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Research article

The status quo and technical development direction of underground gas storages in China

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Abstract

UGS (underground gas storage) construction in China has stepped into a new development stage after years of exploration. The eleven UGSs that have been put into production play an important role in domestic natural gas peak shaving safety and supply guarantee, with designed working gas volume of 180×10^8 m^3, but there are still various difficulties in UGS construction in China. Firstly, the increasing speed of working gas volume is slower than that of peak shaving demand volume. Secondly, the UGS building engineering is difficult in technologies and high in investment costs. Thirdly, safe operation is under high pressure and it is hard to identify and control risks. Fourthly, there are fewer candidate UGS sites in China and UGS building conditions are complicated. And fifthly, it is difficult for those UGSs to realize economic benefits only based on their own operation under the existing natural gas price systems. To sum up, the currently available UGS operation modes and building technologies in China are not sufficient to cope with the challenges resulted from markets and complex geologic conditions. Facing all these challenges, it is necessary not only to explore market driven operation modes, but also to strengthen technology tackling and carry out core technological research and development, including geologic evaluation, gas reservoir engineering, drilling and completion engineering, UGS injection and gas recovery engineering, surface auxiliary technologies and UGS integrity evaluation, so that UGS building efficiency can be increased greatly.

Keywords: China; Underground gas storage (UGS); Peak shaving; Challenge; Geologic evaluation; Injection and withdrawal engineering; Key integrity evaluation technology

1. Faster construction of UGS – a key measure to ensure safe supply of natural gas in China

The pipe network system supporting the great development of natural gas in China has basically been formed with the construction of various types of long distance gas pipelines like Shaanxi-Beijing Gas Pipeline, West-to-East Gas Pipeline, Sichuan-to-East Gas Pipeline, Burma–China Gas Pipeline, Offshore LNG Import Channel and Russia–China East Gas Pipeline (to be constructed). In 2014, the apparent consumption of natural gas reached 1800×10^8 m^3 in China; with the further large-scale exploitation and utilization of domestic conventional gas and shale gas as well as the further growth of demand for clean energy because of domestic environmental protection, the proportion of natural gas in the field of primary energy consumption would steadily increase in China. Based on prediction, gas consumption will reach 3000×10^8 m^3 in 2020 [1] and 5000×10^8 m^3 in 2030, and the dependence on foreign gas will also exceed 50%. Facing such an increasingly severe situation, natural gas production and sale enterprises have to undertake a major social responsibility to ensure the safe supply of natural gas.

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Underground gas storage (UGS) is not only the primary facility for ensuring the safe supply of natural gas but also an important part for ensuring the national energy security. Therefore, it is a significant strategic measure of ensuring the safe supply of natural gas to speed up the construction of UGSs in China. A batch of UGSs represented by Hutubi UGS in Xinjiang province have been built successively in recent years, and the construction of UGS has entered a new development stage up to now, which play an important role in the course of maintaining safe and steady supply of gas in China. However, there is still a big gap between the construction of domestic UGS and the demand of peak shaving. As of today, the peak shaving capacity of UGSs that have been put into production in China is only 2% of gas sales volume, far lower than the average level of 11% of UGS working gas volume in annual gas consumption abroad. As a result, gas supply enterprises are forced to realize production, supply and sales balance by reducing users, increasing the production of gas fields and supplying LNG, which have brought a tremendous pressure for gas sales, gas field development and safe supply of gas. Estimated based on the fact that domestic UGS working gas volume should reach the global average value of 11%, the demand for domestic UGS working gas volume will be 385×10^8 m^3 and 550×10^8 m^3 in 2020 and 2030 respectively. Obviously, the construction of UGS in China has a long way to go.

