_2 into the deep saline reservoirs is followed by major chemo-mechanical and hydrological processes because of the interaction between the injected fluid and the host formation rock [10]. The interaction between the injected CO_2 and the host fluid (usually brine) forms carbonic acid:

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3, \qquad (1)$$

where the low pH environment can dissolve the carbonates and other cementitious minerals [11]. The chemical reaction and especially mineral dissolution can influence pore-network [12], permeability [13] and mechanical behavior [9] of the formation rock.

Although the porosity and permeability of the reservoir rock are crucial factors to efficiently store CO_2, adequate formation strength is required to satisfy the safety requirements of a CO_2 sequestration program [14, 15]. Porosity and permeability determine the storage capacity and injectivity of the reservoir [13]. Furthermore, the reservoir strength should be considered to ensure the wellbore stability [15] and avoid induced seismicity and cross formational leakage [16]. Injecting CO_2 can potentially compromise the elastic (i.e. Young's modulus, Bulk modulus, Poisson's ratio) properties of the reservoir rock [17] since the acidic environment can dissolve the cementing minerals (i.e. calcite and clay). Also, some studies indicated that the stress-strain response of the rock is affected upon mineral dissolution and salt precipitation [17, 18].

Several studies investigated the mechanical impacts of CO_2 injection into the reservoir rocks. Marbler et al. [19] studied the effects of North German basin sandstone exposure to CO_2-enriched brine inside a reaction chamber. Their results indicated that a significant mechanical weakening occurred upon dissolution of calcite and clay minerals. Also, Lamy-Chappuis et al.

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[20] observed that dissolution of carbonates resulted in the mechanical weakening, where the strength properties (i.e. yield and peak stresses) were approximately reduced by 30%. However, the results of the study conducted by Hangx et al. [1] revealed that the mechanical degradation associated with dissolution of carbonate minerals was not significant. Wu et al. [21] indicated that in the absence of carbonate minerals, the exposure of CO_2-enriched brine to rock specimen resulted in insignificant mechanical degradation (Young's modulus remained unchanged), while Shi et al. [22] indicated that the bulk modulus of the clay-rich sandstone significantly decreased upon CO_2-enriched brine exposure.

Different mechanical responses have been observed upon injecting CO_2 into different rock specimens [21-25]. The internal heterogeneity and different rock mineralogy lead to increased complexity of predicting the reservoir rock response to coupled chemo-mechanical and hydrological processes that take place upon CO_2 injection [1, 8, 12]. Also, different geological conditions can result in different mechanical behavior. Therefore, the experimental investigation of the interaction between CO_2-enriched brine with the reservoir rock under different reservoir conditions is necessary to provide important insight on the impact of CO2 injection on mechanical properties of host reservoir rock.

This study evaluates the variation of elastic properties and stress-strain response of a sandstone specimen subjected to CO_2-enriched brine injection. Initially, an XRD analysis was conducted to determine the mineralogy of the specimen. This was followed by mechanical characterization of the sandstone specimen. Then, CO_2-enriched brine was injected into the specimen for 3 days, under different confining and pore pressure levels. This was followed by a chemical analysis to investigate the potential mineral dissolution/precipitation. At the end, the mechanical properties of the sandstone specimen were compared before and after CO_2-enriched brine injection.

2 Methodology

2.1. Experimental Design

The main objective of the experimental program in this study is to capture the variation of elastic properties and stress-strain response of the rock upon injecting CO_2-enriched brine. To this end, the mechanical characteristic of the sandstone specimen was investigated through the isotropic compression test and multi-stage elastic (MSE) experiment. Then, the CO_2-enriched brine was injected under different confining and pore-pressures. The effluent was collected from the downstream side to perform inductively coupled plasma optical emission spectrometry (ICP-OES) analysis. Finally, the MSE and isotropic tests were repeated under the same test conditions to evaluate the potential mechanical degradation of the specimen. The mechanical tests performed on the intact specimen are called pre-test results and the results obtained upon injecting CO_2-enriched brine are referred to the post-test results.

