Foundational Elements of Underground Gas Storage Practices

A U.S. and China Perspective

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Executive Summary

The Environmental Defense Fund developed this report on current conditions and practices of underground gas storage (UGS) in the United States and China with a forward-looking perspective on key elements needed to develop a more comprehensive UGS regulatory program. UGS is key to an effective and reliable gas supply providing operational flexibility to meet an ever-changing supply and demand, notably when supply may be curtailed due to natural or geopolitical reasons. Critical to UGS is a robust regulatory program addressing all phases of operation for the protection of environment, human health and safety.

The United States has a long history of UGS dating back to the early 1900s and over this time period has developed a mature regulatory framework and supporting technical references to guide permitting, design, construction, operations, and decommissioning (including regulatory oversight, and non-compliance enforcement actions). Good, comprehensive technical references include (but certainly are not limited to) American Petroleum Institute (API) Recommend Practices documents (specifically API RP 1170 and API RP 1171)[1, 2], Canadian Standards Association's (CSA) "Storage of Hydrocarbons in Underground Formations"[3] and the Interstate Oil and Gas Compact Commission and Ground Water Protection Council's "Underground Gas Storage Regulatory Considerations".[4]

In the U.S., regulatory requirements fall under both federal and state jurisdictions and although many of the regulatory programs have been in place for many years with improvements evolving over the past two decades, significant unplanned releases of stored gas into the environment have occurred as a result of facility failures, which had disastrous impacts on environment, public health and safety. Most recently, a blowout of a well in 2015 at the Aliso Canyon facility located in California resulted in 6,600 million cubic feet (MCF) (187 million cubic meters (MCM))[5] of natural gas released over 111 days and required the evacuation of over 8,000 households. The resultant natural gas release was the largest un-combusted leakage in U.S. history and roughly equivalent to the annual natural gas usage of 190,000 Los Angeles homes[6]. In response to the Aliso Canyon failure, significant regulatory revisions were initiated and in 2016, the Pipeline and Hazardous Materials Safety Administration (PHMSA), a U.S. federal agency, issued a nationwide interim final rule for UGS facilities with final rules announced in February

2020.[7] More recently a few states have revised their UGS rules or have plans to do so. California is one of those states, and in 2018 issued revised rules incorporating API RP 1170 and API 1171 with several leading management practices including greatly expanded requirements for risk management, emergency response planning, and robust testing and monitoring programs and protocols.

Comparing with the U.S., China is still a newcomer in UGS development. China's first UGS facility was built in 1969 though the first large-scale project did not occur until 1999.[8] Currently there are 27 UGS facilities[9] in China providing storage capacity of 14 bcm at the end of 2019, about 4.5% of the country's annual consumption.[10] However, plans are in place to significantly increase UGS capacity to 30bcm, about 6% of expected annual consumption by 2030, roughly doubling current capacity in just over 10 years.[11]

China's environmental regulations cover a wide range of items and issues important to UGS, and China also leads the world in a number of UGS technologies. However, as evidenced by recent events in the Unites States, a process of continual improvement of regulatory frameworks, technical guidance, operations, and regulatory oversight are critical to maintaining programs and processes that are up-to-date and reflect the latest thought on best practices.

This report presents key elements of a regulatory program, building upon the most recent California regulatory revisions that were driven by the Aliso Canyon incident, the adoption of PHMSA's final minimum uniform federal safety standards, technical and regulatory guidance (including API RPs, Canadian Standards, GWPC report), as well as recommendations by both US and Chinese experts on this topic. The key elements address:

- Permitting and permitting approval (including on-going inspections and permit review as part of facility operation);
- Facility siting;
- Risk management planning;
- Emergency response planning;
- Data collection and records management;
- Technical requirements for construction and operation;
- Leak reporting (including appropriate level of root case analysis of facility of operation failure);
- Integrity testing and monitoring; and
- Decommissioning.

Incorporated in all the key elements is management of change - a leading management practice directed at making sure environmental, health and safety risks are addressed whenever changes occur in management organization or facility operation. Proper protocols for management of change are essential to ensure any changes do not increase existing risks and that new risks are identified, addressed, implemented timely and communicated to all stakeholders.

Key regulatory elements presented in this report provide a basis for developing a robust UGS regulatory program. However, there are areas that can be further developed, particularly in consideration of specific siting and storage conditions. This report identifies the need for further detailed analysis of U.S. and China UGS permitting requirements to pinpoint areas of improvement of the respective country's regulatory framework.

1.0 Introduction

Critical to a reliable supply of natural gas is storage that provides a buffer between fluctuating supply and end use. Sourcing of natural gas originating from either production facilities or importing from other production areas will not normally be at a constant rate. Additionally (and Likely more significantly), the differences between natural gas consumption and supply vary based on daily and seasonal needs by end users as well as potentially more drastic fluctuations caused by natural disasters or unforeseen disruption in a supply source (including geopolitical incidents). UGS provides a buttress for both operational flexibility and allows for the proper design and operation of critical gas transportation infrastructure (including pipelines).

There are three primary types of UGS: depleted hydrocarbon reservoirs, aquifers, and salt caverns. The majority of UGS occurs in depleted hydrocarbon reservoirs. These formations exhibit relatively high permeability and porosity and by their very nature (since they originally housed hydrocarbon reserves) offer a high degree of storage integrity. The existing wells in the reservoir can be converted for gas storage use and additional wells drilled to add to the reservoir gas injection and withdrawal capacity as required.

Aquifer storage is similar to depleted hydrocarbon reservoirs in terms of the nature of the porous rock media used to contain the gas and the methodology for assessing the reservoir. However, the geological characteristics of the aquifer formations are not as well-known as with hydrocarbon reserves requiring additional investigations to determine suitability prior to development.

Salt formations, typically in the form of salt beds or salt domes, can be well suited for UGS. Storage caverns are developed in these salt deposits using water to dissolve and remove a portion of the salt deposits leaving a large open volume (essentially a cavern).

Natural gas figures to play an increasingly significant role in China's strategy to combat air and climate pollution. The percentage of natural gas is expected to increase from current 7% to 15% in the country's primary energy mix by 2030.[12] A quarter of the growth in global gas demand will come from China in the next 20 years.[13] Currently, imported gas accounts for 45% of the country's gas supply.[14] However, China's existing underground gas storage is only 4.5%[15] of the total annual consumption compared to approximately 18%[16] for the U.S. and an international average of 10% – 12%.[17] To balance gas supply and address supply bottlenecks (both geographical and seasonal), China is initiating a new wave of UGS projects. In April 2020, the

Five agencies including the National Development and Reform Commission and the Ministry of Finance jointly issued the "Implementing Opinion on Accelerating Natural Gas Storage Capacity Building", calling for speed-up of gas storage infrastructure construction.[18] Compared with the United States, which has some of the world's oldest and largest UGS facilities, China is a relatively newcomer to large-scale UGS with only about 20 years of experience.

While guidance on UGS design and construction processes are mature and widely available, deviation from sound practices due to poor operating procedures or lax oversight will eventually result in serious environmental, safety, and health effects as evidenced by the recent Aliso Canyon failure which triggered significant amendment of UGS regulations at both the state (California) and federal levels. China has a perfect window of opportunity to develop a world class UGS program, drawing on both engineering and technical design and operational resources as well as well as experience and expertise from both the U.S. and China.

A number of risks to the environment, safety, and human health can originate from surface and subsurface operations including the following (some overlap in both cause and affect).

Environmental Risks

- Loss of storage facility integrity (release of natural gas to subsurface formations and the atmosphere),
- Mechanical failures of surface infrastructure resulting in leaks and spills to the environment, and
- Damage to surface and subsurface infrastructure due to natural disasters.

Safety and Human Health Risks

- Mechanical failure of surface infrastructure resulting in release of natural gas and resultant exposure to both workers and communities;
- Well blowouts, fires, explosions;
- Medical emergencies; and
- Noise and light pollution.

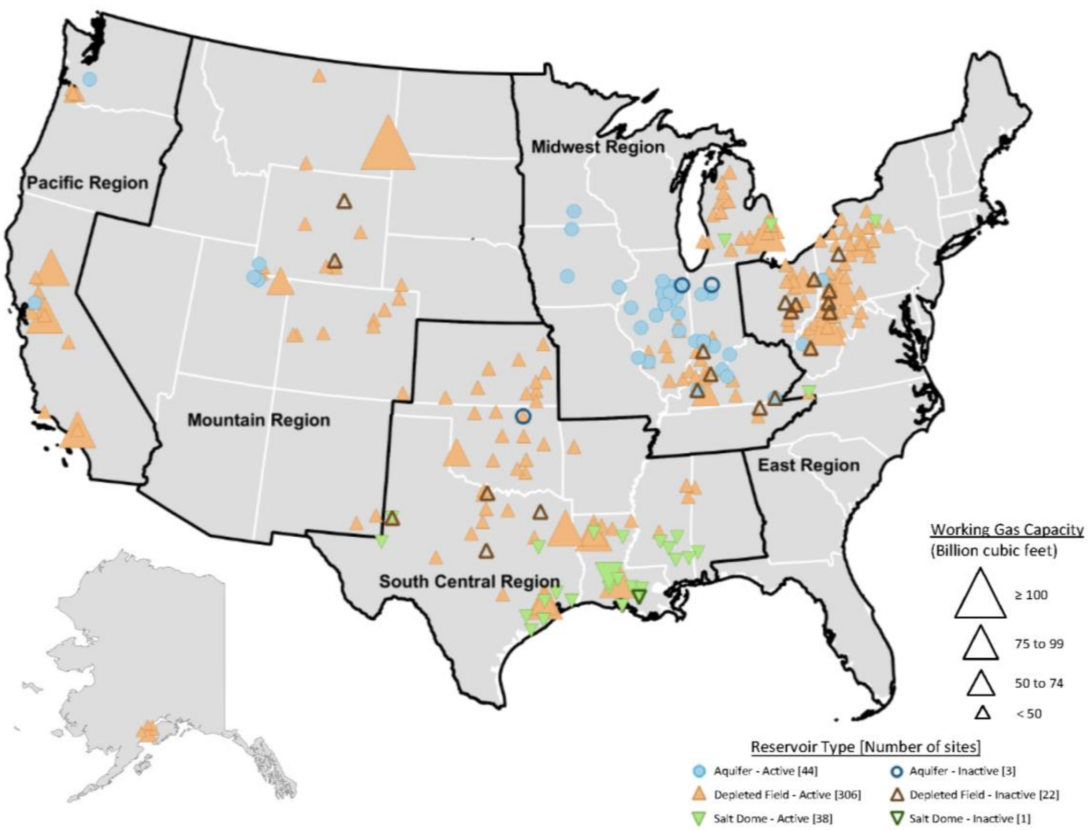
Facility design, construction, and operation must consider these risks, including planning to anticipate and minimize occurrence and severity, as well as response actions to minimize and recover from impacts. This requires more than just technical and engineering design and controls, but also health, safety and environment management processes (including management of change), risk management planning and emergency response planning. These are all addressed in the following sections.