2. Main achievements in UGS construction in China

UGS construction started with a gas reservoir in the Daqing oilfield of China in the 1970s. At the beginning of the 1990s, with the construction of Shaanxi-Beijing Gas Pipeline, the construction of the first real commercial UGS – Dagang Banqiao Dazhangtuo gas condensate field UGS started in 1998, and was put into production and operation in 2000; subsequently, six UGSs were successively built and put into production in the Banqiao gas condensate field, and the Dagang Banqiao UGSs were formed in 2006. From 2000, for the sake of ensuring the safe and steady supply of gas of the West-to-East Gas Pipeline, evaluation on the first salt cavern UGS in China started, which was put into construction in 2005, and the old cavity was put into production and application in 2007, marking the birth of a real salt cavern UGS in China or even in Asia [2]. Represented by the above two UGSs, China opened the prologue of large-scale construction of UGS. After 20 years of development, China's UGS construction has made considerable achievements mainly embodied in the following two aspects.

1) The UGS construction is largely speeded up and the working gas volume has been increased obviously, which play an important role in peak shaving and gas supply ensurance. As of today, a batch of UGSs have been constructed and put into production successively in the Hutubi gas field of Xinjiang Uygur Autonomous Region, the Xiangguosi gas field of Sichuan Province, the Shuang 6 gas field of Liaoning Province, the Suqiao gas field of Hebei Province, the Banqiao gas field of Dagang oilfield, the Jingbian gas field of Shaanxi Province and the Wen 96 gas field of Henan Province in China, and 11 UGSs in total (Table 1), with designed storage capacity of about 400×10^8 m^3, working gas volume of 180×10^8 m^3, and constructed peak shaving capacity of about 40×10^8 m^3. These UGSs have played an important role in peak shaving and gas supply ensurance in China, especially in Beijing area, where the maximum daily peak shaving gas volume available in the UGSs in winter approaches 3200×10^4 m^3, accounting for about 1/3 of daily peak gas consumption in the area in winter. Moreover, after the Hutubi and Xiangguosi UGSs have been put into production, large-scale gas injection started, which ensure the smooth running of import natural gas pipelines, and sufficiently exhibit the function of UGSs.
2) A series of problems related to UGS construction have been successfully solved, and great progress has been made in aspects like construction concept, technique and management of UGSs. In terms of optimization, operation and management of watered depleted gas reservoir UGSs, represented by the Dagang Banqiao UGSs, abundant experiences have been accumulated in various aspects like storage management, operation optimization and project adjustment. In term of construction plan of deep low-permeability carbonate UGSs, represented by Huabei Suqiao UGSs, UGS construction depth reaches 4500 m, creating a world record, and simultaneously, precious experiences in aspects like large size well drilling and completion techniques have been accumulated.

Table 1
Design parameters of UGSs constructed.

Name of UGSs	Storage capacity/ 10^8m^3	Working gas volume/ 10^8m^3	Daily gas injection capacity/10^4m^3	Daily gas withdrawal capacity/10^4m^3
Wen 96	5.9	2.9	200	500
Banqiao Group	69.6	30.3	1300	3400
Jing 58 Group	15.4	7.5	350	628
Liuzhuang	4.6	2.5	110	204
Jintan	26.4	17.1	900	1500
Shuang 6	41.3	16.0	1200	1500
Suqiao	67.4	23.3	1300	2100
Bannan	10.1	4.3	240	400
Hutubi	117.0	45.1	1550	2800
Xiangguosi	42.6	22.8	1400	2855
Shaan 224	10.4	5.0	230	417
Total	404.8	173.9	8780	16304

3. Difficulties in the construction of UGSs in China and their causes

3.1. Major difficulties

Although great progress has been made in the UGS construction in China, due to the existence of objective factors like complex geologic conditions and increasingly harsh surface conditions for UGS construction as well as other factors like relatively late start-up, insufficient experiences, mismatching techniques, weak basic theories and imperfect technical standard systems, a great many problems are confronted in the construction and operation of UGSs, mainly exhibited in the following aspects:

