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# Study on Solution Mining Technology for 3000 Meter Deep Wells

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ABSTRACT

This paper describes solution mining testing of a rock salt deposit in 3000 m deep wells. There are problems with some advanced technologies: hydraulic-fracture and three-pipe oil-blanket for 3000 m deep wells. According to the solution mining test in Gao Feng Mine, analyses of mining equipment, the pipe set combination, and the mining technique show that deep well solution mining is very valuable and an important aspect in the development of solution mining technology.

## INTRODUCTION

In solution mining of rock salt deposits, the use of a new technique of water injection into the well by high pressure multistage pumps makes deep-well mining a possibility. For this reason, the depth of salt stratum it is possible to mine has exceeded 2000 m, merely from a point of view of technology.

However, in the recently explored Wan Xian Salt Basin where the buried depth of the target stratum roof is more than 3000 m, certain solution mining techniques were used and it was found that these proven and successful techniques were limited or even unusable at this depth.

Based on the practice of the Chuan Dong Salt Factory situated in the middle of the Wan Xian Salt Basin, this paper discusses new problems of the technology used in deep-well solution mining. Some new ideas and views are proposed in order that experts in this field can study the technology further and search for more advanced and practical new techniques.

## GEOLOGICAL TEXTURE AND ROCK SALT DEPOSIT CHARACTERISTICS

The Triassic period was one of the most important salt-forming periods in China. During the Early and Middle Triassic periods, the region was dry, many caverns formed in the upper part of Yangtze Basin, and the huge marine rock salt deposits were formed. These are concentrated over the area of Sichuan Province, among which Nan Chong and Wan Xian Salt Basin are the largest (Wang Qing-Ming, 1985).

The distribution area of Wan Xian Salt Basin is roughly similar to the Wan Xian syncline, running from north to east, with the southwest end from Ba Shan Temple of Zhing Xian County and northeast end from the west Yun Yang city, extending about 100 km in length with a distribution area of 2000 square miles.

It is the largest salt deposit known in China at present (Figs. 1 and 2) and $40 \times 10^9$ t of rock salt and $380 \times 10^9$ t) of potential reserves have been explored (Lin Chuang-Lu and Ren Wei-Dou, 1988).

According to the drilling data, there are six salt-bearing strata in Wan Xian Salt Basin, the main characteristics of each being as follows:

$T_2b^{3\text{-}2}$: a single salt layer with a thickness of 1–14 m. It is relatively narrow in distribution with great lateral variation.

$T_2b^{3\text{-}1}$: has 1–3 beds of salts, with an accumulative thickness of 4–18.5 m and an NaCl content of more than 90%.

$T_2b^{1\text{-}1}$ upper salt section: the main salt bed in Wan Xian Salt Basin, wide and stable in distribution and 88% NaCl. Several layers of anhydrite, less than one meter each, are contained within this salt strata, with a thickness of 14–90 m.

$T_2b^{1\text{-}1}$ lower salt section: has a local distribution over the Salt Basin area, with a thickness of 1–43.5 m.

$T_1j^{5\text{-}2}$: includes many layers of rock salt, with an accumulative thickness of 7.5–89.5 m.


Fig. 1. The People's Republic of China.

$T_1j^{4-2}$: includes many thin layers of rock salt, with an accumulative thickness of over 30 m (Lin Chuang-Lu and Ren Wei-Dou, 1988).

Of the above six strata, the $T_2b^{1-1}$ upper salt stratum is the thickest. It is simple in sectional texture and stable in distribution, with a buried depth of 2700–3100 m (Fig. 3). The immediate roof is anhydrite and dolomite, 8–11 m thick. The secondary roof is limestone and dolomite, with a thickness of 35–40 m. The immediate roof has good stability, with vertical compressive strength reaching about 50–120 (MPa) (Lin Chuang-Lu and Ren Wei-Dou, 1988). The salt stratum is the first target stratum to be chosen for mining. Figure 4 shows the column diagram of the salt-bearing formation.

