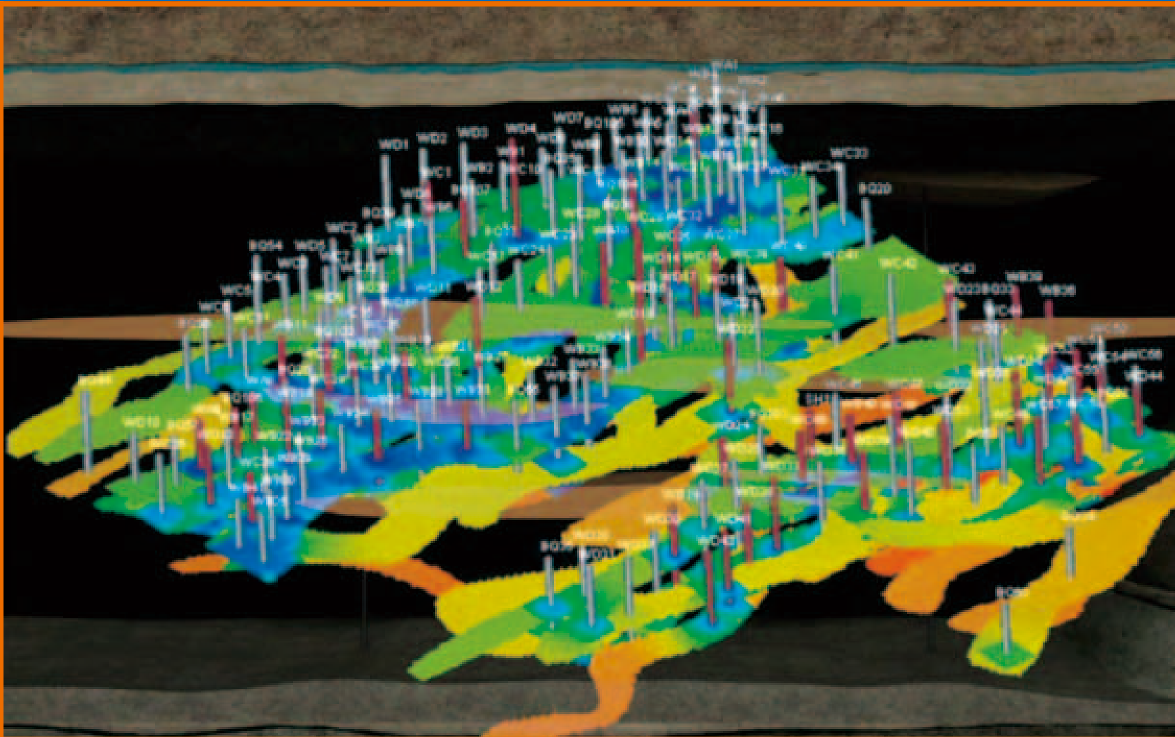


Efficient Development of the Large Tight Sandstone Gas Field in Sulige

China National Petroleum Corporation

Project Description

Located in the north-central region of the Ordos Basin, Sulige is a large sandstone lithologic gas field with gas reservoirs developed in the upper Paleozoic clastic strata at a depth of 3,200-3,500 meters. The gas-bearing layers are mainly Permian sandstone with air permeability of 0.1-2.0mD ($10^{-3}\mu m^2$). The distribution of reserves is characterized by large-area continuity but less concentration, making it difficult to identify the "sweet spots". With proven gas in place amounting to 3.2 trillion cubic meters across an area of 40,000 square kilometers, Sulige is by far the largest onshore gas field in China, featuring low permeability, low pressure and low abundance.