1) Slow UGS construction and productivity-reaching speed and low working gas volume exert a great pressure on peak shaving and gas supply ensurance. Due to the swift growth of gas consumption in recent years, the demand of peak shaving becomes increasingly strong. However, for the lack of construction and operation management experiences in UGS construction in China, the UGS construction and productivity-reaching speed is far behind the demand of peak shaving. For example, the Dagang Banqiao UGSs, which were firstly constructed and put into service in China, show a very slow productivity-reaching speed after 14 cycles of operation, with the achieved working gas volume being only 18.5×10^8 m^3, far lower than the designed index of 30.3×10^8 m^3. The total peak shaving gas volume of PetroChina was about 130×10^8 m^3 in 2012, but UGSs only provided 21×10^8 m^3 peak shaving gas volume, only accounting for 16% of the total (1.9% consumption), and 84% peak shaving gas volume had to be resolved by reducing users, peak shaving of gas fields and supply of LNG, which brought great pressure on gas sales and gas field development. With the further growth of gas sales volume, it is hard to maintain the mode of reducing users and peak shaving of gas fields.
2) The engineering construction difficulty is great, resulting in sharp rise of investment cost of UGS construction. Because the geologic conditions for building gas reservoir type of UGSs are complicated in China, and the burial depth of gas reservoirs is large, and the pressure coefficient of some depleted gas reservoirs is as low as 0.1, it is very hard for drilling [3]. For the sake of ensuring large displacement and high speed injection and withdrawal of UGS wells, large size vertical wells and horizontal wells are usually drilled, resulting in great difficulty of construction project. A case in point is a deep UGS in China. A total of 8 horizontal wells were designed, however, severe and complicated accidents like leakage, poor cementing quality and casing failure occurred in six of them, moreover, the investment in some horizontal wells is up to RMB ¥100 million per well (Fig. 1), all of which have had a great impact on the construction and operation of this UGS. Similarly, among the salt cavern UGSs, the Pingdingshan salt cavern serves as an example. Affected by the creep of deep high temperature salt rocks, it has great difficulty in drilling, completion and cementation.

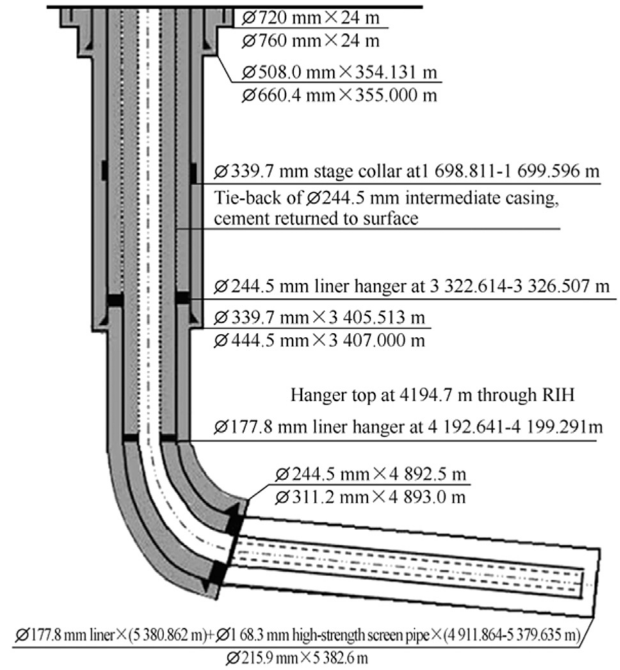

Fig. 1. Casing program of a failure well in an UGS.

3) There is great pressure of safe operation and great difficulty in risk identification and control. As a major measure for ensuring the safe supply of natural gas, the UGS must also be paid high attention to the safety itself. It is shown by foreign data that 65 UGS leakage safety accidents have ever been reported in USA and Europe, and they have resulted in heavy casualties and property losses. Although domestic UGSs have been put into production for only a few years, the risks like the failure of production pipe strings and the destruction of trap sealability resulted from high speed forced injection and withdrawal also severely threaten the safe operation of UGSs. The Banqiao UGSs are a good example. Among the 76 gas injection and withdrawal wells, 74 of them have large potential safety hazards like casing annulus under pressure (Fig. 2), simultaneously, there are also phenomena like unsound safety monitoring, risk prevention and integrity measures.
4) There are only a few UGS site resources and complicated conditions for building UGSs. Among the UGSs constructed in China, the gas reservoir type of UGSs accounts for more than 90%, but are mainly distributed in the hydrocarbon accumulation provinces of northern China; whereas in southern China where the leading market of natural gas exists, the constructed UGSs are dominated by salt cavern UGSs characterized by small working gas volume and scale; besides, no aquifer UGSs have ever been constructed, and the UGS type is single.