The Gao Feng Mining Area is under the Chuan Dong Salt Factory and is currently under development. It is located in the southwest wing of the

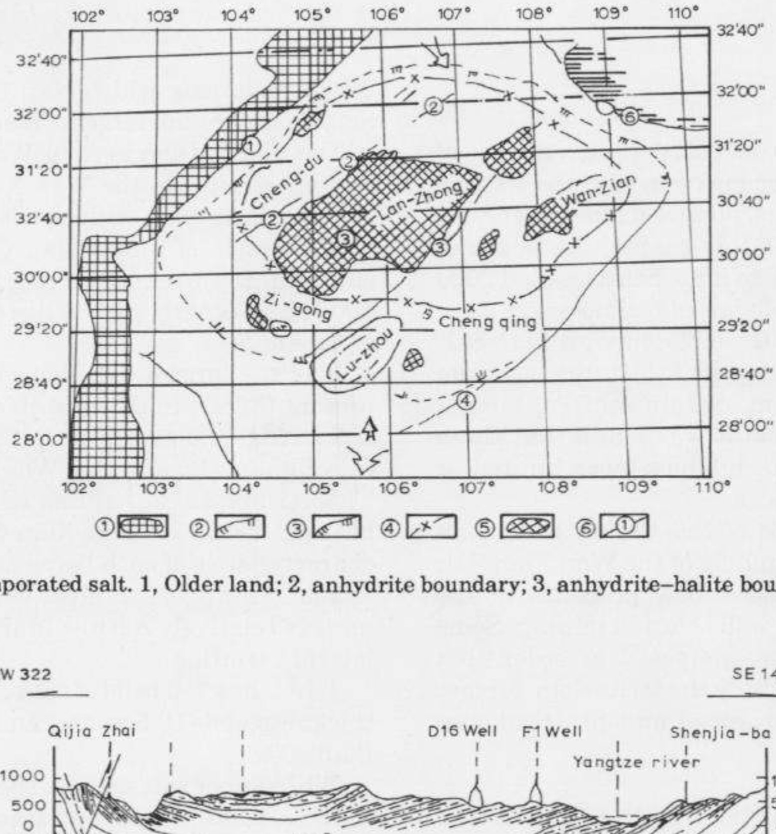


Fig. 2. Distribution of evaporated salt. 1, Older land; 2, anhydrite boundary; 3, anhydrite–halite boundary; 4, halite boundary; 5, halite; 6, fault.

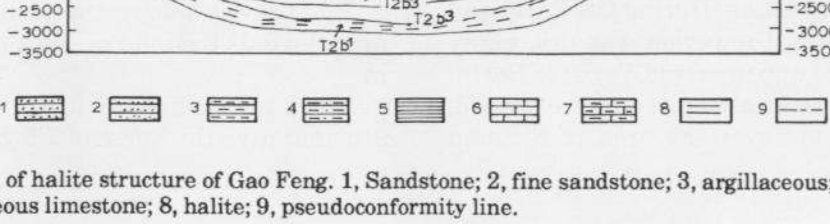


Fig. 3. The cross section of halite structure of Gao Feng. 1, Sandstone; 2, fine sandstone; 3, argillaceous; 4, sandy shale; 5, shale; 6, limestone; 7, argillaceous limestone; 8, halite; 9, pseudoconformity line.

