Technical Development of Solution Mining in Thinly Bedded Rock Salt Deposits of Ziliujing, Sichuan, China

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ABSTRACT

Ziliujing has a long history of salt exploitation and brine extraction and has been reputed as the "Salt City." Well drilling, brine extraction and salt production started at the end of the second century. Xinghai Well—a brine well—which is 1001.4 m deep and the first deepest well in the world, was drilled in 1835 and has been protected as one of the major cultural relics. Extensive exploration has been conducted, great attention has been paid to the investigation and application of exploiting process and techniques, and excellent achievements have been obtained since the founding of the People's Republic of China. What strikes one most is the technical development of solution mining in thinly bedded mono-layer (10–15 m thick) in the depth of over 1000 m. In the case of the unstable caprock of the rock salt, a new drilling technique is adopted, directional dual bores are drilled according to the natural declivity and cavities in the two wells are developed and connected by using oil pad. Drilling cost is reduced by 23%, the speed of the well build-up is increased by 2.4 times, and one well-site is saved. Reduction of pipe laying and simplification of facilities and management are realized during the oil pad operation and production. Saturated brine is produced with the connection of cavities in thin rock salt layers, and the recovery rate is raised. Also described in this paper is some of the experiences in exploiting extremely thinly bedded rock salt with the thickness of 1–6 m.

INTRODUCTION

Ziliujing (meaning Artesian Well) is located in the south of Sichuan Province. It is now under the administration of Zigong Municipality (See Figure 1). Its production area covers 500 square kilometers.

Ziliujing is rich in rock salt, natural brine and gas resources. The history of exploiting brines and natural gas from Ziliujing Anticline is a long one. Apart from sodium chloride of 160–200 g/l, the natural brine contains more than 30 chemical elements, such as boron, potassium, bromine, iodine, lithium, strontium, rubidium and cesium. It is a very good supply for the chemical industry.

Solid rock salt is generally deposited in the depth of 1000–1500 m. There are four rock salt bodies, Weixi Rock Salt being the largest.

Since the founding of the People's Republic of China, the salt industry in Ziliujing has been progressing rapidly and the output has been increased 3.3 times as compared with the highest annual output in the past. Fifteen chemical products are being turned out. According to incomplete statistics, more than 13,000 boreholes have been drilled; 390 million cubic meters of natural brine and 33.2 billion cubic meters of natural gas have been produced since the beginning of the exploitation. Ziliujing has become one of the most important regions of rock salt production in China.

The purpose of the present paper is to discuss the technical development of solution mining in thinly bedded rock salt layers of Ziliujing.

HISTORY OF EXPLOITATION

Exploitation of rock salt in Sichuan started in the Qin Dynasty. As far back as 250 B.C. in the reign of Prince Xiaowen of the Qins, the Shu Governer Li Bing drilled wells, extracted brine and produced salt in Guangdu (present-day Chengdu and Shuangliu region), which opened up the history of exploiting rock salt in Sichuan.

Ziliujing commenced the exploitation at the end of the second century A.D. The first well drilled was Fuyi Well from which brine was extracted and salt was produced. Ziliujing has been reputed as the "Salt City" just because of its salt-making practice with a long history of more than 1,700 years.

The development of well salt depends upon the drilling techniques. Along with the improvement of drilling techniques and the increase of drilling depth, deeply bedded rock salt, brine and gas were exploited.