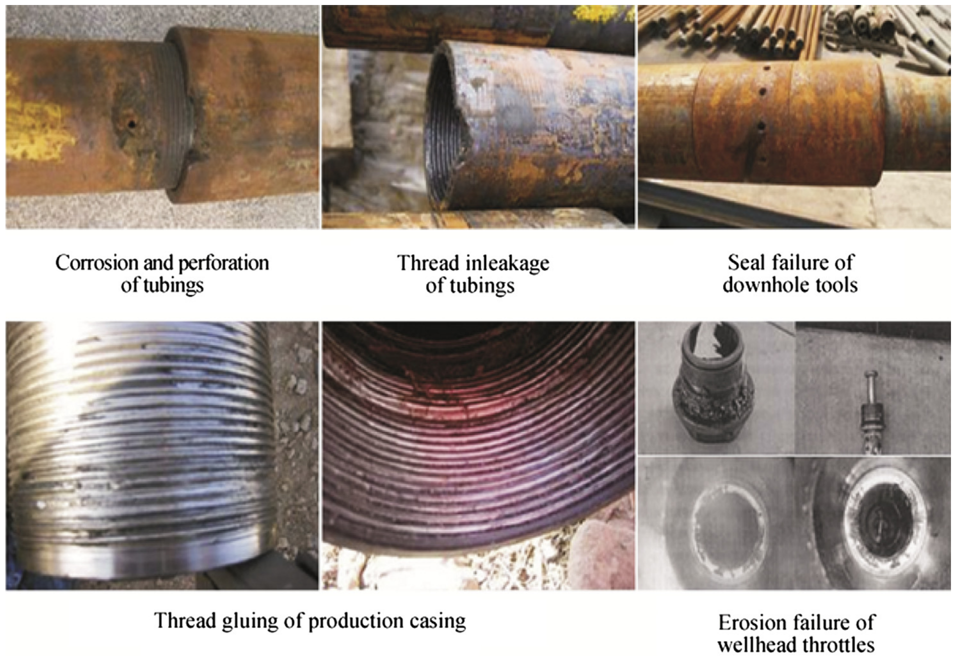

Fig. 2. Common leakage cases in UGS wellbore failures.

At present, gas reservoirs with good conditions have mostly been brought into the scope of UGS construction; whereas the multi-interbed salt beds, the deep and low-permeability oil and gas reservoirs with complicated trap conditions, and the aquifers are the main targets for the construction of UGSs in the future, but the difficulty is great and the risk is high, especially in the downstream gas market development areas such as Circum-Bohai Sea and Southeast Coast where the targets for the construction of UGSs are very scarce. Moreover, the geologic conditions for building different types of UGSs are complicated in China, mainly reflected in that in gas market development areas, the geological structures are fragmentized and the continental depositional settings are complicated. In addition, the depth of building UGSs has also broken the limit in the world, e.g., the burial depth of Su 4 and Su 49 gas reservoir type of UGSs exceeds 4500 m, and that of Pingdingshan and Chuzhou salt cavern UGSs approaches 2000 m. And finally, as for continental salt lake deposited salt beds, the conditions for building the UGSs are complicated due to numerous interbeds, low qualities, great burial depths, making the construction difficulty further increase.