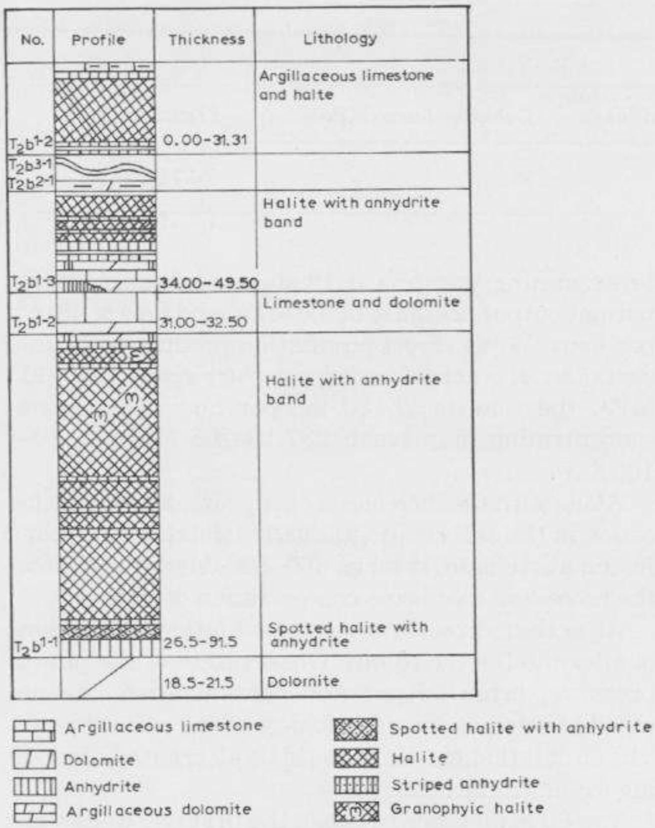


Fig. 4. Geologic column of halite strata.

middle sector of the Wan Xian syncline.

The stratum here dips to the east, with a strike of 320–330° and an angle of dip of 5–10° (Lin Chuang-Lu and Ren Wei Dou, 1988). Table 1 shows the target strata thickness and depth of completed exploration and production wells of the mine.

## DRILLING ENGINEERING

In the Chuan Dong Salt Factory all production and planned wells are constructed with $12^{1}/_{4} \times 9^{5}/_{8} \times 8^{1}/_{2} \times 7 + 6$ inch casing. The 7-inch casing extends down to the anhydrite or dolomite, 3–5 m above the salt/roof interface.

TABLE 1

Salt stratum thickness and well depth of $T_2b^{1\text{-}1}$ upper salt sector (in metres)

| | Well No. | | | | | |
|---|---|---|---|---|---|---|
| | F1 | F2 | D16 | D17 | W1 | W2 |
| Salt stratum thickness | 14.5 | 17 | 76.55 | 21.62 | 77.42 | 324 |
| Roof buried depth | 2847.5 | 2867 | 2998 | 3098 | 2996.8 | 2972 |

The well deviation is limited to within 7° of the vertical. To cement the well, it is required that the surface casing cement should reach the surface; it is also preferable that casing cement of 2000 m in height should also reach the surface.

The test pressure of the casing reaches 12 MPa and it should be guaranteed that the pressure decreases to less than 0.5 MPa in 30 min. The drilling depth of each well in No. 1 mining site is shown in Table 2.

## PRELIMINARY EXPERIMENT OF SOLUTION MINING TECHNOLOGY

So far, 3000 m deep-well solution mining is unusual in the solution mining history. In the Chuan Dong Salt Factory, only the single-well convection technique has been tested. Some proven solution mining technologies are limited or even unusable when tried here. The hydraulic-fracture technique, for example, although rapid in salinity increase, rapid in achieving connection production and also achieves the design standards, does not meet the

TABLE 2

Drilling depth of each well (in metres)

| | Well No. | | | | | |
|---|---|---|---|---|---|---|
| | 101 | 102 | 103 | 104 | 105 | 106 |
| Drilling depth of surface layer casing sector | 142 | 142 | 147 | 147 | 147 | 147 |
| Descending depth of surface layer casing | 140 | 140 | 145 | 145 | 145 | 145 |
| Drilling depth of technical casing sector | 2956 | 2973 | 3007 | 3014 | 3005 | 2993 |
| Descending depth of technical casing sector | 2954 | 2971 | 3005 | 3012 | 3008 | 2993 |
| Designed thickness of salt stratum | 66 | 66 | 66 | 62 | 58 | 59 |
| Completed depth | 3031 | 3084 | 3082 | 3085 | 3072 | 3083 |

TABLE 3

The physical and mechanical testing results

| Rock | Tensile strength (MPa) | Compressive strength (MPa) | Cohesive force (MPa) | Friction angle |
|---|---|---|---|---|
| Dolomite | 4.16–5.57 | 91.01–118.73 | 25 | 65–71° |

requirements needed here where the overburden depth reaches 3000 m.

According to the opinion of some experts, the salt stratum fracture pressure is related to the depth, and is calculated as exceeding 70 MPa (Lin Yuan-Xiong, 1990). It is difficult to meet the requirements of such high pressure using existing Chinese mining equipment and piping sets.