The MSE experiment and CO_2-enriched brine injection were performed using high pressure/temperature fully servo-controlled triaxial device (Autolab 1500) located in Porous Media Laboratory at the University of Vermont (UVM). The device is capable of applying maximum confining pressure (CP) of 70 MPa and differential stress (DS) of 580 MPa for 38.1 mm diameter specimens. As can be seen in Fig. 2, Autolab 1500 is equipped with upstream and downstream intensifiers, where different types of fluids can be injected into rock specimen. The intensifiers are able to pressurize the fluid up to the pore pressure (PP) of 70 MPa.

2.2. Material and Sample Preparation

2.2.1. Rock sample preparation

The rock specimen used in this study was a Triassic Pecos Sandstone, retrieved from a query in Barstow, Texas. A block of Pecos sandstone (see Fig. 1b) was cored to obtain a 38.1 mm × 77.5 mm (diameter × length) specimen (see Fig. 1a). Then, the two ends of the specimen were lapped to 0.001 inch to avoid non-uniform loading during the mechanical testing. The XRD analysis revealed that the Pecos sandstone specimen contains 47.5% quartz, 23% anorthoclase (alkali feldspar), 9.3% microcline, 7.3% calcite, and 12.5% kaolinite.

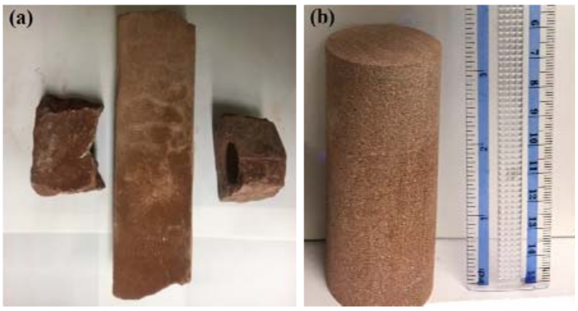


Fig.1. The picture of (a) Pecos sandstone block and (b) the cored specimen.

2.2.2. Mechanical Test

To prepare the sample for the mechanical test, the sandstone specimen was wrapped with copper jacket to isolate it from the confining oil. Then, two pieces of Vitton jacket were epoxied to the two ends of the specimen and the core holders were inserted into the Vitton jacket. Then, the connections between the specimen/coreholder and Vitton jacket were wire tightened to avoid any potential leakage of confining fluid into the specimen. The strain gauge was attached to the specimen to record the axial and radial deformation of the specimen. Finally, the sample was mounted on the base plug and inserted into the test vessel to perform the mechanical experiment (see Fig. 2a).

2.2.2. CO_2-enriched brine injection and preparation

The sandstone specimen was saturated with brine before conducting CO_2-enriched brine injection test. Then, the specimen was inserted into a Vitton jacket that covers the whole length of the sample. The upstream and downstream core holders were inserted into the two ends of the specimen. The steel wires were used to tighten up all the connection between the specimen/Vitton jacket and the core holders. At the end, the specimen was inserted into the test vessel and CO_2-enriched brine was injected from the upstream intensifier towards the downstream intensifier.