2.0 Underground Gas Storage in the United States

The first UGS facility in the U.S. began operation in 1916. Since that time, UGS has expanded to over 400 facilities spread across 31 states. The vast majority of UGS occurs in depleted gas reservoirs (328 facilities accounting for approximately 80% of the working storage capacity) with the remaining storage capacity in aquifers and salt caverns.[19]

Figure 1 shows UGS facilities in the U.S. Storage in depleted hydrocarbon reservoirs are located throughout the U.S., while aquifer storage is more prevalent in the Midwest and salt cavern storage is primarily in the Gulf Coast region. Based on 2017 data, total working UGS capacity in the U.S. represented approximately 18% of total annual U.S. natural gas consumption.[20]

Figure 1: U.S. Underground Natural Gas Storage Facility, by Type (Dec. 2017)



Map Source：EIA, Form EIA－191, "Monthly Underground Gas Storage Report." [21]

Based on recent U.S. Energy Information Administration (EIA) data (2017)[22], the numbers of UGS facilities and storage capacity by type are summarized below.

Facility Type	Number of Facilities	Working Storage Capacity	
		Million Cubic Feet (MCF)	*100 Million Cubic Meters*
Depleted Reserves	328	3,937,382	1,115
Aquifers	47	413,475	117
Salt Caverns	39	500,596	142
Total	**414**	**4,851,453**	**1,374**

Although UGS has been utilized in the U.S. for over 100 years with a long history of technical and operational experience, failures have occurred. A number of these incidents resulted in significant impacts to not only operations and worker health and safety but also surrounding communities and the environment.

In 2001, a salt cavern facility failure in Kansas led to explosions in the nearby town of Hutchinson due to natural gas migrating and accumulating underground and into abandoned wells. The cause was a wellbore failure with 143 MCF (4 MCM) of natural gas being released before response actions, consisting of pressure relief, plugging abandoned wells, and successfully re-establishing the storage integrity of the salt cavern, were performed.[23]

In 2004, a salt cavern UGS facility in Texas experienced a catastrophic release of natural gas that ignited at the wellhead. The cause was the separation of the production casing inside the salt cavern, a breach of above-ground brine piping, and a leak between the master valve and emergency shut-off at the wellhead. It took a little over six days for the fire to self-extinguish fire and have replacement valves installed. This failure resulted in a release of 6,000 MCF (170 MCM) of natural gas, mostly as combusted methane as a result of the initial explosion and resulting fire.[24]

A very recent and significant failure of a UGS facility utilizing depleted gas reserve occurred in 2015 with the blowout of a well at the Aliso Canyon facility in California. This failure ended up being the largest un-combusted methane leak in U.S. history, taking 111 days to plug the failed well, releasing 6,600 MCF (187 MCM)[25] of natural gas, and requiring the evacuation of over 8,000 households. The technical cause was outside surface corrosion of a 7-inch production casing string on one of the over 100 operating wells at the facility. A detailed root cause analysis study was undertaken to better understand all factors that led to this failure and several contributing operational issues were identified including lack of systematic risk management, poor emergency response, lack of blowout contingency plans, historical inappropriate management response to repeated red flags with respect to wellbore integrity and inadequate real-time monitoring.

U.S. UGS Regulation and Recent Developments

Regulatory requirements applicable to UGS fall under both federal and state jurisdiction and have been evolving considerably over the past two decades. On the federal level, the Federal Energy Regulatory Commission (FERC), Pipeline and Hazardous Material Safety Administration (PHMSA, a part of the Department of Transportation), and Environmental Protection Agency (EPA) have regulatory jurisdiction. FERC has authority over market aspects of UGS and PHMSA has operational and safety authority. EPA has jurisdiction over environmental aspects associated with natural gas releases to the air, soil, and water (surface and groundwater). States have authority over intrastate UGS and can implement their own rules for those facilities as long as they are more stringent and compatible with federal minimum standards.

The Energy Policy Act of 2005[26] assigned FERC market authority over storage of natural gas, though not operational and safety authority. In exercising this authority, FERC may authorize a natural gas company to provide storage and storage-related services at market-based rates for new storage capacity placed into service after the date of enactment of this legislation.

Operational and safety considerations related to the interstate transportation and related storage of hydrocarbons has traditionally fallen under both the jurisdiction of the individual states and of the U.S. Department of Transportation, specifically PHMSA. A 2010 court ruling[27] by a U.S. District Court addressed the potential jurisdictional conflict between states (intrastate facilities) and the federal government (interstate facilities) found that Congress had conveyed exclusive power to regulate interstate gas storage facilities to FERC and PHMSA.[28] In 2016, PHMSA was directed to develop safety standards relating to UGS as part of the Pipeline and Enhancing Safety Act of 2016 (PIPES Act).[29] Prior to that time, advisory bulletins directed operators to consult industry guidance and state regulations. Additionally, the PIPES Act provides that the State authorities may adopt additional or more stringent safety regulations for intrastate UGS facilities as long as they are compatible with the federal minimum standards.[30]

In 2016 PHMSA issued an Interim Final Rule (IFR), and in January 2020 announced the final rules,[31] establishing minimum uniform federal safety regulations for UGS including subjecting facilities to inspection by PHMSA or a PHMSA certified state entity. As part of annual certification/agreements with PHMSA, state entities will inspect and enforce federal UGS regulations for interstate and intrastate facilities. Without certification from PHMSA, there would be dual administration of state and federal rules for intrastate facilities. The bulk of the IFR, and now issued as final rules, consists of two API Recommended Practices (RP) incorporated by reference.

- API RP 1170 – "Design and Operation of Solution-mined Salt Caverns used in Natural Gas Storage" (September 2015)
- API RP 1171 – "Functional Integrity of Natural Gas Storage in Depleted Hydrocarbon Reservoirs and Aquifer Reservoirs" (July 2015)

In the same timeframe as the issuance of the IFR, states like California took on efforts to review their respective UGS rules and regulations. With the issuance of PHMSA UGS final rules, states and the federal government now effectively have joint authority of UGS facilities. Ownership of substantive authority depends on whether facilities are classified as intrastate or interstate. As previously mentioned, federal rules apply to interstate facilities though states can be certified to act on behalf of PHMSA but states cannot impose additional rules beyond federal ones. For intrastate facilities, states can implement their own rules that are equal to or more stringent than federal standards and can certify with PHMSA to coordinate regulation of such facilities between themselves and PHMSA.

Many states have regulatory programs addressing UGS facilities with a focus on well integrity issues, particularly in states with a history of oil and gas development. Following more public attention to issues resulting from UGS facility failures and concurrent with recent enhancement of federal regulations, states are reviewing their existing UGS-related rules and considering both more definitive stand-alone UGS rules as well as strengthening existing rules.

California is an example of one state that undertook UGS rule revisions following the Aliso Canyon failure. California's Geologic Energy Management Division (formerly known as the Division of Oil, Gas, and Geothermal Resources) recently finalized new comprehensive rules that are serving as a model for some states in the process of updating their gas storage programs.[32] In addition to following the PHMSA final rules , by incorporating the API RP 1170 and 1171, there were a number of leading practices that were also made a part of the new rules including requirements for risk management, emergency response planning, and robust testing and monitoring programs and protocols. Both API RPs are laced with excellent guidance on risk management, emergency response planning as well as testing and monitoring protocols.

Although the recent PHMSA and California UGS-related rule updates are a positive effort in development of better regulatory frameworks, there remain areas where these programs can be further strengthened. A process of continual improvement is an important aspect of any management program including a regulatory program; therefore, the recent rule updates should be considered a good start on a process of continued evaluation and enhancement.

Other regulatory programs on both the federal and state levels address the release of constituents of concern (methane, VOCs, air toxics, etc.) to the environment including air, groundwater, surface water, soil and sediment. As previously mentioned, EPA has jurisdiction over releases; however, similar state programs could also apply either as a delegated authority to administer a federal program or through direct implementation of the additional and separate state regulatory requirements (with guarantee of equivalency).

In the U.S., methane is considered an air pollutant and regulated under the Clean Air Act. Such emissions take place along the entire oil and gas supply chain to some extent; emissions sources could include activities such as drilling, completion, liquid unloading, processing, storage and transmission, and distribution; infrastructure such as pipelines and storage facilities; and production equipment such as pneumatic controllers, compressors, separators and dehydrators.

Starting in 2009, the oil and gas sector is required to submit methane emissions annual reporting to the EPA under the Greenhouse Gas Reporting Program (GHGRP).[33] The requirements apply to facilities with annual emissions of 25,000 metric tons of CO_2-equivalent or above in the following oil and gas segments: onshore and offshore production, petroleum refining, gathering and boosting, natural gas processing, natural gas transmission, natural gas storage, natural gas distribution, liquefied natural gas (LNG) import and export, and LNG storage. In 2016, the EPA adopted regulations to directly regulate methane (instead of addressing it indirectly through VOCs regulation) from some new and modified oil and gas facilities covering hydraulically fractured oil and gas wells, compressors, pneumatic controllers, pumps, crude oil, and condensate and produced water storage tanks.[34]

From the standpoint of potential impacts to soil and water and subsequent remediation of impacted media, federal programs under the Clean Water Act, Safe Drinking Water Act, and

Resource Conservation and Recovery Act also apply to UGS projects. Again, states could be delegated to administer a federal program or directly implement additional and separate and often more stringent state regulations.

3.0 Current U.S. Underground Gas Storage Technical and Regulatory Guidance

Globally, UGS construction and operational technologies are mature and existing technical and regulatory guidance exists to assist industry and regulators design and operate UGS facilities prudently. As noted in the previous section, recent U.S. federal rules specifically reference two API Recommended Practices; API RP 1170 and 1171. Additionally, Canadian Standards Association's (CSA) "Storage of Hydrocarbons in Underground Formations") and the Interstate Oil and Gas Compact Commission and Ground Water Protection Council's "Underground Gas Storage Regulatory Considerations" offer excellent resources. A summary of these documents is presented in this section. It is important to note that while the technical and operational aspects are relatively straightforward and if followed will result in mechanically competent facilities, failures that present significant issues are quite often the result of inadequate corporate leadership, risk management, emergency response planning and Health, Safety and Environment (HSE) management systems. All of these aspects are critical to both operational and regulatory UGS programs.