The oil/gas-pad technique, which can effectively protect the salt stratum roof, control the rock salt cavity shape, keep production stable and achieve high mining, has no known practical applications for 3000 m deep-well solution mining.

If the three-pipe oil-pad technique is used in the form of a piping set combination of 7 + 5 + 2.25 inch, the net casing/tubing weight of the combination is as heavy as 100 t, making well repairs difficult with simple equipment.

The technique is also limited if applied here owing to the following additional reasons: the oil gravity is 0.85, the brine gravity is 1.18, and the pressure differential is 9.99 MPa when the well is 3000 m deep. In addition, there is a piping set resistance loss and very high pressure of the oil pump is required.

Although it does not effectively control the development of the solution cavity and is liable to expose large roof areas more quickly, which results in collapse and damage to well, the single-well convection technique is evidently superior. It is economical in investment, simple in technological route, easy in operation and can quickly put wells into production.

In the Gao Feng Mining Area, the immediate roof strata is dolomite-bearing anhydrite, with a thickness of more than 10 m. The physical and mechanical testing results of the rock indicated that it has good stability (Table 3).

Based on the structural properties of this salt deposit and considering the load effect of the beam, it has been calculated that the critical span of the cavity roof is approximately 80 m.

Because of the lack of ideal technologies, the single-well convection technique is used in all four production wells in the Gao Feng Mining Area at present.

The construction of the piping set is 7×3.5 inch, i.e. a 3.5 inch drilling rod is used as the central pipe, the brine mining pump is a 12-stage centrifugal with normal output pressure of 9.6 MPa, and flow of 45 $m^3$ per hour. When direct circulation production is undertaken, the actual pump pressure rises to 10–11 MPa, the flow to 25–30 $m^3$ per hour. The brine concentration may reach 237.19–268.75 g/l in 80–100 days.

Along with the increase of cavity size, brine stratification in the salt cavity gradually tends to disappear. In the above case, it takes 400–500 days to complete the process so that brine concentration decreases.

After that, direct or reverse circulation production is alternately carried out. Observation of the pump pressure, brine output and concentration change should be done to avoid blockage of the central pipe. The circulation method should be alternated according to the circumstances.

The 60 m distance between the first two wells was designed to speed natural connection between wells. They were put into test production in May 1988 and October 1991, respectively. After connection, the pump pressure dropped to 8–9 MPa, and the casing convection technique was tried.

First, water was injected into the casing of one well, brine produced from the casing of the other well, at a flow of nearly 90 $m^3$ per hour, brine concentration of 102.81 g/l and temperature of 70°C.

Afterwards, the experiment was rearranged so that water was injected into the casing of one well, brine produced from the central pipe of another well, with the flow decreased to 40 $m^3$ per hour, and brine concentration increased to 268.75 g/l.

In the final experiment water was injected into the central pipe of one well, brine produced from casing and central pipe of another well simultaneously, with a flow of 60 $m^3$ per hour, brine concentration of 237.19–268.75 g/l and a temperature of 58–60°C. The third experiment results were relatively ideal (Fig. 5).

When well W1 was in trial production, the 3.5 inch drilling rod acting as the central pipe was replaced with a 3.5 inch oil pipe of N80 material. The experiment results show that the strength can meet the demands of application completely, with the pump pressure being reduced by 1–2 MPa, flow increased by 10–15 $m^3$ per hour. This proves to be an ideal piping arrangement.

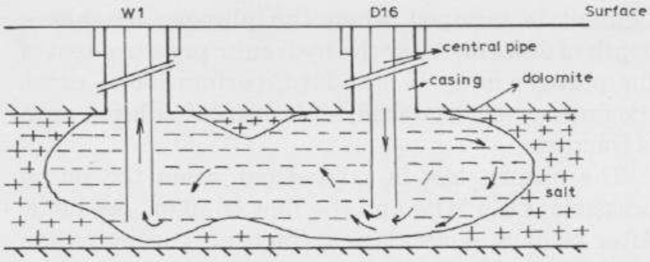

Fig. 5. Natural connection of two wells, Gao Feng area.