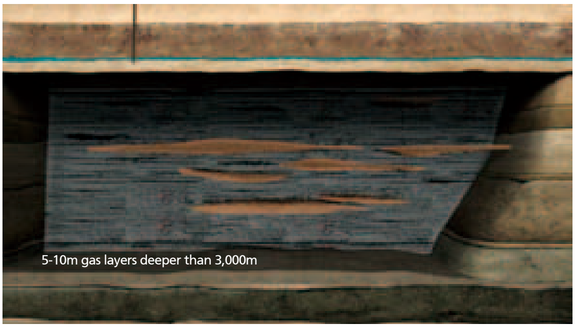
Major challenges to be tackled in tapping the resources include a low individual-well production rate, difficulties in reservoir prediction, and huge investment in surface gathering and transportation systems. After 10 years (2001-2010) of technical research and field testing, a solution package was developed to support an annual capacity up to 13.5 billion cubic meters. As of 2011, there were 4,552 gas wells in operation, producing 13.55 billion cubic meters; 93 gathering stations and 24 trunk lines, capable of gathering 13 billion cubic meters; and 5 processing plants, capable of transporting and processing 23 billion cubic meters, making Sulige field China's largest onshore hub for gas production, transportation and distribution.

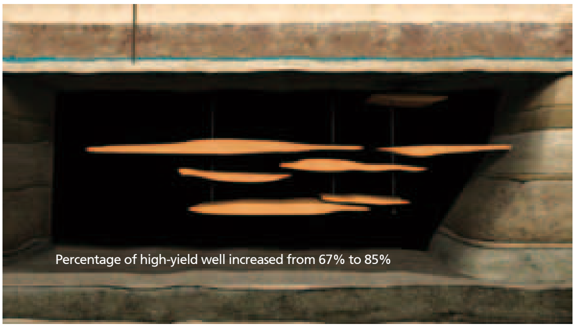
Technological Innovation

The low levels of porosity, permeability and formation pressure, as well as high levels of heterogeneity result in poor continuity and connectivity in sandstone bodies, fewer single-well control reserves, low individual well production rate and rapid pressure drop, making it very difficult to extract the gas efficiently with conventional technologies. The problem is unique and there is no previous experience to draw from. Facing these challenges, technical options were studied and innovated in the pilot development area to develop and improve a solution package for well location optimization, cluster drilling/horizontal drilling, fast drilling, reservoir stimulation, downhole choking, inter-well concatenation and dewatering gas recovery etc. Technical breakthroughs were made in cluster drilling, horizontal drilling and reservoir stimulation to enable significant improvements in development and construction indicators. In particular, the effective reservoir-encountered rate for horizontal wells is 61% with an average single-well daily yield up to 50,000 cubic meters; and 8-layer separate fracturing and 15-layer separate fracturing were achieved for vertical and horizontal wells respectively.

Thin gas reservoir prediction — "sweet spot" identification

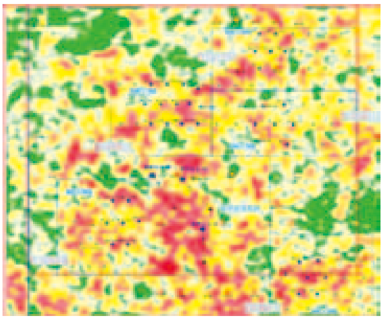
A 2D seismic tool with an enhanced signal-to-noise ratio and higher resolution was developed for the integration of high-precision full-digital seismic techniques. The accuracy of reservoir prediction increased from 10-15 meters to 5-10 meters and the percentage of high-yield wells from 66.7% to more than 85%. Well spacing and well location optimization across this type of reservoir is no longer a problem.





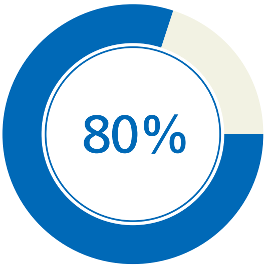
Productivity appraisal of tight gas reservoirs

A first-of-its-kind chart for integrated interpretation of post-fracturing tests in tight gas reservoirs delivers 92.3% consistency in the allocation of production. With the elimination of well testing, the time to start a well can be reduced by an average of 7-10 days and single-well vent gas reduced by 80,000-100,000 cubic meters/time and 300,000 cubic meters/time for vertical and horizontal wells respectively. Natural gas resources are saved and air pollution reduced considerably thanks to the wide use of this technique.