Two documents developed following the Aliso Canyon failure also provide excellent reference material related to UGS facility design and operation, and evaluation and response following a process or facility failure. "Ensuring Safe and Reliable Underground Natural Gas Storage"[35] published in October 2016 is the final report prepared by a Federal Task Force formed by the Department of Energy and Department of Transportation. The report made recommendations on ways to reduce the likelihood of leaks from UGS facilities. A root cause analysis report was published in May 2019 presenting the results of a detailed root cause failure investigation and evaluation of the Aliso Canyon incident.[36]

The following section provides a summary of the four above-referenced key guidance documents for operators and regulators of UGS.

API RP 1170 – Design and Operation of Solution-mined Salt Caverns Used for Natural Gas Storage

This document presents recommendations for solution-mined salt cavern facilities including the following major steps:

- Locating salt structures suitable for cavern development
- Determining gas storage capabilities and flow rate capabilities
- Determining project schedule including in-service dates
- Designing, drilling, and equipping the cavern well
- Designing, drilling, and equipping water supply wells, circulating pumps, and brine disposal wells and facilities
- Designing, solution mining, testing, and placing the cavern into service
- Operating and maintaining the cavern well and cavern to ensure functional integrity

Specific technical practices are detailed including:

- Mechanical integrity testing
- Geologic and geomechanical evaluations
- Well design including wellhead design to both contain the stored gas and allow controlled flow into and out of the cavern system
- Drilling operations
- Cavern solution mining
- Gas storage operations
- Cavern integrity monitoring
- Cavern abandonment

In this document, Chapter 10 and Annex B details integrity monitoring methods for salt cavern systems.

API RP 1171 – Functional Integrity of Natural Gas Storage in Depleted Hydrocarbon Reservoirs and Aquifer Reservoirs

This document "applies to natural gas storage in depleted oil and gas reservoirs and focuses on storage well, reservoir, and fluids management for functional integrity in design, construction, operation, monitoring, maintenance, and documentation practices." The scope of this recommended practice does not include pipelines, gas conditioning and liquid handling, compressors, and ancillary facilities associated with storage.

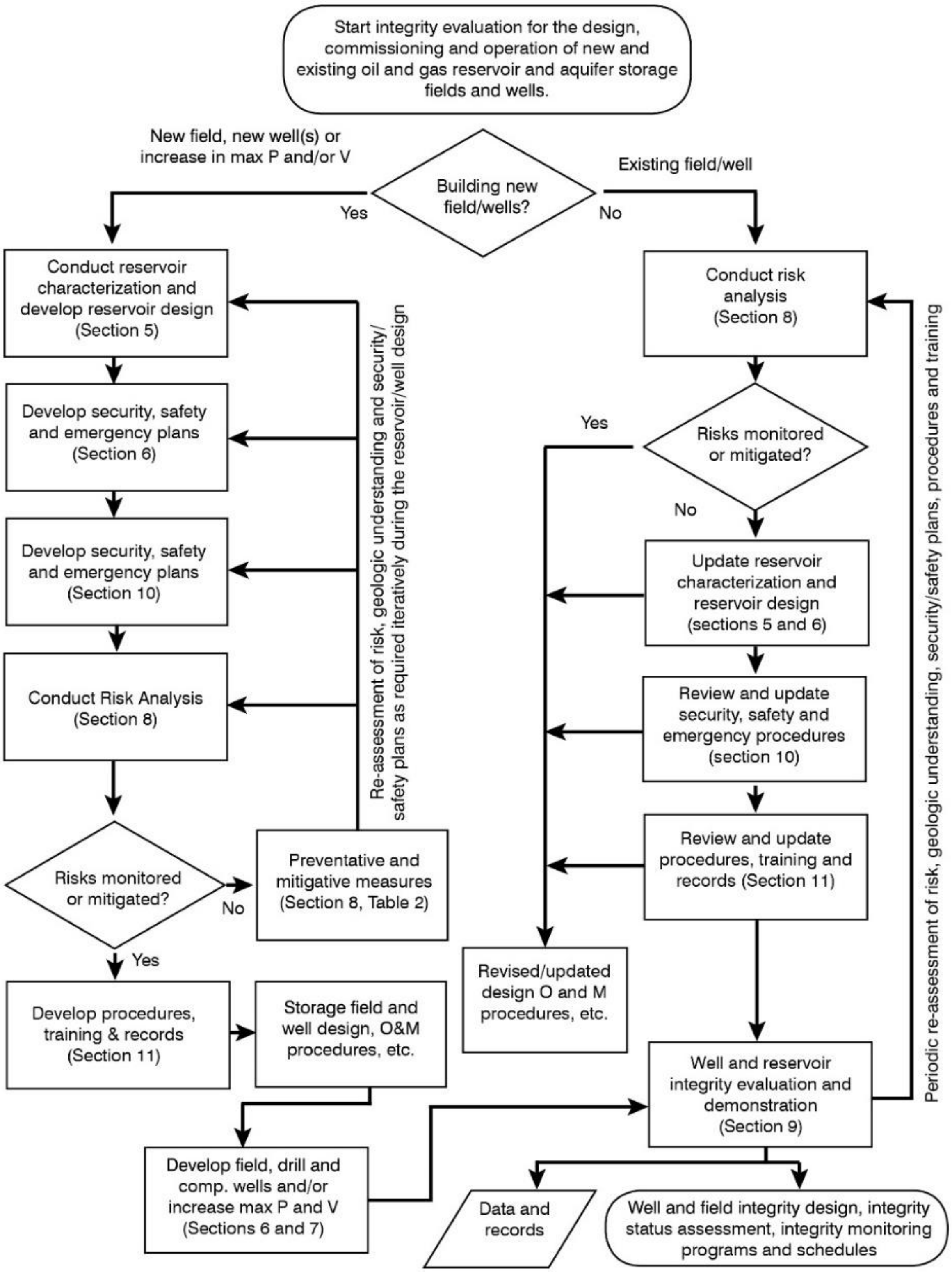
Storage in depleted hydrocarbon reservoirs offers distinct advantages over the other two methods (salt caverns or aquifers) since there is a higher confidence that reservoir storage integrity has been demonstrated. However, the hydrocarbon reservoir integrity has not necessarily been subjected to the increased operational pressures or the repeated cycling pressures that will occur as part of gas storage operations.

Major sections of this document are:

- Functional integrity in the design of reservoirs;
- Functional integrity in the design and construction of wells;
- Functional integrity of reservoirs and wells under maximum reservoir pressure and inventory;
- Risk management;
- Integrity demonstration, verification and monitoring practices
- Site security and safety, site inspections, and emergency preparedness and response; and
- Procedures and training.

A flowchart is presented on the process and documentation for design, commissioning, and operation of new and existing depleted hydrocarbon and aquifer storage fields and wells. This flowchart is reproduced in the Figure 2.

Figure 2: Flow Chart of Document Sections



Chapter 8 of this recommended practice discussed risk management and development of a comprehensive risk management plan. By reference of this document in PHMSA's and California's recently enacted UGS rules, the critical role of risk management in more comprehensive UGS rules and guidance is formally acknowledged. As part of the discussion on risk management, Chapter 8 also includes information detailing potential threats and consequences as well as preventative and mitigative programs.

Other topics to highlight are "emergency preparedness and response" and "management of change"; both addressed in Chapter 11 – "Procedures and Training."

Canadian Standards Association (CSA Group) Storage of Hydrocarbons in Underground Formations (Z341.1-14)

This document "sets out minimum requirements for the design, construction, operation, maintenance, abandonment, and safety of hydrocarbon storage systems" in "naturally formed geologic reservoirs and solution-mined salt caverns" (covers both depleted hydrocarbon reservoirs and aquifers).

Major elements addressed are:

- Materials (including that associated with well construction and operation as well as safety equipment);
- Well completion and conversion;
- Location of underground storage facilities;
- Design and development;
- Development and construction;
- Surface facilities (including emergency shutdown valves);
- Operations and maintenance;
- Monitoring and measurement;
- Safety; and
- Plugging, abandonment and site restoration.

This document includes technical guidance in annexes including:

- Mechanical integrity testing of salt cavern storage; and
- Risk assessment.

Risk Assessment is addressed in both the body of the guidance text and in annexes. Under "Design and Development, Risk Assessment", it states a number of items an operator shall do to establish a risk assessment process, perform baseline risk assessment, evaluate severity of identified risks, review and update the risk assessment, and retain records for a set period of time (15 years) after the decommissioning of the facility.

Further under "Operations and Maintenance" it states that an emergency response plan must be established, and this plan must include:

- Procedures for the safe control and shutdown of the facility, or parts of the facility, in the event of a failure or other emergency, as well as safety procedures for personnel at emergency sites;
- Testing and updating of the plan annually with results documented and records kept on site for five years; and
- Demonstration of operator familiarity with the plan.

Annexes provide specifics regarding risk assessment including scope, definitions, concepts (including risk analysis, risk evaluation, and measure of risk), process, evaluation, and documentation.

Ground Water Protection Council Underground Gas Storage Regulatory Considerations

In 2017, the Ground Water Protection Council issued a report titled "Underground Gas Storage Regulatory Considerations." This report provides background on UGS in the U.S., the federal and state regulatory framework including state permitting considerations and technical and operational guidance. Important to note is that the report follows the Aliso Canyon incident and subsequent PHMSA rule updates but predates more recent state UGS rule revisions in California and Oklahoma. At the time of the writing of this report, two additional states, Illinois and Indiana have initiated UGS rule revisions.

Within the state permitting discussion, areas of focus are:

- Geologic site characterization;
- Engineering review;
- Area review;
- Siting and spacing considerations;

- Operational requirements near sensitive areas; and
- Drilling through storage reservoir (specifics provided between reservoir storage type and cavern storage type).

From the standpoint of technical aspects, specific elements include:

- Well drilling, construction, and conversion;
- Well integrity testing;
- Reservoir integrity;
- Injection and withdrawal well operations and maintenance;
- Monitoring and observation wells;
- Wellhead and surface facilities; and
- Temporary abandonment, well closure, and restoration.

