CCUS: 4441979

# A New Utilization of CO2 as Cushion Gas for Synergistic Geological Sequestration in Underground Gas Storage（UGS-CCS）

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This paper was prepared for presentation at the Carbon Capture, Utilization, and Storage conference held in The Woodlands, TX, 30 March – 01 April.



## Abstract

Natural gas underground gas storage (UGS) generally uses natural gas as the cushion gas, but the cost of cushion gas accounts for about 50% of the total investment in UGS, which greatly increases the construction and operating costs. The use of CO2 as a cushion gas can reduce the long-term backlog of natural gas investment on the one hand, and on the other hand, it can improve oil recovery and achieve geological storage of CO2. This innovative approach not only expands the $CO_2$ sequestration capability of gas storage facilities but also enhances the resource utilization value of $CO_2$, creating synergistic effects that achieve both economic and environmental benefits. The cushion gas replacement technology coupled with $CO_2$ sequestration can be implemented in three distinct phases: (1) during the construction phase, $CO_2$ is gradually injected to replace cushion gas, reducing initial investment while initiating carbon storage; (2) in the operational phase, $CO_2$ injection maintains reservoir pressure while facilitating continuous carbon sequestration; and (3) at the abandonment phase, complete displacement of residual natural gas with $CO_2$ achieves maximum carbon storage potential, transforming the depleted reservoir into a permanent carbon sink. This integrated solution presents a paradigm shift in underground gas storage operations by simultaneously addressing cost efficiency and climate change mitigation objectives.

## Introduction

Underground gas storage (UGS) plays a vital role in natural gas peak regulation and energy security, where cushion gas (25-75% of total inventory) serves as a permanent pressure buffer to ensure operational efficiency through cyclic expansion/compression during gas injection/withdrawal. While natural gas remains the conventional cushion gas choice, its significant capital costs1 (~30% of total UGS investment) and non-recoverable nature substantially impair project economics. Against growing global decarbonization pressures, this study proposes an innovative $CO_2$-based cushion gas solution that synergistically addresses cost reduction (through replacing expensive natural gas) and climate change mitigation (via geological $CO_2$ storage), presenting both theoretical and practical advancements for sustainable energy infrastructure development.

The utilization of inert gases as cushion gas presents operational challenges, particularly regarding potential mixing with natural gas that may compromise peak-shaving gas quality, reduce enthalpy values, and impact pipeline network stability. However, extensive research demonstrates the considerable advantages of inert gas alternatives, as evidenced by France's two decades of successful nitrogen cushion gas implementation2. Numerical simulations indicate that maintaining inert gas concentrations within 15-17.91% effectively prevents mixing with working gas3-6. $CO_2$ emerges as the most promising candidate due to its superior compressibility (2-3 times that of methane), cost-effectiveness, and environmental benefits. A technically viable solution involves implementing a "central natural gas injection - peripheral $CO_2$ injection" well pattern configuration combined with gas diffusion dynamics control, creating stable reservoir zoning that maintains necessary pressure while minimizing gas mixing risks. This approach offers significant potential for optimizing underground gas storage operations.

This paper systematically reviews the research progress on inert gas as cushion gas, investigates mixing mitigation strategies, and analyzes its economic viability and future development trends, aiming to provide theoretical references for the optimal design of gas storage facilities. The advancement of inert gas cushion technology promises to enhance the safety and operational lifespan of underground gas storage systems. With continued technological progress, inert gas applications are expected to play an increasingly significant role in gas storage optimization, offering broad prospects for future industry development and innovation in this field.

## Current Status of Cushion Gas in Underground Gas Storage

During the operation of underground gas storage (UGS), it is necessary to retain 25%-75% of the natural gas as cushion gas to maintain the required pressure for gas withdrawal, inhibit aquifer movement, prevent water intrusion, and ensure the stability of the storage facility7-8. For depleted oil/gas reservoirs and aquifer-based UGS, cushion gas typically accounts for 40%-75% of the total storage capacity, whereas for salt cavern UGS, it ranges between 25%-50%. When a storage facility is decommissioned, a significant portion of the cushion gas cannot be economically recovered with current technologies. The use of inert gases or industrial waste gases can reduce natural gas losses and lower capital expenditures9.