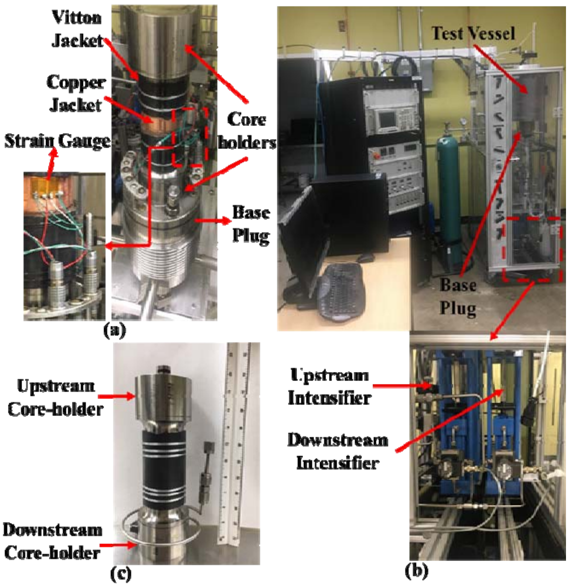


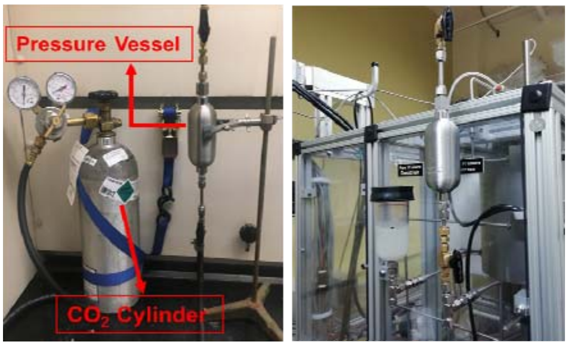
Fig. 2. Photos of sample preparation for (a) mechanical and (b) flow-through tests and (c) pore pressure intensifiers of AutoLab 1500.

The synthetic brine solution was prepared by mixing NaCl, KCl, $CaCl_2$, Na_2SO_4, $MgCl_2$, and $MgSO_4$. Table 1 represent the chemical composition of the synthetic brine solution that was used to prepare the CO_2-enrich brine solution. The salinity of the synthetic brine solution is 12.2 %, which simulate the typical salinity of the deep saline reservoir [8].

Table 1. The chemical composition of the brine solution.

Salt Type	Concentration (mg/liter)
NaCl	110438.2
$CaCl_2$	8675.4
Na_2SO_4	18.4
$MgCl_2$	813.5
$MgSO_4$	18.4
KCl	2245.5

To prepare the CO_2-enriched brine solution, CO_2 was injected into a 150 cc pressure vessel under the pressure of 1.1 MPa, where two-thirds of the vessel (~ 100 cc) was initially filled with the synthetic brine. Then, the injection process continued till the pH of the CO_2-enriched brine decreased to 3.2. Then, the pressure vessel was replaced with the existing reservoir to inject the CO_2-enriched brine into the specimen. Fig. 3 illustrates the details of CO_2-enriched brine preparation.



(a) (b)

Fig. 3. Photos showing (a) preparation of CO_2-enriched brine and (b) attaching the pressure vessel to Autolab 1500.

2.3. Experimental Details

2.3.1. Isotropic compression test

At the beginning of the mechanical testing, the rock specimen was loaded under isotropic condition (i.e. No DS was applied). The CP was increased in a stepwise fashion (5 MPa increments) from 0 to 30 MPa, which represent different reservoir condition to estimate the compressibility (i.e. bulk modulus) of the sandstone specimen under different isotropic conditions.

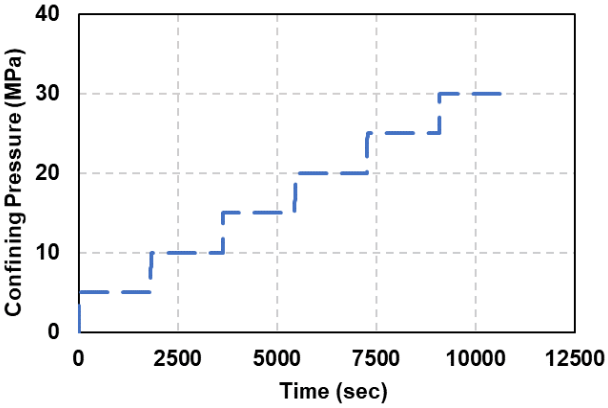


Fig. 4. Stress Path followed during isotropic compression.