It is noteworthy that significant discussion (entire and separate sections) is presented about risk management and emergency response planning. These components are regarded in the U.S. as critically important and California devoted significant energy to bolster these issues in their new regulations.

Risk management is a dynamic, ongoing process requiring periodic updates and undertaking to assess and make appropriate risk reduction measures for threats and hazards associated with UGS operations. Major issues addressed in risk management efforts include:

- Potential threats and hazards to human health, safety, and the environment;
- Assessment and appropriate ranking of potential threats and hazards to human health, safety, and the environment;
- Potential threats and hazards to a storage facility that can affect well and reservoir integrity and performance;
- Preventative and mitigating measures to monitor and/or reduce risk; and
- Contingency provisions (e.g. emergency response plans – addressed further below) to guide the response to unplanned or emergency events (note this is addressed in more detail in API RPs 1170 and 1171).

Integral into risk management is risks reduction and a widely accepted metric to assess that risk reduction is appropriate to a level that is "as low as reasonably practicable" (ALARP).[37] This is a process of identifying risk reduction actions in a manner that demonstrates through reasoned and supporting arguments that there are no other practicable options that could reasonably be adopted to further reduce risks.

Emergency response planning, although related to risk management, is a separate effort with the goal of protecting life, property, and the environment. An emergency response plan is designed to help prevent and mitigate impacts as a result of emergency situations. The emergency response plan preparation process is dynamic and ongoing and involves multiple stakeholders (including first responders, regulators, internal staff and leadership, media, and community representatives).

At a high level, emergency response planning includes and is dependent on the following:

1. Total commitment of leadership and staff with a clear purpose and scope, expressed in appropriate policies, processes and procedures;
2. Identification of needed resources, response team organization, roles and responsibilities, and comprehensive internal and external communication systems;
3. Planning that includes goals, objectives, an incident management system, risk assessment and comprehensive hazard identification;
4. Coordination of response actions with government or other emergency response entities;
5. Development and implementation of a plan that has clear procedures, recordkeeping, incident management protocols, and incident termination/recovery steps; and
6. Comprehensive training and education programs aimed at training and educating personnel to consistently display competency in executing the plan.

Related to the last bullet, all exercises and drills should test the emergency response plan effectiveness with lessons learned and corrective actions implemented. Integrating all interested parties/agencies and incorporating their input is vital for a successful plan.

4.0 Underground Gas Storage in China

Natural gas demand in China has undergone rapid growth as the country replaces high-polluting coal with cleaner burning natural gas to address pressing air pollution challenges. Natural gas supply in China is now met by a number of sources including importation (via pipeline or liquefied natural gas tanker) and expansion of domestic production.

China's natural gas consumption sees an annual growth of 17.5% in 2018, reaching 280 BCM (9,888 CMF).[38] By 2040, China's natural gas demand is projected to more than double, an increase larger than the rest of developing Asia combined.[39] China overtook Japan as the world's largest natural gas importer in 2018.[40] Over 45 percent of China's natural gas demand is met by imports,[41] concentrating supply points in border and port areas. About 40 percent of the imported gas comes from pipeline, with the rest 60 percent supplied by LNG.[42]

At the same time, China's domestic gas consumers have become increasingly diversified in both users and location, creating challenges to meet demand during high use periods.[43] Prior to 2000, chemical and industrial sectors accounted for more than 80 percent of gas use.[44] Today, over 50 percent of gas is used by power and residential/commercial sectors, and the trend continues upward.[45] This shift results in rising seasonal supply/demand imbalances, which highlight the need for a more substantial gas storage and transportation network. The distances between natural gas sources (both imports and domestic production) and increasingly numerous and diverse users present additional challenges to both siting of gas storage facilities and pipeline transport to and from these facilities.

China's UGS development is still at a relatively early stage. Though the first UGS site in China was built in 1969, large-scale storage projects did not occur until 1999 after the completion of China's first long-distance gas pipeline that transported gas from Shaanxi province to Beijing.[46] The associated UGS development played an important role in addressing seasonable demand fluctuation in the capital region. Currently, there are 27 underground storage facilities in China (compared to around 400 in the United States). The China National Petroleum Corporation (CNPC) manages 23 facilitates, the China Petroleum and Chemical Corporation (Sinopec) operates three, and Towngas (a city gas distributor) owns one.[47] At the end of 2019, China's storage capacity could only cover slightly over 4.5% of the country's annual consumption,[48] far below the international average of 10-12 percent. [49]

To narrow the gap, the government took a series of measures to promote open access and interconnectivity of natural gas infrastructure such as de-bundling of transmission and storage prices, launch of a national oil and gas pipeline company, and target-setting for storage expansion. By 2020, national oil companies are required to have storage capacity equivalent to 10 % of their annual contracted sales, city distributors' storage must be able to meet 5% of their supplies, and local governments must ensure three-day storage for their jurisdictions.[50] In 2018, the national working gas storage capacity was 9.3 BCM (328 BCF).[51] The goal is to reach 14.8 BCM (523 BCF) by 2020, and to 35 BCM (1,236 BCF) by 2030.[52] In response to these signals, both CNPC and Sinopec are accelerating UGS planning and construction and are building large-scale underground facilities, at least doubling the current facilities in only 10 years. CNPC plans to build 23 additional facilities during the 14th Five Year Plan (2021-2025) and establish six regional UGS centers (northeast, northern China, northwest, southwest, central-west and central-east).[53] Sinopec plans to build the country's largest UGS cluster in central China.[54]

In ramping up its UGS infrastructure to manage the increasing use of natural gas in all sectors of the economy, China faces a number of logistical and engineering challenges, including:

- Geographic distance between sources of natural gas (domestic production and imports) and population centers and other user locations;
- Mandated rapid increase of storage volumes that requires relatively quick decisions to be made on location, storage volumes at specific locations, and completion of design, construction, and operations; and
- Challenging geological conditions.

Most of the depleted oil and gas production fields that could be repurposed for gas storage are in the northeast, central and west regions. But market demand is greatest along the eastern seaboard, where most underground formations are salt caverns and aquifers and are challenging for gas storage.[55]

Currently most UGS in China occurs in depleted oil and gas fields (24 of the current 27 storage facilities). The majority of these oil and gas fields are of low permeability, with depths typically below 2,500 meters with some exceeding 4,500 meters. In comparison, 95% of the world's UGS facilities are shallower than 2,500 meters.[56] Moreover, the depths at the potential salt cavern facilities are generally in formations 500 meters deeper than the typical cavern UGS.[57] Generally speaking, deeper cavern UGS is more expensive and technically riskier than shallower cavern UGS.

China Underground Gas Storage Environmental Management

China UGS facilities are governed by a of environmental and safety laws, regulations and technical specifications.

On the national level, the EIA and operations of UGSs are governed by the following major statutes concerning the protection of environment (air, water, soil and noise), ecology, farmland, and wildlife as well as energy conservation and clean production.[58]

1. Environment Protection Law (revised 4/24/2014);
2. Law on the Prevention and Control of Atmospheric Pollution (revised 10/26/2018);
3. Law on the Prevention and Control of Water Pollution (revised 6/27/2017);
4. Law on the Prevention and Control of Soil Contamination (revised 1/01/2019);
5. Law on the Prevention and Control of Solid Waste Pollution (revised 11/07/2016);
6. Law on the Prevention and Control of Ambient Noise Pollution (revised 12/29/2018);
7. Environmental Impact Assessment Law (revised 12/29/2018);
8. Water and Soil Conservation Law (effective 3/01/2011);
9. Land Management Law (effective 8/28/2004);
10. Water Law (revised 7/02/2016);
11. Clean Production Promotion Law (effective 7/01/2012);
12. Energy Conservation Law (revised 7/02/2016);
13. Circular Economy Promotion Law (revised 10/26/2018);
14. Forestry Law (Revised 8/27/2009);
15. Wildlife Protection Law (revised 10/26/2018)
16. Oil and Gas Pipeline Protection Law (effective 10/01/2010);
17. Urban and Rural Planning Law (revised 4/23/2019);
18. Emergency Response Law (effective 11/01/2007).

In addition to the national statutes, relevant national, local and industrial regulations and technical guidelines and specifications are in place to protect the safety and environment throughout the UGS construction and management. Appendix A includes a sample listing of UGS industry-level and CNPC enterprise-level standards.

With respect to environmental management, in pursuance of the *Catalogue for Classification Management of EIA of Construction Projects*,[59] UGS projects are required to conduct comprehensive evaluation (vis a vis compiling a simpler EIA form or a mere EIA filing) over their environmental impacts on air, water, soil and noise. As part of the reform to streamline decision-making and delegating power to lower-level agencies, provincial environmental authorities (instead of the national agency) are now in charge of the review and approval of UGS environmental impact assessment.[60] Currently, except for a certain circumstances,[61, 1] development of oil and gas fields and UGS are not included in the *2019 Catalogue for Discharge Permitting Management for Stationary Resources*.[62] Except for wastewater discharge is subject to the *Technical Specification for Application and Issuance of Pollutant Discharge Permit - Wastewater Treatment General Process* (HJ1120-2020), there is no pollution discharge permitting requirement for development of oil and gas fields or UGS on the national level.

Additionally, UGS facilities in China are subject to a safety assessment and the developer will need to obtain an enterprise-level safety production permit. This process is under the jurisdiction of the Ministry of Emergency Management. This ministry is responsible for emergency management, work safety, and emergency rescue.

China's UGS Air Pollution Prevention and Control and Methane Emissions Management

There could be multiple emissions sources during the UGS life cycle. Taking UGS built from depleted oil and gas reservoir for example, potential sources for air emissions include drilling, well completion, gathering and processing, compressing, dehydration, venting and flaring, storage tanks, liquid unloading, wastewater reinjection, natural gas injection and withdrawal, combustion, boiler flue gas, and vehicular discharge etc.

For illustration purposes, figures in Appendix B depict possible emission sources from the various operations associated with UGS.

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[1] Annual emissions of SO2 or NOx exceeds 250 tons; annual dust emissions exceed 500 tons; annual COD discharge exceeds 30 tons, or annual nitrogen emissions greater than 10 tons, or annual phosphorus emissions greater than 0.5 tons ; total annual emissions of ammonia nitrogen, petroleum and volatile phenol exceed 30 tons; or pollution equivalent (conversion method based on China Environmental Tax Law) of a single toxic or hazardous air pollutants or water pollutant exceeds 3,000.