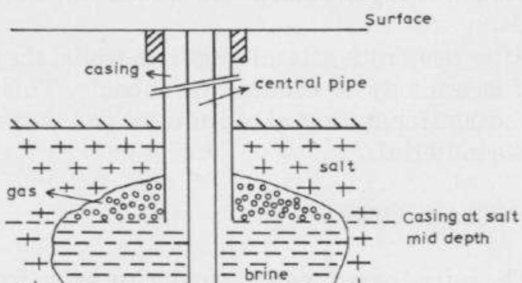

Fig. 6. Gas blanket.

There are four production wells now in the Chuan Dong Salt Factory. Roof collapse phenomenon has not occurred whether they are connected or not. The central pipe is seldom blocked. The results indicate that single well convection connection technology could be used in the practice of 3000 m deep-well solution mining, provided the salt stratum roof has good mechanical properties.

## PROBLEMS STILL TO BE STUDIED AND SOLVED

In all production wells of the Gao Feng Mining Area, there is an abnormal phenomenon that the brine produced is more than the fresh water charged. According to the December 1990 production report of well W2, the fresh water pumped was 6.385 $m^3$ and the brine produced was 9.785 $m^3$. The proportion of the two above was 153.25%, that is, the brine was about 1.5 times the volume of the water. A flammable gas was noted at the brine outlet, no doubt natural gas from the well.

In the case of direct circulation production, natural gas is dissolved in the brine. Under high pressure, 1 $m^3$ of the brine can contain in solution the same volume of the gas.

Natural gas flows out with the brine, having no great influence upon the normal production. The actual brine produced is of significance. In the case of reverse circulation production, the pump pressure is increased to the same extent and the brine produced reduced because the sectional area of the central pipe is 3 times less than that of the casing. This decreases the normal production. The problem remains to be solved. The question remains whether the casing should be made to reach the middle position of the salt stratum (Fig. 6). This can determine the position of the gas-pad.

At the beginning of creating the cavity, less natural gas overflows from the relatively small cavity. The cavity area increases gradually along with the increase in cavity volume; the casing then becomes exposed and natural gas overflows upwards.. In the case of direct circulation, the gas is dissolved in the brine or rises to the ground along with the brine through the annular space between the central pipe and casing. If the casing is exposed to the extent that natural gas accumulates above the casing outlet, an oil-blanket layer is set up.

The oil blanket is easier to form in the case of reverse circulation production. It is well worth studying the use of the overflowed natural gas to set up a gas-pad layer for 3000 m deep wells. Such experiments are planned in the Gao Feng Mining Area in the next stage.

In the mining area, the designed distance between production wells is 70 m. The cost of drilling and completing deep wells is 2–3 times higher than that used for drilling and completing middle or shallow wells.

Twin brine wells do not last long if the wells are too closely spaced. Greater distance between wells improves profit, but takes a longer time to develop. If the space increases to 100–130 m, it takes an uneconomical 3–5 years to be connected with only single-well convection. In addition, before connection, collapse and under-pit accidents may occur if too great an area of the roof is exposed,

Besides using the natural gas for carrying out gas-pad tests as mentioned before, the two-pipe oil-pad experiment might be carried out using the experience learned from shallow wells. When the two-pipe oil-pad technique is used, the casing is also made to reach below the salt strata middle depth (Fig. 7). With the help of natural drift of continuous thin oil pad, the balanced mining operation is carried out from below to above to protect the roof and to speed up well connection. After connection, the central pipe of both wells may be lifted (Fig. 8) and the technical casing is used as the production pipe for the purpose of achieving a high mining rate and high brine concentration.

If the kind of technologies prove successful for testing here, we are sure that effective mining will

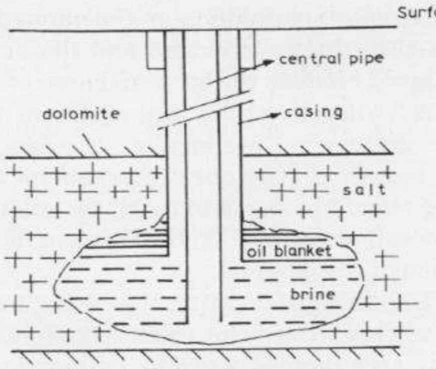


Fig. 7. Two-pipe oil blanket.