As early as the year 589, drilling depth of 200–300 m

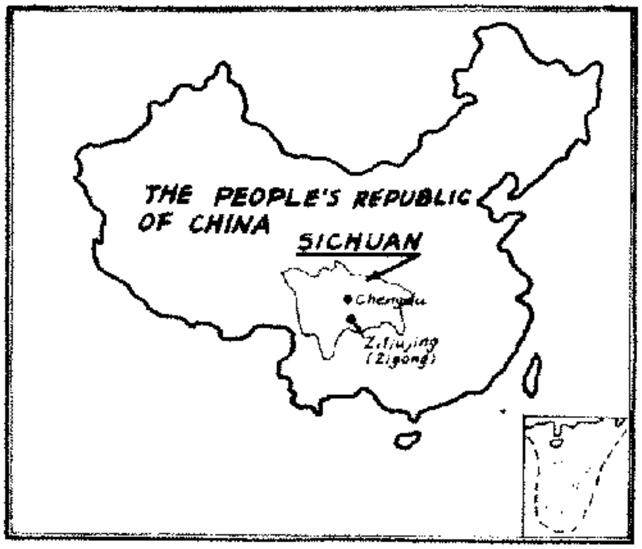

Figure 1. Location of Ziliujing.

was reached. The year 1552 saw the prosperous development of the salt industry when salt was first produced by utilizing natural gas as heat energy. In 1821, wells with a depth of over 900 m could be drilled. Xinghai Well, which was drilled to the depth of 1001.4 m in 1835, is the first deepest well in the world.

In 1850, Mozi Well—the first well with the high capacity of one million cubic meters of natural gas per day—was drilled. It was then called the "King of Fire." It was the first gas well with high yield in the early days.

In 1982, the discovery of Dawenbao Rock Salt, which is thinly bedded mono-layer (4–6 m thick) in the depth of over 1,000 m, was made during the deeper drilling of Fayuan Well. It was the first time that the thinly bedded mono-layer of rock salt at a depth of over 1,000 m in Ziliujing was exploited.

In 1935, Dongyuan Well was drilled; it is a gas well with low pressure. It has been serving for 47 years with an accumulated output of 400 million cubic meters of gas. Its present daily capacity still remains more than 20,000 cubic meters.

The percussion drilling technique then used included drilling, casing, fishing logging and recording operations, and the methods of brine extraction by hoisting means, simultaneous exploitation of brine and gas, and cavity connection were used in the deep, uncased holes. The reason why the drilling and exploiting technique used in the oil and gas industry has enormous effect on the progress of the human civilization is undoubtedly the derivation, inheritance and development of the techniques of drilling and exploiting rock salt, brine and gas in ancient China.

Extensive exploration has been conducted and the reserves of salt and brine enlarged in Ziliujing region since the founding of the People's Republic of China. Meanwhile, investigation and application of exploiting process and techniques have been given attention. In 1967, a large rock salt body—Weixi Rock Salt—was discovered. 1971 saw the commencement of exploitation at the Weixi Rock Salt deposit, which plays an important role in the development of the salt industry in Ziliujing.

Drilling technique is also progressing at a rapid pace due to the adoption of rotary drilling and turbodrilling rather than the old percussion drilling. The method of single well convection in the thinly bedded rock salt deposit was practised in the 1960s. In 1971, hydraulic fracture and directional jetting fracture were used. In 1975, the oil pad method was adopted and the exploitation of rock salt with cavities connected by the control of oil pad succeeded.

Gas-lift, pumping units and submersible pumps are widely used to extract natural brine, which has resulted in the increase of brine production, and the demand for the development of the chemical industry is basically satisfied.

GEOLOGY

General

Sichuan Basin is a well-known artesian basin that is composed of a series of NE asymmetric anticlines and synclines.

The exploiting area in Ziliujing covers Ziliujing Anticline, Xinglong Anticline and Dengguan Anticline. They spread in parallel with the axial lines directed 30°–40°NE. Both limbs are asymmetric and the ratio of macro-axis to brachy-axis is from 6:1 to 2:1. Brine and natural gas are enriched. The main development of the NE and NW faults controls the enrichment and migration of the natural brine.

Weixi Rock Salt is located at the western fringe of Weiyuan Anticline. Dashanpu, Dawenbao and Guojia'ao small rock salt bodies are situated at the southern limb of Ziliujing Anticline (Figure 2).

The drilled strata within the region are of the Jurassic continental sediment, Triassic continental and marine alternating sediments and Triassic marine sediment. For detailed description, see Table 1.