5) Under current domestic gas pricing system, the benefit of building UGSs cannot be reflected. Because there is no peak-trough difference between winter and summer gas prices at present in China, the investment in the construction of UGSs can only be recovered by means of gas pipelines. If capital pay-off and operation benefit are considered by taking the UGSs as independent facilities, it would be hard to reflect the contribution of UGS construction to the overall benefits of natural gas business. Meanwhile, pipeline assets are possibly optimized and reorganized in the future in China, and the investment, operation and management of UGSs are possibly separated from that of gas pipelines, therefore, how to realize sustainable development of UGSs will be a great challenge.

3.2. Causes for difficulties

1) The forward-looking fundamental researches in UGS operation patterns and technical and economic policies are insufficient, and mainly reflected in: ① an integrated strategic planning for UGS realm has not yet been formed in China, and enterprises cannot overall promote the UGS construction as per planning; ② there is lack of systematic optimization layout study related to a variety of peak shaving modes like market, pipe network, UGS, gas field and LNG; and ③ because UGS operation patterns and the peak shaving gas prices have not yet been established, the investments of enterprises in the UGS construction are hard to be returned, which inhibits the enthusiasms of enterprises in the investments in UGS construction.
2) The overall level of geologic gas reservoir engineering theory is low, and the technical means of assessment are deficient. Although some experiences and means have been obtained in project design of watered-out sand gas reservoir type of UGSs, they are hard to meet the demand of scientific construction and optimizing operation of different types of complicated UGSs, which are mainly reflected in: ① the UGSs are designed referring to the gas field development, and the core concepts have not yet been thoroughly updated; ② there is lack of systematic study on the high speed injection and

withdrawal mechanisms and operating efficiencies of UGSs built in reservoirs with different lithologies and physical properties; ③ the UGS construction theories and control methods of deep multi-interbed salt rocks are still in exploration; and ④ the site selection assessment criteria and exploration and evaluation methods of aquifer UGS are still at exploratory stage.

3) The existing drilling and completion engineering techniques do not suit to the requirements of UGS like long life cycle operation and quick capacity reaching, which are mainly reflected in: ① the problem of safe drilling and reservoir protection of big hole horizontal wells in low-pressure reservoirs has not yet been solved, and the old well plugging tools are deficient; ② the ductile cement slurry system, pressure sealing technology and casing design technology under alternating stress have not yet been established; ③ the efficiency of cavity building and brine discharge by gas injection is low, and the old cavity transformation and utilization difficulty is great; and ④ drilling and completion standard systems conforming to the special and complex geologies of China have not yet been formed.
4) The injection-withdrawal technological systems conforming to the injection and withdrawal characteristics of UGSs have not yet been formed, which are mainly reflected in: ① alternating load and corrosive medium coupling effect are not taken into account in the design of injection and withdrawal strings, and definite bases are deficient in the type selection of downhole tools; ② the study on string failure mechanisms only stays in the study of single factor, the workover rate of injection and withdrawal strings is high, and the workover cycle is short; ③ the property of protective liquid in tubing-casing annulus cannot be self-healed, and the effective response time is hard to be ensured; ④ the cathodic protection system is being at an exploratory stage, and the potential safety hazard of casing string failure is great; and ⑤ thorough study has not yet been conducted on the sanding mechanisms under forced injection and withdrawal behavior, the initial sand control completion mode is not effectively directed, the wellbore instability risk is high, and the injection-withdraw capability is affected.
5) The technology for processing the produced gas is single, and the critical equipment depends on import, which are mainly reflected in: ① the produced gas processing technology cannot meet the demand of large scale development, and the surface construction cost is high; and ② the critical equipment like compressors and assorted spare parts depend on import, the replacing frequency of vulnerable parts is high, the quantity required is large, the lead time is long, and the price is high.
6) The safety management is short of effective technical support, and the integrity technology and standard system are unsound, which are mainly reflected in: ① the core technologies like selection of applicable strings, assessment on trap and cavity sealability, control of wellbore quality, risk assessment, integrity detection and assessment, maintenance and repair and abandonment disposal remain to be systematically studied; and ② Integrated integrity management system from design to operation of geology-wellbore-surface has not been formed, and omnibearing operation monitoring and relevant risk management and control standards and specifications have not been formed either.