As early as 1972, France's Beynes UGS employed a mixed gas (60% hydrogen and carbon dioxide) as cushion gas, and subsequent injection-withdrawal operations confirmed that the mixed cushion gas had no adverse effect on the quality of the produced gas. Later, France implemented combustion byproducts (87.4% nitrogen and 11.2% $CO_2$) at the Saint-Clair-Sur-Epte aquifer UGS, low-calorific mixed gas at Germigny-Sous-Coulombs UGS, and nitrogen at Saint-Illers UGS (constituting 20% of the cushion gas). In all cases, the produced gas met calorific standards without contamination. The Saint-Clair-Sur-Epte UGS achieved notable economic benefits by using 20% inert gas ($N_2$ and $CO_2$) and 80% natural gas as cushion gas1,10.

In 1981, Denmark's feasibility study on the Tonder aquifer UGS demonstrated that replacing 10% of cushion gas with nitrogen did not compromise gas usability. In 1986, the U.S. developed a cushion gas system using inert gas, with theoretical studies at Hanson UGS (Texas Gas Transmission Company) showing no nitrogen detection in the produced gas. For salt cavern UGS, inert gases (e.g., nitrogen or industrial waste gases) are used as cushion gas, with specialized membrane containers isolating working gas to prevent mixing—a patented technology adopted in the U.S., Australia, Bulgaria, and eight European countries11.

International research and field applications confirm that partial substitution of cushion gas with inert gases effectively maintains reservoir pressure and reduces investment costs. When inert gas constitutes no more than 20% of the total cushion gas, it does not affect the quality of the produced gas.

Domestic researchers have conducted early-stage studies on using inert gases as cushion gas during the initial phases of UGS (Underground Gas Storage) development. Wang Xiyong et al.12 examined the feasibility and advantages of $CO_2$ as cushion gas based on the physical properties of $CO_2$ and $CH_4$, proposing through numerical methods that $CO_2$ exhibits superior compressibility near its critical pressure. Utilizing $CO_2$ as cushion gas could also enhance $CO_2$ recovery in gas reservoirs undergoing $CO_2$-enhanced gas recovery (EGR). Tan Yufei et al.6 analyzed the thermodynamic properties of $CO_2$, confirming its viability as cushion gas and identifying optimal thermodynamic conditions. Li Guotao et al.5 further supported $CO_2$ as a viable option through numerical simulations, though they emphasized the need for comprehensive technical and economic feasibility assessments.

Despite these theoretical studies, all operational UGS facilities in China currently use natural gas as cushion gas, with no field applications of inert gases reported to date. The country's 29 existing UGS facilities have a combined total storage capacity of 65.4 billion cubic meters (BCM), including 28.1 BCM of working gas and 37.3 BCM of cushion gas. The cushion-gas-to-total-capacity ratio ranges from 32% to 66%, averaging 57%.

**Feasibility Analysis of $CO_2$ as Cushion Gas with Integrated Geological Sequestration in UGS**

The selection of cushion gas for underground gas storage (UGS) requires two key characteristics: high compressibility to maximize storage capacity during injection and deliver sufficient drive energy during withdrawal, and significant viscosity contrast with natural gas to minimize mixing. When $CO_2$ exceeds its critical temperature (31.26°C) and pressure (7.3 MPa), it transitions into a supercritical state, exhibiting liquid-like density, gas-like viscosity, and exceptional compressibility.

The higher density of $CO_2$ compared to natural gas helps maintain reservoir pressure during UGS operations, while the density contrast promotes gravitational segregation, reducing mixing potential. Additionally, $CO_2$ viscosity increases with pressure and remains substantially higher than that of natural gas under typical storage conditions, further inhibiting intermixing. These properties—density, viscosity, and compressibility—collectively make $CO_2$ an ideal cushion gas, ensuring stable reservoir performance while maintaining distinct stratification from natural gas.

Injecting $CO_2$ into deeper zones of the reservoir while producing $CH_4$ from shallower intervals enhances production efficiency. This configuration mitigates $CO_2$ breakthrough and miscibility, allowing $CO_2$ to gradually fill the reservoir from the bottom upward, thereby improving both horizontal and vertical displacement efficiency.