Rock Salt Deposit

The superstratum over the salt deposit is a uniclinic stratum with little fault development. The simplicity of the hydrogeological conditions gives a good preservation.

The Weixi rock salt body exists in the carbonatite stratum of T_2l^{3-1}, which is a deposition of neritic lagoon facies. The rock salt deposit is characterized by large area, great reserves, shallow depth (820–1030 m), high grade (NaCl ≥ 95%), single layer, thin bedding (10–15 m), stability, simple structure, flat occurrance (dip angle: 3°–6°, directed NW) and good preservation. It is of the bedded deposit. The salt is easy to be exploited.

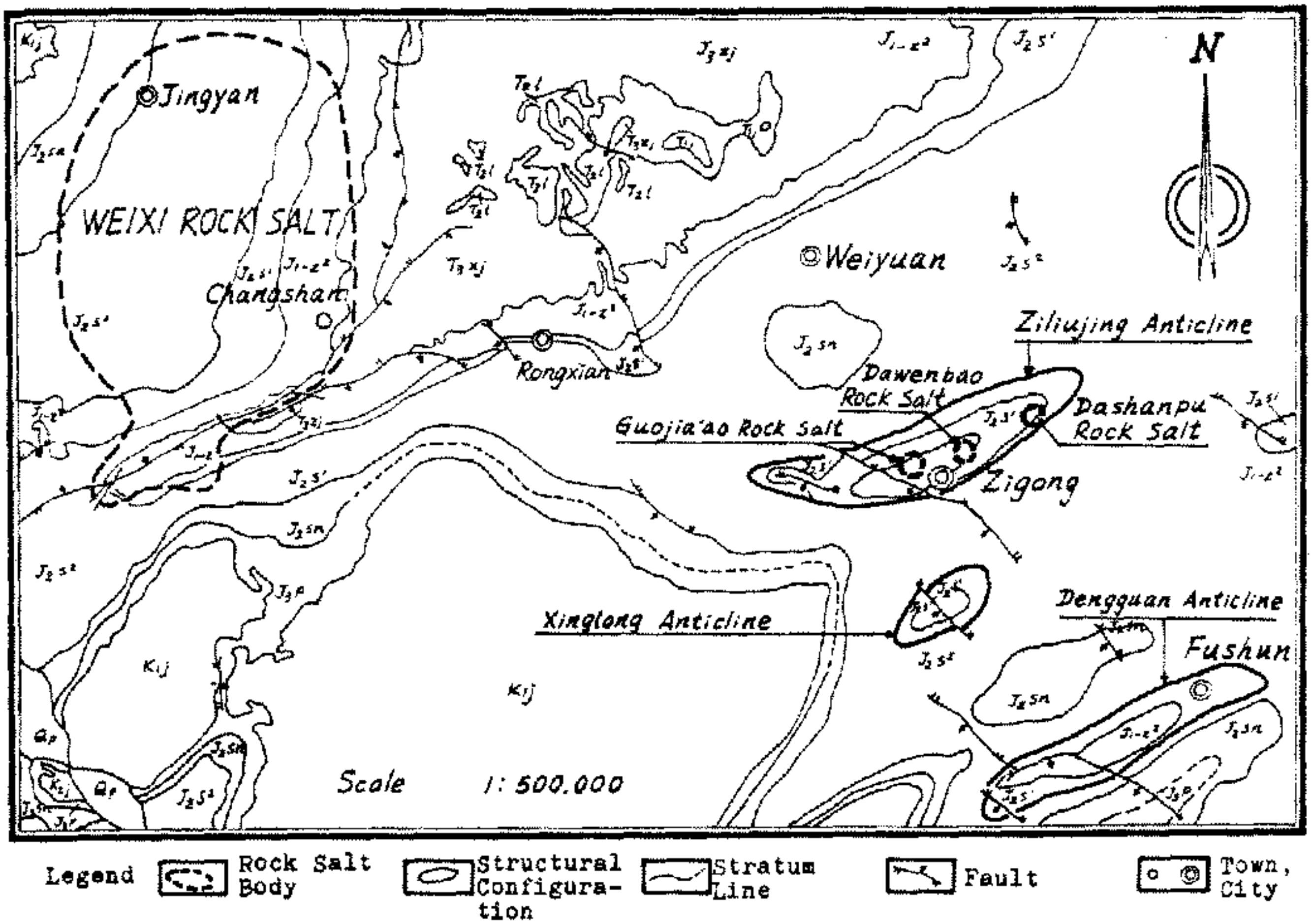

Figure 2. Regional geology of Ziliujing.