4. Key essential technologies for UGS construction

The construction of UGSs is a systematic engineering, involving such aspects like geologic area selection and assessment, drilling and completion engineering, surface construction engineering, UGS operation monitoring, integrity management and safety evaluation. Observed from the systematic summing-up of UGS construction technical systems and the urgent technical requirements of UGS construction for the moment, the UGS construction in China needs to strengthen technical research in five aspects, so as to form the assorted technologies in UGS construction and operation management suitable for complex geological conditions in China.

4.1. Geologic and gas reservoir engineering assessment technique for porous UGSs

After more than 10 years of construction and operation, porous UGSs represented by Dagang Dazhangtuo UGS have accumulated a series of technologies and experiences, especially, the core technologies for transforming gas reservoirs into UGSs have basically been mastered [4–6]. However, in view of the increasingly complicated UGS construction geologic conditions in China, the present technologies and experiences cannot meet the requirements of UGS construction and operation in the future, and it is in dire need of conducting research on the key technologies like dynamic evaluation on UGS trap sealability, evaluation on UGS construction and injection and withdrawal mechanisms under the conditions of high speed injection and withdrawal, UGS capacity parameter design and injection and withdrawal optimization. The theory in building UGSs in oil reservoirs or aquifers is basically in blank, especially, the technologies in prediction on balance and gas loss of multicycle oil and gas facies fluid, exploration evaluation and test of aquifer traps are in dire need of solving. In addition, due to the complicated distribution of fluid under the ground in the course of injection and withdrawal of porosity formation UGSs, the UGS monitoring technologies represented by the low-cost 4D microseismic monitoring technique are in dire need of research.

4.2. Geologic engineering assessment technique for salt cavern UGSs

In terms of salt cavern UGSs, after more than 10 years of research, the first salt cavern UGS, represented by the Jintan UGS in China, has made great progress in aspects like cavity building design, cavity building engineering and operation management, and the technologies like geologic evaluation of salt bed, single cavity optimization design, operation pressure interval determination, stability evaluation, UGS capacity parameter optimization and sealability evaluation have basically been formed [7]. However, with the expansion of salt bed UGS construction towards multi-interbed, low-grade and middle-deep layer, the existing techniques cannot meet the requirements of building UGSs in complicated salt beds. In terms of cavity building control, the technologies like simulated prediction of cavity building under complicated salt bed conditions, twin hole and horizontal dissolved cavity building control are in dire need of strengthening study. In terms of salt cavern stability study and interbed collapse prediction control, although a lot of related researches [8,9] have been conducted in China, the technologies like prediction on stability and creep in operational process of deep salt beds, prediction and control of heavy parting in salt beds, utilization mode and means of porous space in accumulation at the bottom of cavity, and salt cavern operational process monitoring need to be further studied, so as to meet the requirements of building UGSs in complicated salt beds.

4.3. Drilling and completion techniques for UGSs

After more than 10 years of development, the drilling and completion techniques for UGSs have achieved good results in China. However, deep UGSs represented by Huabei Suqiao UGS, have encountered a lot of problems in the course of drilling and completion of big holes, such as complicated accidents frequently occurring in drilling, long drilling period, and high cost. The key techniques represented by lost circulation resistance and plugging in drilling and completion of gas reservoir type of UGSs under low pressure coefficients, and horizontal well and directional well drilling, completion and cementation of large wellbore are in dire need of research. Moreover, with the ceaseless development of salt cavern UGS towards the deep zone, the technologies for deep salt bed drilling, completion and cementation under the circumstances of large wellbore are also in dire need of developing. In terms of drilling and completion equipment, for the sake of ensuring the integrity of wellbore, welded casing technology has been adopted abroad, but it has not yet been tried in China up to now, and there are no related facilities and experiences. In terms of drilling and completion engineering of salt cavern cavity building, the drilling and completion technology of vertical well and single cavity building is still mainly adopted in China; for the purpose of breaking the restriction of surface conditions, the technical problems related to drilling and completion and cavity building technology of high angle deviated wells and cluster wells need to be conquered.