2.3.2 Multi-stage elastic (MSE)

The MSE test is performed to investigate the elastic properties of sandstone specimen under different CP and DS levels. The MSE test can be considered as an alternative for single stage triaxial test since the variable response of sandstone specimen can be captured under different loading conditions [23-]. The elastic properties (Young's modulus, shear modulus, Poisson's ratio) of the specimen before and after injecting CO_2-enriched brine was determined at each loading/unloading stage. The stress path followed during the MSE test is illustrated in Fig. 5.

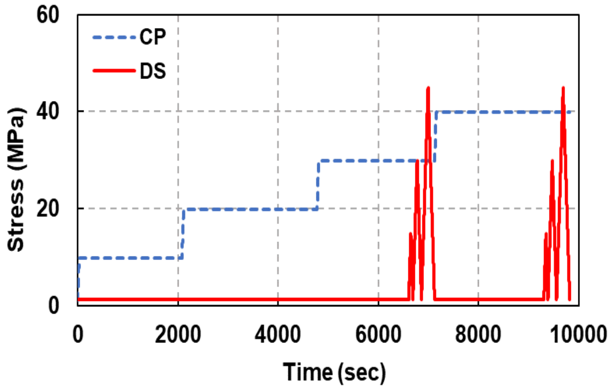


Fig. 5. Stress Path followed during MSE test.

2.3.3. CO_2-enriched brine injection

The CO_2-enriched brine was injected into the sandstone specimen for 3 consecutive days. A constant injection rate of 8.8×10^{-5} cc/sec was applied during the whole injection process. During the first day of injection, the CP was 15 MPa and PP was 7.5 MPa. Then, the CP and PP increased to 30 and 15 Mpa and then to 45 and 21.5 MPa during the second and the last day of CO_2-enriched brine injection, respectively. During the experiment, the effluent was collected to perform ICP-OES analysis.

3 Results and Discussion

3.1. Isotropic compression

Fig. 6 indicates the variation of bulk modulus before (i.e. pre-test) and after (i.e. post-test) injecting CO_2-enriched brine into the sandstone specimen. The post-test results revealed that injecting CO_2-enriched brine significantly reduced the compressibility of the sandstone specimen, where in average the bulk modulus of the specimen decreased by 22.7%.

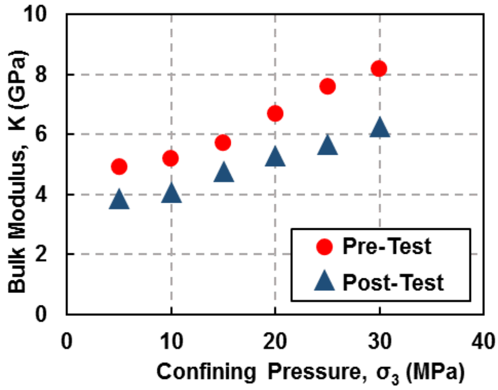


Fig. 6. Variation of bulk modulus at pre- and post-test condition.

3.2. MSE test

The stress-strain response of the sandstone specimen at pre- and post-test conditions is illustrated in Fig. 7. According to the results, the stress-strain behaviour of the sandstone specimen significantly affected upon injecting CO_2-enriched brine, where the higher rates of axial and radial deformation was observed at post-test condition. As can be seen in Fig. 7, the difference between the stress-strain response at pre- and post-test conditions becomes more significant when the CP level is increased from 30 to 40 MPa. The elastic moduli (Young's modulus (E), Poisson's ratio (ν), and shear modulus (G)) of the specimen was estimated before and after injecting CO_2-enrcihed brine (see Table 2 and 3). Estimation of elastic moduli revealed that the Young's and shear modulus significantly decreased, while the Poisson's ratio increased.

Table 2. The summary of the elastic moduli during MSE test (pre-test).