TABLE 1

Geological Series

Geological Stage				
System	Series	Code	Lithology	Thickness (m)
Cretaceous	Lower	K_1j	Sandstone with mudstone	308–401
Jurassic	Upper	J_3p	Mudstone with sandstone	88–337
	Middle	J_2sn	Intercalation of mudstone and sandstone	907–1067
	Lower	J_1z	Mudstone with sandstone and limestone, gas in limestone	200–244
Triassic	Upper	T_3xj	Intercalation of shale and sandstone, yellow brine in middle and lower sandstone	487–551
	Middle	T_2l	Dolomite and limestone with anhydrite, rock salt in the middle, black brine and gas in lower limestone	399–609
	Lower	T_1j *	Limestone, dolomite and anhydrite, black brine and gas in upper limestone, rock salt in the upper and middle, gas in lower limestone	383–511

*Drilling is not finished.

The profile of the saline series is mainly composed of limestone intercalated with anhydrite, dolomite and halite with simple structure and clear sequence (See Figure 3). The vertical fissures develop actively because there is a layer of loosened limestone (2-5 m thick) over the salt layer. Its bad stability has brought about disadvantages to the exploitation.

The salt bodies of Dawenbao, Dashanpu and Guojia'ao are located in the stratum of T_1j^{4-4}. They are characterized by small area, small reserves, deep burying (1000-1500 m), high grade (NaCl ≥ 93%), single layer, thin bedding (1-6 m), stability, simple structure and comparatively good preservation. It is of the lenticular deposit. Its profile shows that there are anhydrite, dolomite and halite. The overlying and underlying strata of the salt deposit are of compactibility with high stability and no collapse, which have created advantages for the exploitation of the rock salt.

NEW DRILLING TECHNIQUE

The exploitation of well salt depends largely upon the drilling means. How to reduce the drilling cost and increase the speed of well build-up is an important subject. A new technique was adopted in 1979, and the directional dual bores were successfully drilled in Weixi Rock Salt. Such a new technique for drilling in the rock salt, which did not need any conventional deflection tools, made full use of the geological features. The natural declivity was found out by comprehensive study and analysis based on the actual well inclination data from the electric logging records of the mining area. Two boreholes were drilled at the same wellsite without moving the drilling rig. The two hole tops were 1.5 m apart and the maximum deflection of the well bore was less than 8°. The two boreholes were drilled into the rock salt layer according to the designed azimuths, respectively. It was specified in the design that one of the dual bores should be along the trend and the other along the dip of the layer, and that the bottom distance between the two holes should be within the range of 70-100 m. Figure 4 diagrammatically depicts the layout and the horizontal projection of the directional dual bores in the rock salt deposit.

The drilling cost is reduced by 23% and the speed of well build-up is increased by 2.4 times. What is more important is that the drilling preparation work of one well is lessened, moving the drilling rig is not necessary and the wellsite is saved.