Innovative development well patterns

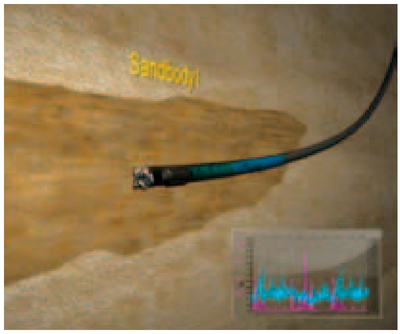
The development well patterns in the field have been optimized to extend the period of stabilized production by at least 30%, achieving a ratio of controllable reserves per well of more than 80%.



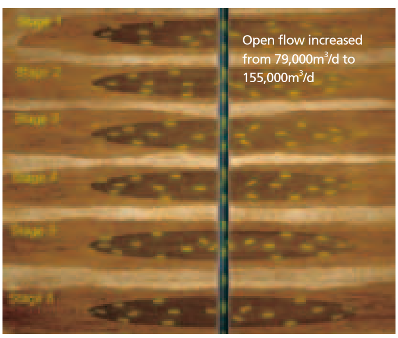
Controllable reserves per well

Cost-effective fast drilling

A new technique was introduced to measure multi-phase flows of liquid (mud), solid (rock debris), and gas (air, nitrogen and natural gas) during the drilling process. PDC bits with involute tooth arrangement and asymmetrical cutters were developed. These techniques enable significant cost savings by reducing the average drilling period from 38 to 18 days for an average along-hole depth of 3,450 meters.



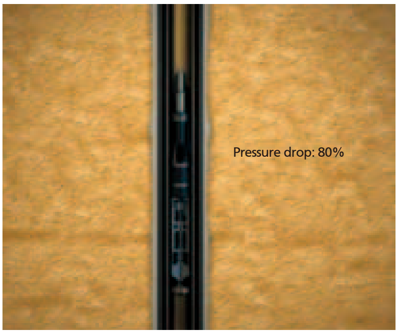
Separate layer fracturing and commingled production



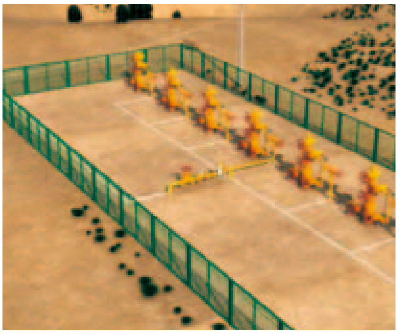
A specific pipe string system for separate layer fracturing and commingled production has been developed to enable 7-layer continuous fracturing without pulling the string, resulting in a doubling of output per individual vertical (directional) well.

High-temperature and high-pressure downhole choking

High temperature and high pressure resistant downhole choke valves were developed for downhole throttling, pressure reduction and hydrate prevention. This technique is critical with regard to gathering gas at low-to-medium pressure levels and reducing surface construction costs.



Inter-well concatenation for low-to-medium pressure gas gathering



The proprietary technique of inter-well concatenation has been developed for low-to-medium pressure gas gathering, leading to a decrease in single-well surface pipeline length by 50% and the reduction in single-well surface construction costs from RMB 4 million to RMB 1.5 million.

Subsurface and Surface Integration

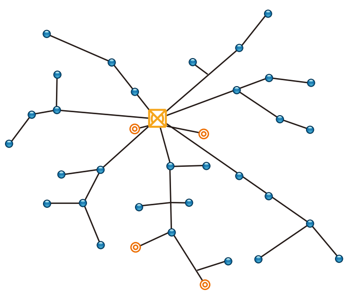
The integration and innovation of wellbore and surface technologies have played an important role in implementing the Sulige project.