Air emissions from UGSs are governed by China's air pollution prevention and control law (revised in 2018).[63] Specifically, the air law requires co-control of conventional air pollutants and greenhouse gases (including methane) (Article 2); and installation and operation of vapor recovery devices at oil and gas facilities such as UGSs (Article 47).

Other existing and proposed regulations/standards/guidelines concerning oil and gas air emissions include *Technical Standards for Environmental Inspection for the Completion of Construction Projects – Oil and Gas Production,*[64] *Technology and Policy for Pollution Prevention and Control of Oil and Gas Production ("Technology and Policy"),*[65] *Emissions Standards for Coalbed Methane/Coalmine Methane (Trial, 2008),*[66] *Air Pollutants Emission Standards for Onshore Oil and Gas Production (under government review), EIA Technical Guideline for Onshore Oil and Gas Production Projects (Draft for Comments, October 2019)*,[67] and *Notice on Strengthening EIA Management for Oil and Gas Industry(December 2019).*[68]

With respect to methane emissions regulation, since greenhouse gases such as methane are not considered "pollutants" in China, the current regulatory focus is on safety, while encouraging recapture and reutilization of emitted gas for energy conservation. UGS methane accounting mainly follows the *Greenhouse Gases Accounting and Reporting Guidelines for China Oil and Gas Producing Enterprises* (Trial). [69] Where recapturing is not feasible, flaring is preferred over venting. Piloting of oil and gas methane emissions recovery and reutilization is emerging at the local level. For example, Heilongjiang Province now requires reduction of hydrocarbon emissions and recommends recapture of methane emissions and reutilization of the recovered gas.[70]

Regular leak detection and repairs (LDARs) are typically a central part of methane mitigation strategy. In China, LDAR has been widely deployed in downstream petrochemical industries to detect fugitive VOC emissions, but it is yet to be fully implemented in upstream oil and gas development or in transmission and storage segment.[71] In May 2019, China's environmental ministry issued the Standard for VOCs Fugitive Emissions which applies to materials with VOC content of 10% or above and at facilities with at least 2000 connectors.[72] Since natural gas typically has less than 10% VOC content, this standard would leave out natural gas facilities and apply to certain oil production/transmission/storage facilities that meet the criteria. In pursuance with the standard, starting July 2019, LDAR shall be conducted for valves, flanges, pumps, connectors, and storage tanks etc. at new facilities; and at existing facilities starting July 2020. While this standard is a step forward in controlling upstream VOCs emissions from some oil facilities, its coverage is rather limited and does not apply to methane. Given methane is a potent short-lived greenhouse gas and a precious commodity, it is important to adopt regular LDAR requirements for methane as well as VOCs throughout the entire oil and gas supply chain for emissions abatement.

China Oil and Gas Waste Water Management

Wastewater is generated from various sources in oil and gas development, production, and further management including gas storage operations. Related to UGS, wastewater generation includes that from salt cavern development as well as ongoing operations of the storage facility whether salt cavern, depleted oil and gas reserves, or aquifer storage. Oil and gas wastewater is mainly managed through two methods: surface discharge after treatment and reinjection. For surface discharge, the quality of the treated water must meet national and local wastewater discharge standards such as *Integrated Wastewater Discharge Standards* (GB 8978-1996).[73] For reinjection of onshore oil and gas produced water, it is required that the water quality post-treatment meet the Recommended Water Quality Standards and Analytical Methods for Reinjection into Clastic Oil Reservoir (SY/T5329, 2012).[74]

At the time of this writing, the *Water Pollutants Discharge Standards for Onshore Oil and Gas Production* is undergoing government review. Before the finalization and approval of this Standard, treatment of produced water must follow the guidelines aforementioned.

From China's perspective to prevent surface and ground water contamination, it is necessary to establish national environmental standards concerning produced water reinjection or surface discharge, supplemented by monitoring and reporting systems. Also, it is necessary to conduct research and analysis of the recipient geologic formation to demonstrate the feasibility of underground reinjection.

China's UGS Quality Control, Health Safety and Environment (QHSE) Management System

Quality Control mainly covers engineering design, product procurement, construction, completion and operation, to help ensure safe and reliable gas storage.

For surface construction, quality control plans must be developed and implemented in accordance with the engineering design documents and standards, followed by appropriate auditing, inspection and supervision.

For UGS construction, the key tasks for QHSE management include personnel training, safety protection facilities, operational licensing, hazard identification and control, identification of environmental attributes and evaluation, engineering supervision and inspection, and accident investigation and response.

Post construction, the focus should be on land restoration, soil and water conservation, inspection on impact over farming, and timeliness of documentation.

Trial operation requires leadership establishment, training, pre-work safety analysis and inspection, lock-out and tag-out, safety visualization, emergency plan and drill, and environmental protection measures.

Occupational health. Under the *Law of Prevention and Control of Occupational Diseases (revised in 2018)*,[75] the design of UGS facilities must comply with national health regulations such as Industry and Enterprises Design Health Standards, and ensures implementation of appropriate preventive measures against hazardous and toxic substances, noise, and dust etc.

Safety management. UGS safety implementing measures are required under the *Law* for *Safe Production*.[76] UGS safety control systems shall provide for automatic control for gas injection/withdrawal, emergency shutdown, fire detection, equipment and pipeline anti-corrosion and insulation, power supply and distribution, safe relief, fire station and fire protection, anti-toxicity and chemical hazards, anti-noise and natural disasters. In addition, an integrated monitoring system for stratum, wellbore and surface must be established to conduct real-time monitoring, analysis and early warning throughout the whole lifecycle to ensure safe operation.

Environmental protection. Appropriate measures must be implemented to address air, wastewater, noise, and solid waste pollution, and for ecological protection and restoration. Precautionary measures and emergency repose plans are required to ensure safe operation and minimization of environmental risks.

UGS environmental risk prevention and ER measures generally include: evaluating old wells around the UGS, apply cement sealing to close those wells that cannot be utilized; deploy surface and underground well control facilities, and conduct regular inspection and maintenance to ensure normal operating conditions; strengthen pressure monitoring of water injection formation to avoid overpressure and exceedance over reinjection layer capacity.

When accidents occur, timely notice should be sent to affected public for evacuation. Strict accident reporting system and Emergency Plan should be formulated and align with local government's ERP. Emergency drills should be carried out to ensure readiness.

5.0 Key Recommended Elements of a Robust Underground Gas Storage Regulatory Program

Considering an increased use of natural gas in both the U.S. and China, and thus the need for expanded UGS capacity and related infrastructure, this section presents recommended elements that should be considered in developing a more robust regulatory program. A number of these elements may already exist but likely not all, especially in the detail as presented here.

The following discussion builds upon the most recent California regulatory revisions that were driven by the Aliso Canyon incident, the adoption of PHMSA's final minimum uniform federal safety standards, technical and regulatory guidance (including API RPs, Canadian Standards, GWPC report), as well as recommendations by experts on this topic. However, the key elements presented in this section are only a start. Specific items must be addressed based on facility and site-specific circumstances and conditions.

Foundational Elements

Approval of Underground Gas Storage Projects

Project approval in terms of authorizations or permits is required before storage operations can be initiated. Approvals are issued only when it is clearly demonstrated the project will prevent damage to life, property, the environment, health and natural resources. Reference to accepted standards (i.e. applicable API documents or similar) are used to determine specifics to design, construction, and operation.

The regulatory authority will review projects periodically but at least once every three years to verify adherence to terms and conditions of approval. This is in addition to regular and ongoing inspections of the facility. If inconsistencies to approval terms are found, the regulatory authority will notify the operator to cease operations immediately. Appropriate response actions must be developed and conducted with regulatory oversight to correct identified inconsistences before operations may resume.

Risk Management Plans

For each new project the operator must submit for approval a comprehensive project-specific risk management plan. For projects already in operation, a plan must be submitted within 6 months of the regulation's effective date. The risk management plan must demonstrate the project will confine the stored gas and that risk of damage to life, property, environment and natural resources have been adequately evaluated with appropriate preventative and mitigative measures deployed. The Regulatory Authority may request any and all data it deems necessary to support the plan and project in addition to what the operator may have submitted.

A risk management plan responsive to required risk reduction goals (developed through the "As Low As Reasonably Practicable" metric or otherwise) shall include, but not limited to:

- Risk assessment methodology;
- Assessment of potential threats and hazards;
- Preventive and mitigative measures;
- Accident scenarios;
- Frequency and range of consequences;
- Well-by-well basis as required;
- Severity prioritization;
- Documentation;
- Regular and periodic reviews of plan elements and performance;
- Design and construction standards;
- Safety features;
- Relation to surface culture;
- Risks of servicing and installation;
- Proximity to environmentally sensitive areas;
- Physical protection measures;
- Topography;
- Weather;
- Geologic hazards;
- Mechanical integrity issues;
- Monitoring protocols;
- Assessment of human and staffing factors;
- Training programs;

- Equipment maintenance;
- Emergency response plans;
- Internal and external communication; and
- Stakeholder input/interface.

The operator shall always adhere to all elements of the approved plan unless a variance has been evaluated and approved by the Regulatory Authority. Risk management plans shall be made public except for elements that have been approved by the Regulatory Authority as confidential.

Operators must allocate and clearly demonstrate to the Regulator's satisfaction, adequate resources to effectively implement the risk management plan. Approved risk management plans must present evidence that the plan is supported by executive leadership down to include all operating personnel.

As part of risk management, a risk based well integrity management system must be developed and proactive measures implemented to ensure system integrity on a well-by-well basis. Cathodic protection must be implemented as appropriate to include surface casing. Operators must minimize and control corrosion.

Preventive and mitigative measures are to be developed and implemented to manage all threats and hazards and an operator must develop and maintain a corporate/division(s) risk management policy.

Additional significant items specially mentioned in referenced technical guidance include the following.

- The Canadian standards specify the risk assessment process in detail while the California standards are stipulated in some cases in broader terms.
- The GWPC report clearly stipulates preventive and mitigative measures are to be developed for all threats and hazards.
- API RP 1171 stipulates that a lack of data is not justification to exclude a specific hazard – when lack of data is identified a process should be initiated to collect the data, document both the lack of data and the need to collect the data, and carefully examine the unknown risk of moving forward using assumptions based on incomplete information.
- API RP 1171 stipulates the use of multi-disciplinary teams in both developing and implementing risk management plans.

- API RP 1171 specifically mentioned robust records retention of risk management.
- Performance measures should be developed that include independent audit functions, proactive measures to address emerging risks and lagging measures to evaluate the program's past performance and trends for the entire program, not just the risk assessment process.