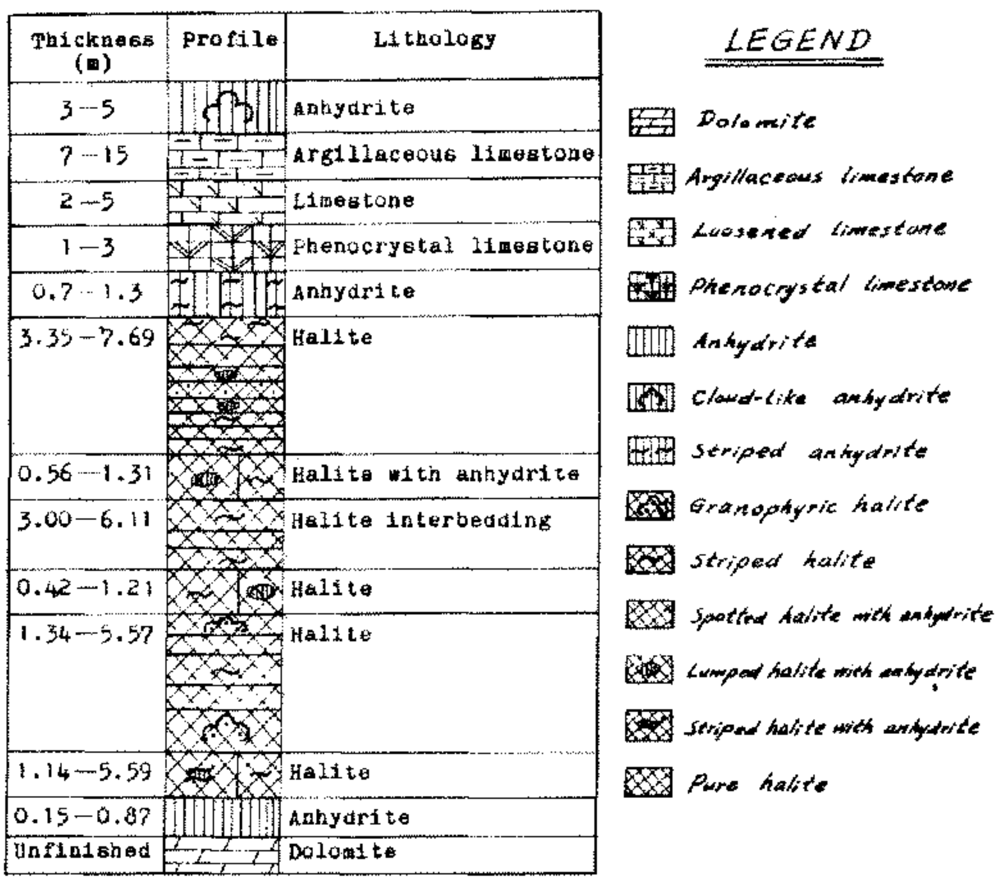

Figure 3. Profile of Weixi saliferous strata.