The safety of $CO_2$ geological storage primarily hinges on leakage risk mitigation. Underground gas storage (UGS) site selection involves rigorous sealing integrity assessments to prevent natural gas migration, complemented by comprehensive monitoring systems. Consequently, $CO_2$ storage within UGS facilities offers effective leakage control. Before large-scale commercial deployment of $CO_2$ geological storage, critical operational aspects—including storage integrity, capacity optimization, monitoring protocols, risk assessment, and mitigation strategies—must be thoroughly validated.

Global CCS (Carbon Capture and Storage) pilot projects reveal significant cost barriers delaying widespread commercialization, despite technological maturation in developed nations (e.g., the U.S., Canada, the Netherlands, Germany). China remains in the early research phase. Naturally occurring $CO_2$ in hydrocarbon reservoirs and dedicated $CO_2$ storage formations demonstrates long-term stability, where $CO_2$ persists as a supercritical fluid or dissolves in oil/brine phases—confirming viable geological storage conditions. Environmentally sustainable and aligned with emission reduction goals, repurposing $CO_2$ as cushion gas in UGS represents a forward-looking strategy for synergistic energy storage and carbon management.

## Conclusions

The integration of $CO_2$ cushion gas replacement and geological storage in natural gas underground storage (UGS) facilities represents a crucial technological pathway for achieving carbon peak and carbon neutrality goals. With advancing technologies and enhanced international collaboration, this field is poised for rapid development. The substitution of conventional cushion gas with $CO_2$ not only expands the carbon sequestration capacity of UGS but also enhances its socioeconomic benefits, presenting significant potential for future applications. The synergistic technology of cushion gas replacement and $CO_2$ storage encompasses three key phases: (1) During UGS construction and operation, $CO_2$ is injected as cushion gas to maintain reservoir pressure while enabling concurrent $CO_2$ storage; (2) Upon UGS decommissioning, $CO_2$ completely displaces the remaining natural gas, achieving permanent geological $CO_2$ sequestration. This integrated approach transforms UGS into a dual-function infrastructure for energy storage and carbon management, aligning with global decarbonization strategies.

## References

Lekkala S R .Impact of injecting inert cushion gas into a gas storage reservoir[J].Dissertations & Theses - Gradworks, 2009.

Li, G., Song, G., Zhang, J. et al. 2008. Theoretical Study on Using $CO_2$ as Cushion Gas in Underground Gas Storage. Natural Gas Exploration and Development, (02): 61–63+68+81.

Sofregaz L F，Knudsen J E，Dong A S. Inert gas in tonder aquifer storage: a complete preliminary computer study. SPE: 16863，1987

Jiao, W., Wang, Z., Li, J. 2008. Numerical Simulation of Inert Gas as Cushion Gas in Aquifer Underground Storage. Journal of Harbin Institute of Technology, 40(12): 1949-1955.

Wang, B., Yan, X., Yang, X. 2013. Study on Injection-Production Migration Patterns of Inert Gas as Cushion Gas in Underground Natural Gas Storage. Science Technology and Engineering, 13(31): 9184-9189.

Tan, Y., Chen, J. 2001. Simulation Study on Mixing of Cushion Gas and Working Gas in Underground Natural Gas Storage. Journal of Harbin Institute of Technology, (04): 546-549.

Tan, Y., Cao, L., Lin, T. 2006. Feasibility Analysis of $CO_2$ as Cushion Gas in Underground Natural Gas Storage. Oil & Gas Storage and Transportation, (03): 12-14+61+8-9.

Cao, W., Liu, X. 2004. Application of Low-cost Inert Gas as Cushion Gas in Salt Cavern Storage. Natural Gas Industry, 24(09): 136-138+18.

Song, J., Liu, S., Li, Q. et al. 2007. Underground Gas Storage Technologies Abroad. Inner Mongolia Petrochemical Industry, (08): 209-212.

Laille J P, Molinard J E et al. Inert gas injection as part of the cushion of the underground storage of Saint-Clair-Sur-Epte, France, SPE 17740,1988

Dek M R. Natural gas underground storage: inventory and deliverability.1996

Wang, X., Huang, X., Wang, X. et al. 2005. Feasibility Study on Using $CO_2$ as Cushion Gas in Underground Gas Storage. Pipeline Technique and Equipment, (01): 22-24.

Sun, X., Zeng, F., Liu, H. 2012. $CO_2$ Geological Storage and Enhanced Natural Gas Recovery. Bulletin of Science and Technology, 28(10): 11-13+16. DOI:10.13774/j.cnki.kjtb.2012.10.002