4.4. Injection and withdrawal engineering technology for UGSs

In terms of injection and withdrawal engineering for UGSs, after more than 10 years of exploration and field practice, some techniques have already become mature [10]. However, there is still a certain gap between the mastered injection and withdrawal engineering technologies for UGSs and the requirements of injection and withdraw engineering of complicated UGSs, and some technical bottlenecks await to be solved, mainly including failure mechanism and protection technique of string under the circumstance of high intensity multicycle injection and withdrawal, multiple measure separate zone injection and withdrawal technology under the circumstance of one well pattern, long-lasting transformation technique for inefficient reservoirs on the basis of keeping integrity of wellbore and cap rocks, sand prevention and control technique for high permeability reservoirs under the circumstance of large displacement and high differential pressure, material optimization of injection and withdrawal strings and optimization and formalization of downhole tools under the circumstance of different gas qualities and temperatures and pressures, etc. In the meantime, it is also of great importance to establish a set of technical standards and specifications of injection and withdrawal engineering suitable for the geologic conditions in China.

4.5. Surface engineering technique for UGSs

The surface engineering technique for UGSs is basically the same as the surface engineering technique for conventional gas field development, with particularity mainly lying in the surface gas injection system and the large-scale surface processing system. At present, the surface engineering technique for UGSs is basically mature in China, and it has met the requirements of construction and operation of domestic UGSs [11,12]. However, the above-ground equipment of domestic UGSs mainly depends on import; especially, ground compressors completely depend on import. For the purpose of meeting the requirements of peak shaving gas withdrawal of UGSs, the surface produced gas processing system is generally large in scale and poor in flexibility. In view of this, in the realm of surface engineering technique for UGSs, localization of core facilities, especially the localization of compressor manufacturing should be realized. Meanwhile, in terms of surface produced gas processing, the development of produced gas processing facilities towards the direction of large scale and flexibility should be realized, and flexible produced gas processing scheme should also be adopted, so as to meet the requirements of widespread fluctuation in peak shaving of different types of UGSs.

4.6. Integrity assessment technique for UGSs

The integrity evaluation and management of UGSs is the key to evaluation on their safe construction and operation. The object involved includes geological structures, wellbores and ground equipments, and in time span, it involves the integration from design, construction to operation or even the full life cycle when an UGS is abandoned. Although the management system frameworks like sealability detection of gas reservoirs and salt cavern UGSs have preliminarily been established [13], and the method for risk assessment classification of salt cavern

UGSs and prediction of land subsidence has preliminarily been formed [14,15], and the evaluation mechanisms like string integrity evaluation, trap sealability static evaluation, and UGS compressor fault diagnosis, detection and evaluation have also been established in recent years in China, they still cannot meet the requirements of integrity management of the entire UGSs, and the integrity detection technique and equipment still depend on import. The core technologies like selection of applicable strings, control of wellbore quality, and risk assessment, integrity detection and evaluation, maintenance and repair and abandonment disposal of gas reservoir type of UGSs remain to be systematically studied. Meanwhile, assorted operation monitoring and risk management and control standards and specifications need to be established. In view of the integrity of geological structure, a whole set of evaluation and detection means, especially prediction and monitoring techniques for integrity destruction of faults and cap rocks in the course of injection and withdrawal under the crustal stress circumstances. In view of wellbore integrity, corresponding evaluation and detection techniques need to be formed. Moreover, a set of information database and management system that can meet the integrity management of different types of UGSs need also to be established, so that various types of integrity accidents can be effectively prevented, diagnosed and analyzed, thus improving the scientificity and systematicness of integrity management.