Emergency Response Plan

An operator must develop an emergency response plan (ERP) to be approved by the Regulatory Authority and ready for immediate implementation. It must contain a schedule for drills and the drills must demonstrate the operator's readiness to interact with equipment, all stakeholders, all services and provide local emergency response entities 30 days to review and provide input.

The plan at a minimum must address wellhead collisions, fires, blowouts, explosions, hazardous material spills, failure of equipment, natural disasters, leaks, well failures and medical emergencies.

The ERP will at a minimum include a clearly written policy, goals and objectives, an incident management system that addresses resources, communications and incident documentation, action plans with assigned authorities, accident response measures, ensure response resources are appropriately positioned prior to an emergency, schedule for regular drills that involves all stakeholders including the Regulatory Authority, effective training program with clearly stated goals, recordkeeping, regular evaluation and update of the plan, protocols for emergency reporting, personnel roles and responsibilities; up-to-date emergency contact information, public notice protocol, and integrates seamlessly with the risk management plan.

There should be a stipulation that a large, uncontrollable leak that may potentially impact surrounding communities must be reported as soon as practicable.

Operators should perform annual updates to their ERP and the plan's effectiveness should be further evaluated by annual no-notice exercises engaging all key stakeholders. All drills and exercises must contain mechanisms to demonstrate competency and proficiency. Training programs as well must demonstrate competency, not just regulatory training requirement training frequency.

Additional significant items specially mentioned in referenced technical guidance include the following.

- The Canadian standards include:
    - Annual updates or more frequently as required by frequent hazard identification. ERP's are viewed as living documents that require frequent update based upon operational, organizational, personnel, and regulatory changes and lessons learned from real world experiences.
    - Criteria and procedures to ensure instructors are indeed qualified.
    - Specifically address security of the facility.
    - A document on emergency preparedness (EP) and response that provides a comprehensive template. This methodology provides for consistent emergency response design and ease of review, update and sharing of lessons learned. It includes sample plans, roles, responsibilities, risk estimation grids, forms, audit criteria and table of contents for EP manual.
- The GWPC report includes:
    - An objective, independent and competent audit function to continually assess the emergency response plan.
    - ERP content organization that separately address planning and implementation.
    - Strong consideration for conducting no-notice drills.
- API RP 1171 includes:
    - specifically calls for the implementation of plans to ensure and manage site safety and security noting specific details to assist in that effort. The risk management program must address this as well.
    - Calls for operators to address cyber security.

The root cause analysis performed after the Aliso Canyon failure recommended the development of well control plans that include full understanding of well specific performance parameters.

Underground Gas Storage Project Information Disclosure

The operator must provide enough information that demonstrates the project will contain the stored gas and that the project will not jeopardize life, health, property, environment or natural resources.

At a minimum the operator must provide to the Regulatory Authority continuous reserve reconciliation; surface and subsurface safety devices and methods; produced water disposal plans; operating pressures and volumes; engineering, geophysical, reservoir and geologic (structure, stratigraphy, cross-sectional analysis) data supporting containment and isolation;

surface locations and neighboring culture; analysis of other, non-project wells within a specified area around the UGS facility (area of review); operational monitoring; mechanical integrity maintenance; and the planned drilling, well conversion, completion and equipping plans.

The Regulatory Authority may, on a case-by-case basis, and in their discretion, request any and all data/information needed to substantiate project integrity.

The operator shall provide the Regulatory Authority with any changes in operating conditions that would require update or modification of the project plan originally submitted.

All data will be submitted in an electronic format unless the operator demonstrates that is not feasible.

The operator may request, and the Regulatory Authority may grant confidentiality.

The Regulatory Authority will make the project data publicly available except insofar as the project data or parts thereof have been granted confidential status.

Operators must submit information required by the Regulatory Authority in a timely fashion.

Wellbore Diagrams

Casing (wellbore) diagrams are to be provided and adhere to including at least numerous significant items that fully characterize wellbore construction (casing details, valves, hole parameters, perforated intervals with details, any plugs or other wellbore jewelry, geologic information such as markers, formations and zones of interest, depths (measured and true), cement information, wellhead valves and safety valves, ground water, elevations and location) and anything deemed necessary to accurately and fully describe the well(s) in the project. This applies to all wells associated with a UGS facility including operation wells (injection and withdrawal wells), any orphaned and plugged wells within the area of review.

Directional surveys are to be provided for directionally drilled wells.

Wellbore diagrams are to be submitted in an electronic format.

Included information will be wellbore elements that provide primary and secondary barriers.

Evaluation of Wells Within the Area of Review (AOR)

The following stipulated requirements are the minimum and may be expanded at the discretion of the Regulatory Authority to ensure other wells within the AOR are not a conduit for stored gas migration.

All wells within the AOR must be evaluated for potential to allow stored gas to migrate outside approved gas storage zones.

Plugged and abandoned wells shall comply with local plugging requirements, and the Regulatory Authority may require wells to be re-entered to bring them into compliance. If plugged and abandoned wells in the AOR do not have sufficient integrity, alternative measures to prevent stored gas migration may suffice at the discretion of the Regulatory Authority.

The GWPC report differentiates between AOR and buffer zone. Buffer zones may extend beyond specific wells within the AOR. Buffer zones may also be either vertical or lateral in nature. Buffer zones provide an additional measure of safety and security.

Records Management

Operator must establish a records management program and submit the plan to the Regulatory Authority. All records that relate to conformity with operating conditions and terms shall be maintained for the project lifetime. A records management program shall employ a filing and storage plan that ensures easy access and security. The program shall also employ a record of records history and modifications. Records must be easily retrieved and produced for inspection by the Regulatory Authority.

Additional significant items specially mentioned in referenced technical guidance include the following.

- The Canadian standards require maintaining records for 15 years past the project decommissioning.
- API RP 1171 requires records to be kept for the life of the project.

Well Construction Requirements

The operator shall design, construct, modify, and maintain gas storage wells and every other well penetrating the gas storage reservoir to effectively ensure mechanical and reservoir integrity under anticipated operating conditions.

Key elements of well construction requirements include the following:

- No single point of failure may pose an immediate threat to loss of control of gas. (the afore referenced resource "Ensuring Safe and Reliable Underground Natural Gas Storage" provides good discussion on single point of failure issues).
- Wells must be constructed with primary and secondary mechanical well barriers. The primary barrier is exposed to withdrawal and injection and must be able to withstand full operating conditions. The secondary is not exposed to withdrawal and injection under normal operating conditions. It must also be able to withstand full operating conditions.
- Provide examples of primary and secondary mechanical barriers (see Current California UGS rules).[77]
- Casing strings, to include connections, are required to withstand operating conditions.
- Cement requirements are addressed as well as wellhead components and configurations.
- If wells do not or cannot comply with the regulatory requirements, the operator may file for an alternative solution (variance) but that solution must effectively adhere to the requirements of the authority.
- Regulations must address intermediate casing mechanical requirements.

API RP 1171 requires the development and implementation of O&M procedures prior to beginning operations.

Mechanical Integrity Testing

Mechanical integrity testing shall include the following.

- Temperature and noise logs to be run at least annually to ensure integrity. Logging shall include repeat sections of appropriate spans to allow verification of data accuracy. Anomalies identified that may indicate a possible loss of integrity must be reported immediately and the Regulatory Authority may require the well to be shut-in.
- Casing wall thickness shall be evaluated by standard logging means at least once every 24 months. If the wall thickness is deemed at any time to be insufficient to hold 115% of max allowable pressure, the well shall be repaired and shall not be used for injection or withdrawal without Regulatory Authority approval. The Regulatory Authority, at its sole discretion, may allow less frequent wall thickness testing.
- Regular pressure testing (generally not to exceed 5-year interval) of the production casing or tubing is on a case-by-case basis depending upon the well and the Regulatory Authority. If a

well fails a pressure test, the operator must immediately notify the Regulatory Authority and the well may not be used for injection or withdrawal until the situation is rectified to the satisfaction of the Regulatory Authority.

- Newly constructed wells or a reworked gas storage well must be pressure tested.
- The Regulatory Authority has the authority to modify testing standards at its discretion.
- The Regulatory Authority shall be notified 48 hours prior to testing to allow time to schedule a witness.
- All mechanical integrity testing data shall be documented, and results sent to the Regulatory Authority.
- Frequency of casing integrity testing is based upon the operator's risk analysis of the UGS facility and associated wells.

Pressure Testing Parameters

- Pressure testing must be with a liquid unless the Regulatory Authority approves testing with gas.
- Operator must consult with the Regulatory Authority about fluid types or additives that deviate from brine.
- Pressure testing must be measured and recorded with accuracy within 1% of the max allowable injection pressure.
- Conduct pressure tests at an initial pressure of at least 115% of max allowable injection pressure at the wellhead.
- Pressure tests will last one hour.
- A successful test will be a decline of less than 10% in the first 30 min and 2% in the second 30 minutes.
- Regulatory Authority may modify pressure tests on a case-by-case basis.

Monitoring Requirements

The operator daily must monitor for the presence of gas in all annuli by pressure analysis; use real-time SCADA (supervisory control and data acquisition) or similar systems.

Monitoring requirements include the following.

- Material balance of the storage reservoir and send verification no less frequently than annually to the Regulatory Authority. This can be done through typical measures such as observation wells, operating wells' pressures, liquid levels, withdrawal, injection, subsurface geophysical logs and offset, non-project wells' parameters.

- Real-time data gathering including appropriate alarms and response protocols. An example can be found in Texas' underground gas storage rules (Texas Administrative Code Title 16, Part 1 §3.96) that includes addressing leak detector installation and testing, and warning systems.[78]
- Observation wells should be used around, above and below the reservoir to monitor potential pathways of communication or migration.

The operator shall notify the Regulatory Authority of deviations from norm that jeopardize containment or mechanical integrity. This includes unanticipated casing pressures that must be reported and prudently managed.

The operator must submit a plan for conducting a baseline and subsequent gas detection. The Regulatory Authority must approve such plan.

The operator must adhere to the Regulatory Authority approved inspection and leak detection/inspection protocol. An example can be found in the new California rules (Section 1726.7 subdivision (f)). The use and deployment of leak detection tools and methodologies may use various means based upon location specific operating conditions. California Air Resources Board requirements include ambient air monitoring, daily or continuous leak monitoring at injection/withdrawal wellheads, and submission of monitoring plans to agency for approval.[79]

Inspection, Testing, and Maintenance of Wellheads and Valves

An inspection, testing, and maintenance of wellheads and valves program shall include the following.