CP (MPa)	DS (MPa)	E (GPa)		ν (%)		G (GPa)	
		L*	UL*	L	UL	L	UL
30	0-15	26.7	28.4	16.8	17.6	27.8	29.0
	0-30	23.4	23.4	18.6	19.2	24.7	24.7
	0-45	23.0	23.1	19.6	20.6	24.1	24.1
40	0-15	29.2	29.6	18.2	17.8	NA	NA
	0-30	25.2	24.4	19.2	18.4	NA	NA
	0-45	24.1	23.9	19.6	19.4	NA	NA

L: Loading; UL: Unloading

Table 3. The summary of the elastic moduli during MSE test (post-test).

CP (MPa)	DS (MPa)	E (GPa)		ν (%)		G (GPa)	
		L*	UL*	L	UL	L	UL
30	0-15	21.1	22.6	27.0	24.1	21.4	23.0
	0-30	21.4	22.2	26.4	24.2	21.7	22.7
	0-45	21.2	21.8	24.0	25.0	21.8	22.3
40	0-15	21.9	23.4	24.1	23.2	NA	NA
	0-30	22.3	23.1	24.5	22.9	NA	NA
	0-45	21.9	22.7	22.9	23.5	NA	NA

L: Loading; UL: Unloading

3.3. Discussion

3.3.1. ICP-OES Analysis

The ICP-OES analysis was performed on the synthetic brine and the effluent collected upon injecting CO_2-enriched brine. Table 4 compares the concentration of cations in the synthetic brine and the effluent. The results indicated that the concentration of the Na, K, Ca, and Si in the effluent significantly increased. This can be an indication of mineral dissolution upon injecting CO_2-enriched. According to the mineralogy of Pecos sandstone, accumulation of Ca can be attributed to dissolution of calcite minerals.

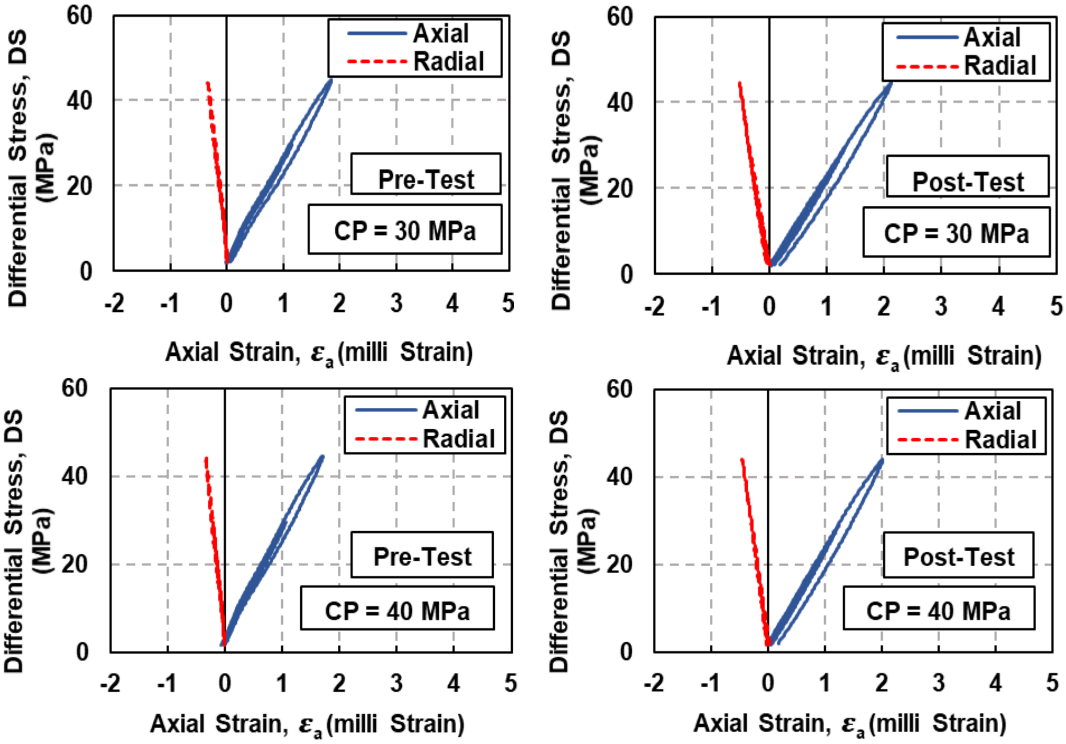


Fig. 7. The stress-strain response of the specimen during MSE test at pre- and post-test.