5. Conclusions

1) UGSs have played an important role in peak shaving and safe and steady supply of gas in China, but there is still a big gap with the peak shaving demand of the country, therefore, the UGS construction is a long-term and arduous task.
2) After many years of development, UGS construction techniques have made great progress, however, the formed UGS construction techniques are insufficient to cope with the challenges resulted from the increasingly complicated UGS construction conditions in China.
3) It is the key to solving the problems confronted by UGS construction at present in China to rely on scientific and technical progress and strengthen technical research; therefore, the study on core technologies in aspects like geologic evaluation and gas reservoir engineering, drilling and completion engineering, injection and withdrawal engineering of UGSs, surface auxiliary technology and UGS integrity evaluation must be strengthened, so as to largely improve the UGS construction efficiency, effectively cope with the ever-growing demand of ensuring the safe supply of natural gas, and promote the sustainable development of UGSs in China

References

[1] Jiang Zi'ang, Feng Meng, Zhang Hong, Li Jun. Reflection on how to push forward the natural gas revolution in China. Nat Gas Ind 2015;35(3):120−4.
[2] Ding Guosheng. General introduction on key technologies of the construction of Jintan underground salt cavern gas storage. Nat Gas Ind 2007;27(3):111−3.
[3] Pu Qiang, Liu Wenzhong, Fan Xingliang, Wang Dongbo. Fast and safe drilling and completion technologies for low-pressure formations in the Xiangguosi gas storage. Nat Gas Ind 2015;35(3):93−7.
[4] Ma Xiaoming, Yu Beibei, Ma Dongbo, Zhang Shunci, Cheng Yabin, Wang Kexin, et al. Project design and matching technologies for underground gas storage based on a depleted sandstone gas reservoir. Nat Gas Ind 2010;30(8):67−71.
[5] Yang Yi, Li Changjun, Zhang Hongbing, Liu Enbin. Design program of underground gas storages optimized by fuzzy integrated evaluation method. Nat Gas Ind 2005;25(8):112−4.
[6] Xu Hongcheng, Wang Jieming, Li Chun. Inventory verification of underground gas storage based on a flooded and depleted gas reservoir. Nat Gas Ind 2010;30(8):79−82.
[7] Li Jianzhong, Li Qi, Xu Hongcheng. Sealing testing techniques of underground gas storage based on salt caverns. Nat Gas Ind 2011;31(5):90−3.
[8] Shi Xilin, Li Yinping, Yang Chunhe, Qu Dan'an, Ma Hongling. Research on mechanical mechanism of interlayer collapse in solution mining for salt cavern gas storage. Rock Soil Mech 2009;30(12):3615−20.
[9] Chen Weizhong, Wu Guojun, Dai Yonghao, Yang Chunhe. Stability analysis of abandoned salt caverns used for underground gas storage. Chin J Rock Mech Eng 2006;25(4):848−54.
[10] Fu Taisen, Yao Shizhe, Ji Chengxue, Li Wei. Injection-producing well completion technique in Wen 96 underground gas storage. Oil Drill Prod Technol 2013;35(6):42−7.
[11] Tao Weifang, Wang Yongfa, Yue Kejing, Jin Lianshan, Wang Siyao, Hu Zhiyuan. Combined operation technology of gas injection and production process in underground gas storage based on flooded hydrocarbon reservoirs. Nat Gas Ind 2011;31(5):93−5.
[12] Liu Zibing, Zhang Wenchao, Lin Liang, Xue Gang. Ground technology for the construction of underground gas storage in the southern Yulin gas field, Changqing gas zone. Nat Gas Ind 2010;30(8):76−8.
[13] Wei Donghou, Dong Shaohua, Liang Wei. Applied research of integrity management system and related technologies of underground gas storage. Oil Gas Storage Transp 2015;34(2):115−21.
[14] Jia Chao, Zhang Qiangyong, Zhang Ning, Liu Jian, Li Shucai, Yang Chunhe. Preliminary research of risk classification for underground salt rock gas storage. Rock Soil Mech 2009;30(12):3621−6.
[15] Ren Song, Jiang Deyi, Yang Chunhe. Numerical simulation research on ground subsidence after salt cavern gas storage collapsing. Rock Soil Mech 2009;30(12):3595−601.