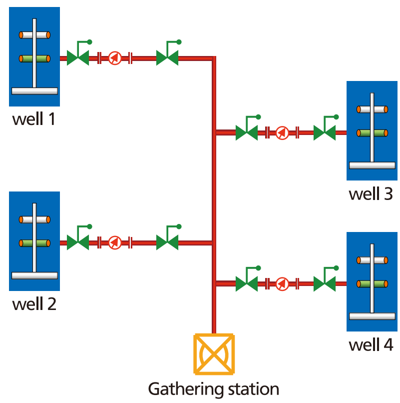
Innovations in downhole choking and low-to-medium pressure gas gathering

Unlike conventional techniques where heater chokes and hydrate inhibitors are used, throttled and cooled natural gas is heated by the temperature field to prevent hydrate formation and reduce the pressure in surface gathering pipelines. The average oil pressure after throttling is 3.88MPa, less than 20% of that before throttling, making it possible to gather gas at low or medium pressure levels and reduce surface construction costs. The uptime rate is increased from 67.0% to 97.2% and the pressure surge in the formation is reduced, resulting in a higher recovery rate. The non-heating, non-inhibitor approach also helps save energy and reduce emissions. It has been used in more than 2,700 wells, reducing methanol use by 12kt/a (standard coal equivalent), gas use for heating furnace by 192kt/a (standard coal equivalent) and vent gas during plugging break-down by 131kt/a (standard coal equivalent).

Integration of small-drop surface layout and inter-well concatenation

Changes in surface elevation are mild at the Sulige gas field, resulting in small drops between surface pipelines. Wide downhole choking application leads to similar levels of production pressure among individual wells. Based on a series of field tests in inter-well concatenation, single-well multiphase flow measurement, wellhead emergence block valve, and wellhead wireless data transmission etc., a cost-effective approach for gas gathering at low-to-medium pressure levels has been developed, integrating downhole choking, non-heating at the wellhead, non-inhibitor, low-to-medium gas gathering, differential pressure measurement, inter-well concatenation, atmospheric temperature separation, two-stage supercharging, centralized processing and digital control. The gas pipeline system comprises concatenated branch pipelines that are brought into the trunk line before reaching the gathering stations. The pipelines from new wells can be included whenever and wherever required. The approach is applied in over 5,000 wells, reducing single-well pipeline length by 36%. This is a brand-new gas gathering solution following the "single-well gathering" and "high-pressure gathering" methods.





Gas pipeline connecting and gathering pattern in Sulige Gas Field

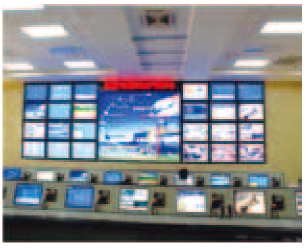
Standardized design for gas gathering process

Standardized designs of processing plants and gathering stations, and standard procedures for procurement, project management and cost estimating have been introduced. Standardized layouts have been designed for 14 types of processing plants and gathering stations of various scales across the gas field, shortening the design cycle by 30%.

Modular construction of gathering and processing facilities

A modular approach has been adopted to facilitate prefabrication, line production, delivery and on-site assembling of process modules for processing plants and gathering stations. This approach is used in the construction of all processing plants and gathering stations. The integration of standardized designs and process modules helps reduce the installation period of gathering station from 30 to 10 days, with the overall construction period reduced from 111 to 30 days. As for processing plants, the construction period has been reduced from 14 to 9 months. The processing plants and gathering stations thus constructed are 100% acceptable and 92% of them are rated as excellent.

Remote monitoring



The digital production management system of Sulige gas field has seven elements, including operation management, digital well monitoring, emergency remote shutdown, emergency response and rescue. The optimization and upgrading of critical equipment allow the system to support three major management functions, i.e. real-time monitoring of production data, auto remote control and intelligent security supervision, enabling unattended operation at gas gathering stations and making the process less labor-intensive. This results in staff downsizing of 50% and meanwhile meets the gas field's management needs.

Project Summary

The project comprises a series of research efforts and production operations. Seven major development tests have been conducted as scheduled. The project benefits from state-of-the-art technologies and cost-effective initiatives. The actual construction period was two years shorter than planned. The number of field operators has decreased by 50%. The management structure has been further streamlined to facilitate a shift from on-site monitoring to remote monitoring. Operational safety has also been ensured and the local ecological environment has been protected during project execution.

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