Also, the higher concentration of K and Si in the effluent solution can be due to dissolution of clay minerals such as anorthoclase and microcline. However, the concentration of Mg reduced in the effluent indicating that the magnesium precipitated in another phase (magnesite or magnesite or magnesium calcite).

Table 4. ICP-OES analysis results on effluent and influent.

Metal	Conc. in Brine (mg/L)	Conc. in Effluent (mg/L)	Change (mg/L)
Na	43248.8 ± 61.6	43975.4 ± 61.6	726.6
K	1134.9 ± 12.8	1227.3 ± 12.8	92.4
Mg	209.3 ± 8.2	124.5 ± 8.2	-64.8
Ca	3132.7 ± 13.3	3120.9 ± 13.3	211.3
Al	BDL*	BDL*	NA
Si	BDL*	34.2 ± 2.3	31.2

BDL: Below detection limit; NA: Not Applicable

3.3.2. Mechanical Analysis

The results of the isotropic compression and MSE test indicated that a mechanical degradation occurred due to CO_2-enriched brine injection. Isotropic compression test results revealed that the bulk modulus of the specimen significantly reduced upon injecting CO_2-enriched brine. Shi et al. [22] also observed that the bulk modulus of caly-rich rock remarkably decreased upon CO_2-enriched brine injection. The minimal hysteresis behavior and plastic deformation observed in stress-strain response of the rock can be attributed to the fact that the applied CP levels were high enough to close the existing microcracks. According to Amadei and Stephanson [26], the non-linear, hysteresis, and plastic behavior of the rocks, which are usually due to opening, closure, and slippage of the microcracks, often becomes less pronounced upon increasing the confining levels. However, compared to the pre-test results, a more pronounced hysteresis behavior and plastic deformation was observed in post-test stress-strain response of the rock, especially in axial direction.

Estimation of the elastic moduli indicated that the bulk, Young’s, and shear moduli of the specimen significantly decreased at post-test condition. Generally, increasing the CP level during the MSE test resulted in enhancing Young’s and shear modulus in pre- and post-test condition. However, the average reduction of Young’s modulus at CP of 40 MPa (i.e. 15.2%) was higher than CP of 30 MPa (i.e. 11%). Degradation of elastic properties and more pronounced non-linearities (i.e. more plastic deformation and hysteresis) in stress-strain response of the specimen after CO_2-enriched brine injection can be attributed to dissolution of cementing (i.e. calcite and clay) minerals. Rathnaweera et al. [15] and Lamy-Chappuis et al. [20] also observed that dissolution of cementing minerals resulted in a mechanical degradation due to weakening of the mineral grain bonding.

4 Conclusion

Evaluation of the elastic properties and stress-strain response of the rock at pre- and post-condition revealed a significant degradation in elastic properties. On average, under the CP of 30 and 40 MPa the average Young’s modulus of the specimen decreased by 11% and

15.2%, respectively. Also, the stress-strain response of the sandstone specimen indicated a more pronounced plastic deformation and hysteresis behaviour upon CO_2-enriched brine injection. This mechanical degradation can be attributed to the dissolution of cementing minerals upon injecting CO_2-enriched brine. Based on the results of this study, CO_2 injection can potentially lead to mechanical deterioration of the reservoir rock, which must be considered during the entire CO_2 storage program (i.e. designing the injection plan, injection operation, post-injection monitoring).

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