- Testing of surface and subsurface safety valves required every 6 months.
- Testing in accordance with API RP 14B "Design, Installation, Operation, Test, and Redress of Subsurface Safety Valve Systems".
- Wellhead and pipeline isolation valves to be tested annually.
- Inoperable valves to be repaired within 90 days or T&A the well.
- Valves to be installed to provide for isolation so wells may be accessed.

- Wellheads and valves must be able to withstand max operating pressures.

The Regulatory Authority offices to be notified 48 hours prior to testing for option to witness and all testing documentation to be maintained for a period of time as specified by the Regulatory Authority.

Well Leak Reporting

A "reportable leak" must be defined and include any leak that poses a significant present or potential hazard to public health and safety, property, or to the environment. EPA Method 21 – "Determination of Volatile Organic Compound Leaks" is a good reference and provides details on equipment and supplies; and sample collection, preservation, storage, and transport.[80] The Regulatory Authority must be immediately informed of a "reportable leak."

The operator must fully analyze and report to the Regulatory Authority all tubular leaks and failures with mitigative measures to repair and remedy.

An evaluation of the reason for failures resulting in leaks is an important element in identifying causes and measure to minimize failures in the future. A detailed root cause analysis was performed following the Aliso Canyon failure and this was certainly justified considering the size and resultant impacts that were a result of this failure. However, the scope and detail of a root cause analysis will vary, the critical element is such analysis is conducted and recommended step to address identified deficiencies developed and implemented. A resource to assist with this effort is API RP 585, "Pressure Equipment Integrity Incident Investigation".

Requirements for Decommissioning

A decommissioning plan will be submitted to and approved by the Regulatory Authority. At a minimum this plan must address managing remaining gas in storage, intended use of wells after decommissioning, any plans for repurposing, and requested information by the Regulatory Authority.

Additional significant items specially mentioned in referenced technical guidance include the following.

- The Canadian standards address in significant detail for the decommissioning process and procedures.

- The GWPC report addresses procedures for temporary abandonment and management of such wells to ensure wellbore and reservoir integrity is monitored and maintained.
- A good technical reference is API Bulletin E3 "Plugging and Abandonment Practices".

Management of Change

Management of change （MOC) is a leading management practice directed at making sure environmental, health and safety risks are addressed whenever changes occur in management organization or facility operation. Management of change is designed to ensure any changes do not increase existing risks and new risks are identified and addressed.

API RP 1171 stipulates the development of a formal management of change process for all aspects of the facility and project with clear procedures as detailed below.[81]

General

Revision of procedures and processes is an acceptable practice, but the operator shall require changes to be accomplished in a controlled manner. The program documentation, framework, and procedures shall be revised before the change can be implemented. Not all changes need be approved through a formal MOC process. Some changes are expected and may not be subject to a formal change control process. The operator should define the types of changes determined to be significant and requiring a MOC.

Scope

The operator should develop and maintain an MOC process that addresses changes in equipment, processes materials, or procedures. The MOC process should include procedures to identify impacts associated with changes and determine the effect of the change on the storage facility. The MOC process should address approval authority and responsibility for the change and document implementation of the change.

An MOC procedure should include a process for approval of deviations from the procedures when necessitated by abnormal/emergency conditions.

The operator should update procedures, communicate and document changes to procedures in accordance with the operator's MOC process, and verify that personnel *engaged in operating and maintaining the storage reservoir and wells are aware of and trained in those changes.*

6.0 Conclusions and Follow-on Efforts

Underground gas storage's operation dates back to over 100 years ago, and there have been several sound technical guidance documents developed for design, construction, and operation of UGS facilities. But As evidenced by the aforementioned UGS facility failures in the U.S., Mere adherence to leading technical practices is not enough to prevent serious health, safety and environmental threats which can and do undermine the best technical efforts.

Benchmarking of UGS leading management practices provide a basis for development of more robust technical frameworks and regulatory programs.

This entails more than just sound design and construction or regulatory permitting (although those are certainly important elements), but also on-going operation evaluations and reviews, and regulatory oversight and inspections. This includes having plans and processes developed and implemented when mechanical or operation failures occur. Risk management and risk assessment are key components in working to prevent failures and effectively addressing emergency situations when failures occur.

Key elements include not only the technical guidelines for UGS life cycle management, but also more detailed planning processes, on-going monitoring programs and tools, and applying ALARP goal setting and metrics to the risk reduction program. Risk management plans that include risk assessments and emergency response plans are critical. Additionally, data gathering and evaluation of that data regarding design parameters, construction conditions and on-going operations is important. The latter incorporates periodic and routine testing and monitoring, leak detection, and leak reporting. Finally, encompassing all elements are specific programs and processes for continual improvement and management of change. Although the identified key regulatory elements provide a basis for developing a robust UGS regulatory environment, there are areas that should be further developed, particularly in consideration of specific siting and storage conditions.

China has announced targets to expand UGS capacity in the coming decade. It is an opportune time for China to evaluate its current regulatory program for improvements, drawing on available technical guidance, lessons learned from facility failures, and recent regulatory improvements. China can build upon its existing UGS regulatory framework to develop a more robust program to prepare for the varied issues and conditions that will be presented as part of the planned UGS capacity expansion. Recently, the government called for accelerating the issuance of environmental permitting rules as part of its environmental governance reform mandates.[82] Given USG is currently not covered under environmental permitting, a meaningful follow-on project would consist of a detailed analysis of U.S. and China UGS permitting processes to identify areas of improvement of the respective country's environmental regulatory framework. The comparison could lead to the creation of a model permitting framework which would serve as useful guidance to inform implementation, especially if China seeks to streamline and delegate authority more toward local regulators.

Appendix A – Sample Listing of China Industry-level and China National Petroleum Corporation Enterprise-level Standards for Underground Gas Storage

A Sample List of China Industry-level UGS Standards

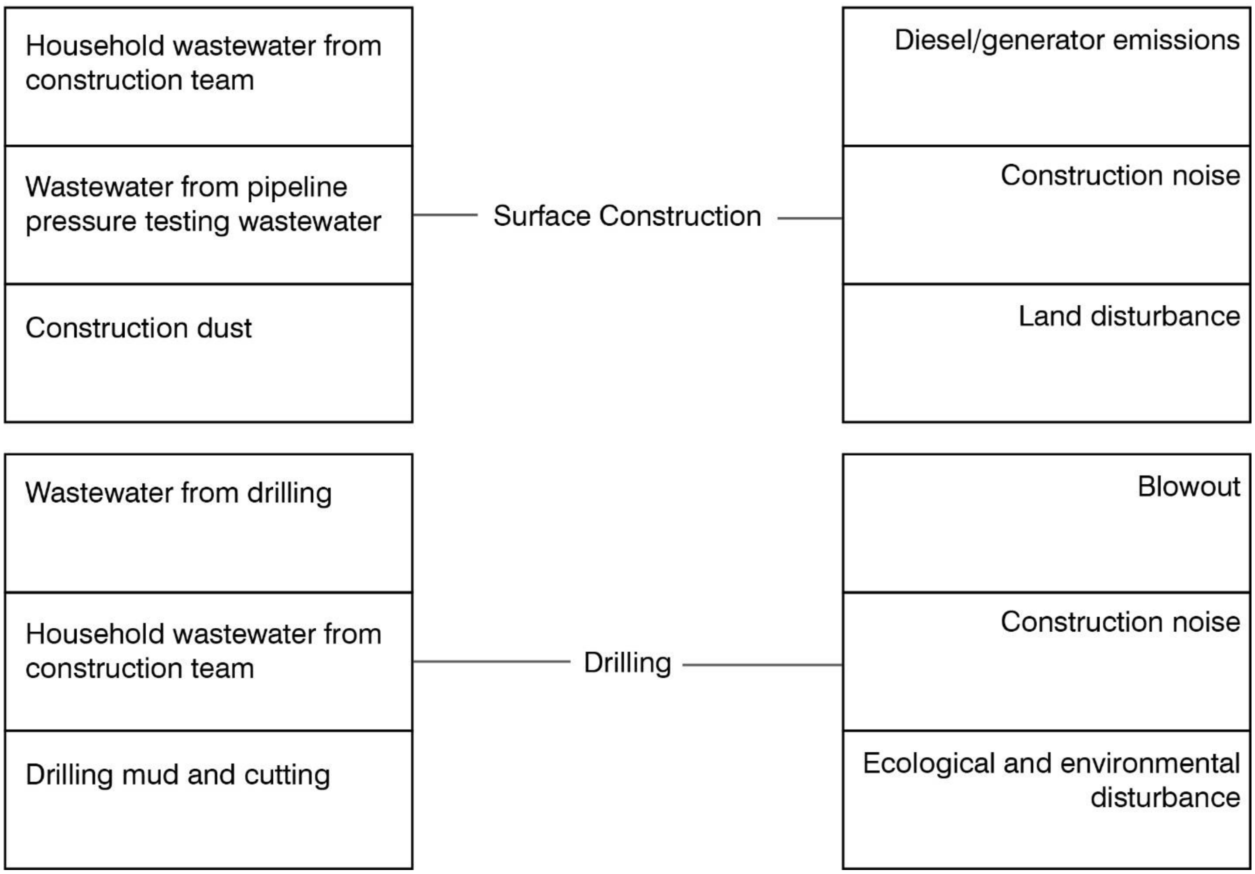
1. Design Standards on UGS (3/01/2012)
   地下储气库设计规范 SY/T 6848-2012
2. Technical Safety Standards on Depleted Oil and Gas Reservoirs UGS (3/01/2018)
   油气藏型地下储气库安全技术规程 SY/T 6805-2017
3. Operation Standards on Injection and Withdrawal Wells for Converted UGS in Depleted Oil and Gas Reservoir (5/01/2010)
   油气藏改建地下储气库注采井修井作业规范 SY/T 6756-2009
4. Recommendations on the Selection and Design of Casing Strings for Injection and Withdrawal in UGS (8/01/2017)
   地下储气库注采管柱选用与设计推荐做法 SY/T 7370-2017
5. Technical Standards on Energy-efficient Engineering Design of Gas Transmission Pipelines and UGS (12/01/2012)
   天然气输送管道和地下储气库工程设计节能技术规范 SY/T 6638-2012
6. Technical Safety Standards on Salt Cavern UGS (5/01/2011)
   盐穴地下储气库安全技术规程SY 6806-2010
7. Standards on Engineering Design of Well Perforation and Completion of Injection and Withdrawal Wells in Depleted Oil and Gas Sandstone Reservoir (1/01/2007)
   枯竭砂岩油气藏地下储气库注采井射孔完井工程设计编写规范 SY/T 6645-2006
8. Technical Safety Standards and Regulations on Natural Gas Injection into Oil and Gas Field (11/01/2011)
   油气田注天然气安全技术规程 SY 6561-2011