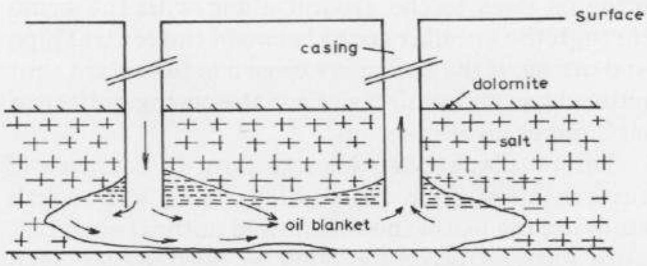


Fig. 8. Two wells oil blanket sketch.

be promoted, brine output increased, and the well service life lengthened. Moreover, down-hole pipe accidents will be decreased, the cost of well maintenance and the cost of brine will be reduced, and the consumption of pipe materials will be cut down. We consider deep-well brine mining as a technique which is well worth studying and carrying out tests.

As described above, it is not only technologically difficult but also expensive in terms of drilling costs to complete a 3000 m deep well. In the Gao Feng Mining Area, except for the target stratum $T_2b^{1-1}$, the thickness of the $T_2b^{1-3}$ and $T_2b^{3-2}$ strata exceeds 10 m. The two strata are protected by 7 inch cemented casing. If perforation is used to exploit the rock salt from them one by one or simultaneously after the brine concentration of the target stratum $T_2b^{1-1}$ becomes uneconomical, the well service life will be prolonged, costs will be reduced, profit improved, and the natural resource used more rationally. In well D17, $T_2b^{3-2}$ strata is the target, thus the well depth is 2700 m.

Near Shi Bao Zai in the west part of the Wan Xian Salt Basin, brine has been produced successfully from the $T_2b^{1-3}$ strata by using perforation technology in an oil well, (No. B4 abandoned). In well B4, the salt strata buried depth is as much as 2786 m, with a thickness of 15.5 m. Seven inch casing extends to 4171.26 m in a natural gas well where the salt stratum is protected by the casing and cement. Cement is pumped when the plunger reaches a depth of 2832 m. After the hydraulic pressure test of the plunger is up to standard, perforation is done, the formation is acidized, and the mining brine path is fractured.

The mining test is carried out when the pump pressure is 6.5 MPa and the flow is 40 $m^3$ per hour. After 20 days of circulation, the brine concentration reaches 221.88 g/l (Fig. 9). One of the study and test aims of the Gao Feng Mining Area is to apply perforation technology to the experimental B4 well, for reference to exploit multi-strata rock salt from deep wells.

After deep rock salt mining from wells, the cavity roof is unlikely to collapse or subside. This is an advantage for storage of oil, natural gas or chemical waste materials.

## CONCLUSIONS

The initial experiment was to mine brine from the 3000 m deep well in the Gao Feng Mining Area. Further advances in practices will occur. At present, deep-well solution mining technology is seldom reported, so we have limited examples to follow. However, the technology is worthy of further study. It represents an important direction for solution mining technology development in the future.

This paper presents my own new views and opinions for review by the world's solution mining experts, and I encourage participation in this technology to facilitate breakthroughs.

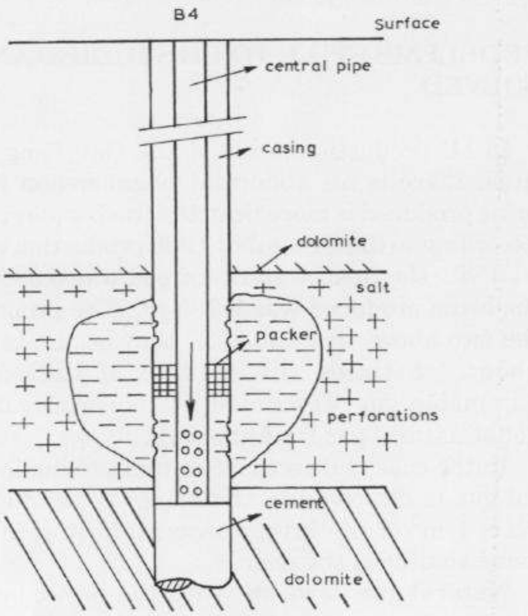


Fig. 9. Sketch of B4 well.

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