A Sample List of CNPC Enterprise UGS Standards

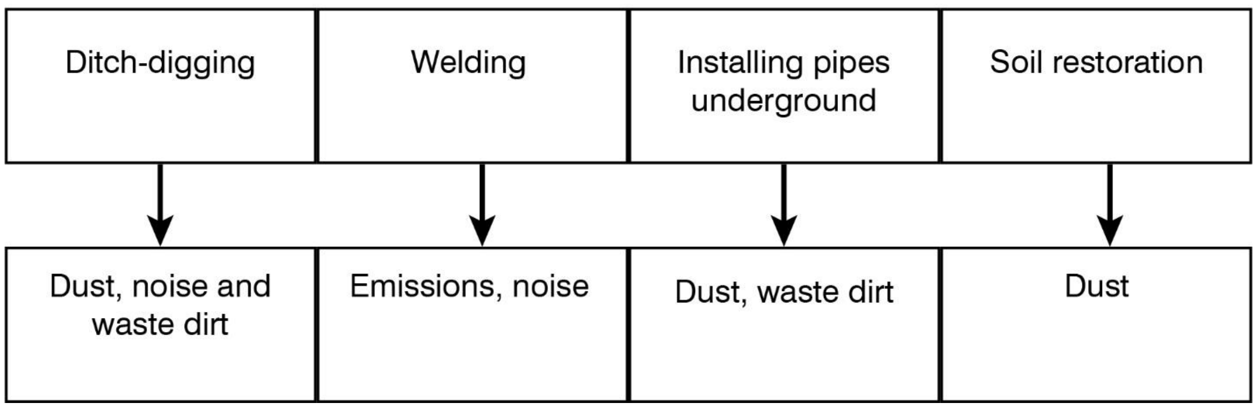
1. Calculation of Natural Gas Loss in UGS, Part I: Gas Reservoir
   地下储气库天然气损耗计算方法第 1 部分：气藏型 Q/SY 195.1-2007\
2. Operations and Management Standards on UGS Converted from Oil and Gas Reservoir, Part I: Gas Reservoir Management (Confirmed in 2014)
   油气藏改建地下储气库运行管理规范第 1 部分：储气库气藏管理（2014 年确认）Q/SY 1183.1-2009
3. Operations and Management Standards on UGS converted from Oil and Gas Reservoir, Part II: Injection and Withdrawal Well Management (Confirmed in 2014)
   油气藏改建地下储气库运行管理规范第 2 部分：储气库注采井管理（2014 年确认）Q/SY 1183.2-2009
4. Operations and Management Standards on UGS converted from Oil and Gas Reservoir, Part III: UGS Surface Facilities Management (Confirmed in 2014)
   油气藏改建地下储气库运行管理规范第 3 部分：储气库地面设施管理 Q/SY 1183.3-2010
5. Technical Standards on Plugging Abandoned Wells in Oil and Gas Reservoir (Confirmed in 2015)油气藏型地下储气库废弃井封堵技术规范（2015 年确认）Q/SY 1270-2010
6. Cavern Design Standards for Salt Cavern UGS (Confirmed in 2016)
   盐穴储气库腔体设计规范（2016 年确认）Q/SY 1416-2011
7. Technical Standards on Solution Mining of Salt Caverns (Confirmed in 2016)
   盐穴储气库造腔技术规范（2016 年确认）Q/SY 1417-2011
8. Technical Standards on Sonar Detection in Salt Caverns Confirmed in 2016)
   盐穴储气库声纳检测技术规范（2016 年确认）Q/SY 1418-2011
9. Measures on Safety Assessment of Casing Strings in UGS
   地下储气库套管柱安全评价方法 Q/SY 1486-2012
10. Guidelines on Risk Assessment of In-Service Salt Cavern UGS
    在役盐穴地下储气库风险评价导则 Q/SY 1599-2013
11. Technical Conditions for UGS Casing
    地下储气库套管技术条件 Q/SY 1703-2014
12. Technical Standards on Well Drilling and Completion in Salt Caverns UGS
    盐穴型储气库钻完井技术规范Q/SY 1859-2016
13. Technical Standards on Air Tightness Testing of Wellbore and Salt Caverns of UGS
    盐穴型储气库井筒及盐穴密封性检测技术规范 Q/SY 1860-2016

14. Inspection Approval Testing Criteria for Drilling and Completion of Injection and Withdrawal Wells in Oil and Gas Reservoirs
    油气藏型储气库注采井钻完井验收规范 Q/SY 01009-2016
15. Design Standards on Injection and Withdrawal Wells in Depleted Oil and Gas Reservoirs
    油气藏型地下储气库注采完井设计规范 Q/SY 01012-2017
16. Methods for Designing Storage Capacity Parameters of Sandstone Reservoirs UGS
    砂岩气藏型储气库库容参数设计方法 Q/SY 01021-2018
17. Criteria for Dynamic Monitoring Data Acquisition on Depleted Gas Reservoirs UGS
    气藏型储气库动态监测资料录取规范 Q/SY 01022-2018
18. Technical Standards on Well Drilling and Completion of Depleted Gas Reservoirs
    气藏型储气库钻完井技术规范Q/SY 01561-2019
19. Geological and Technical Engineering Standards on the Construction of Depleted Gas Reservoirs UGS 气藏型储气库建库地质及气藏工程设计技术规范 Q/SY 01636-2019
20. Design Standards on the Injection and Withdrawal System in Salt Caverns UGS
    盐穴储气库注采系统设计规范Q/SY 06024-2017
21. Surface Engineering Design Standards on Solution Mining System in Salt Caverns
    盐穴储气库造腔系统地面工程设计规范 Q/SY 06025-2017\
22. Process Design Standards on Oil and Gas Storage and Transmission, Part V: UGS
    油气储运工程工艺设计规范 第 5 部分：地下储气库 Q/SY 06305.5-2016
23. Design Standards on Auto-Control Instruments in UGS
    油气储运工程地下储气库自控仪表设计规范 Q/SY 06306-2016
24. Engineering Design Standards on Oil and Gas Storage and Transmission, Part II: UGS
    油气储运工程总图设计规范第 2 部分：地下储气库 Q/SY 06307.2-2016
25. On-Site Safety Inspection Standards for Oil Companies, Part 21: UGS Sites
    石油企业现场安全检查规范 第 21 部分：地下储气库站场 Q/SY 08124.21-2017
26. Design Standards for Well Completion for Injection and Withdrawal Wells for Depleted Oil and Gas Reservoir UGSs
    油气藏型地下储气库注采完井设计规范 Q/SY 01012-2017

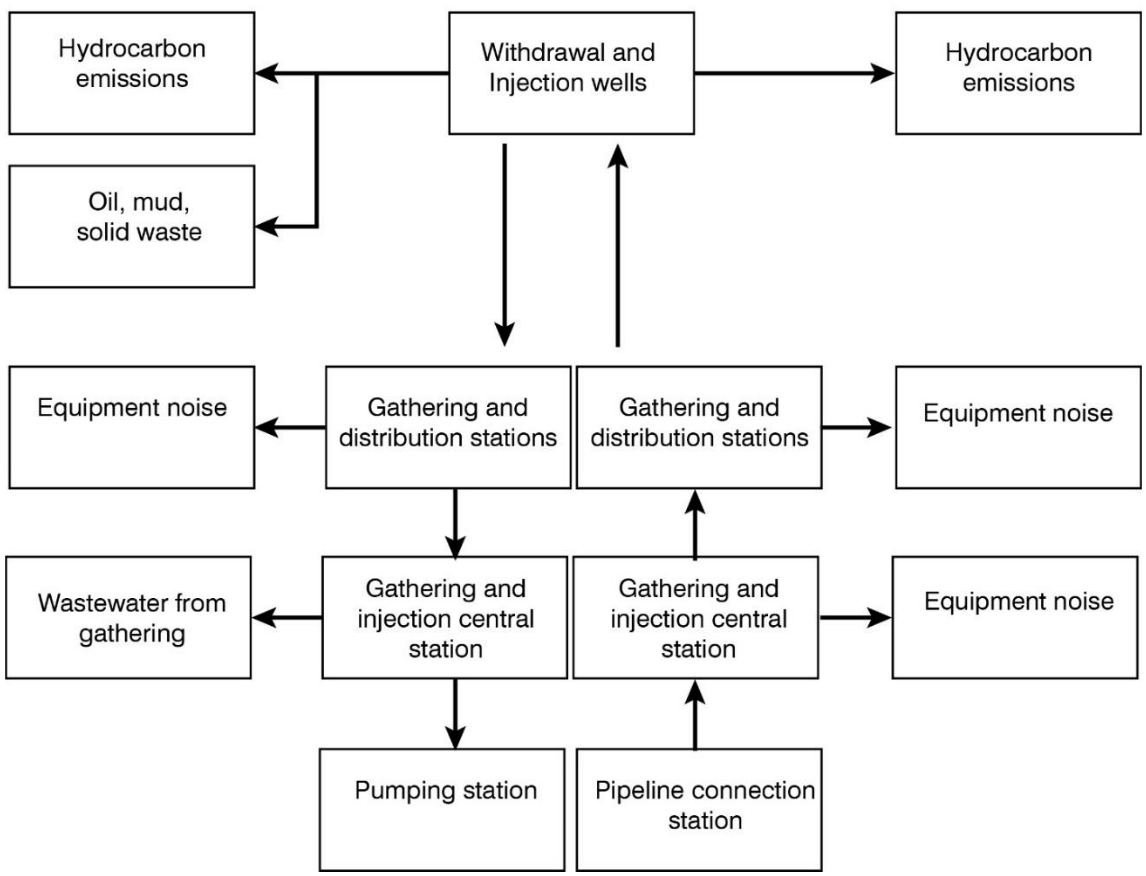
Appendix B – Depiction of Emission Sources During Underground Gas Storage Facility Construction and Operation



Emissions Sources during Surface Construction and Drilling



Emissions Sources during Pipeline Construction Phase



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