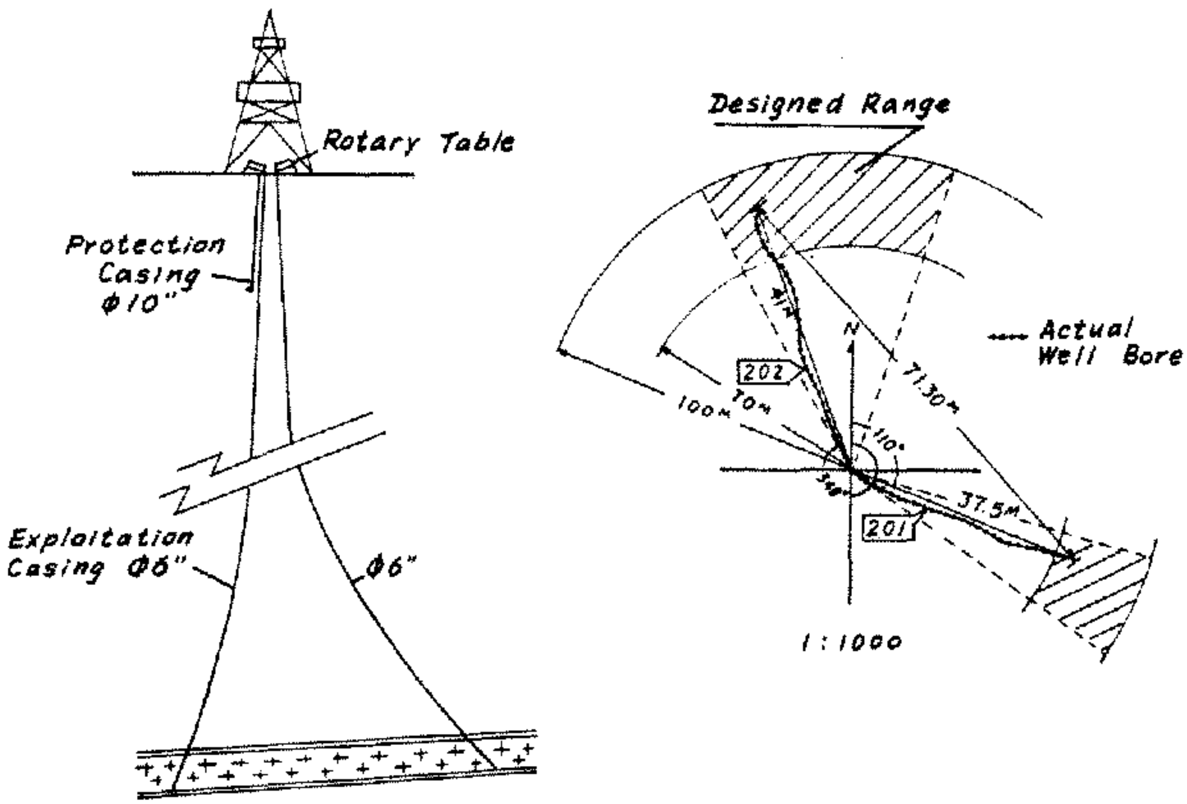

Figure 4. Layout and horizontal projection of directional dual bores.

It has been proved through practice in recent years that this new drilling technique can meet the technical requirements for rock salt mining and that it is especially suitable for the mining of rock salt with cavity connection controlled by oil pad.

SOLUTION MINING OF THINLY BEDDED ROCK SALT

Geological features vary with different mining areas in Ziliuging region. The main task of the solution mining research is that different solution mining techniques are applied to different areas so as to raise the economic benefits.

What we had to do first was to choose a proper brine extracting technique to substitute the old hoisting method which had been used for more than one thousand years. To improve a conventional technique was rather difficult. The first step we took was to conduct the single-well convection on an industrial scale. It was proved to be true that a new technique had many advantages over the old; thus, vast vistas for developing the brine extracting techniques were opened. Not long after, hydraulic fracture was conducted, including surface directional fracture and downhole directional fracture. Later, single-well oil pad and dual-bore oil pad methods were developed. The development of brine extracting techniques in the course of more than twenty years includes the following stages.

Single-Well Convection Method

The single-well convection method was first tried in Well No. 3 of Dawenbao Rock Salt in 1960. Welded seamless tubes were used as the exploitation casing because no proper tubes were found at hand. Two years later, the well was abandoned because of the damage of the welds of the exploitation casing. This method, however, raised the brine yield by 3.3 times as compared to the old hoisting method. During the production period, the annual salt output was up to 70,000 tons. Therefore, the old hoisting method was gradually substituted by the new one. In 1967, the single-well convection method was adopted at Dashanpu small rock salt; the thickness of the salt layer was only 1–6 m. Significant economic benefit was obtained.

This technique began to be used at Changshan Rock Salt in 1972. Five year's experience in 12 wells proved that in the circumstances of unstable caprock, the disadvantages of the single-well convection method were apparent as follows:

- Low yield of slat produced, generally 20,000–30,000 t/y.
- Short duration of salt production, generally 4–8 months, and

- Both the casing and the tubing at the lower part are apt to deform, bend and break.

Hydraulic Fracture

While the single-well convection method was being practised at Changshan Rock Salt, we made an experiment in hydraulic fracture in 1971. It was conducted in a set of three wells (No. 104, No. 105 and No. 106) laid out in a triangle with a well spacing of 131 to 167 m. Fracturing fluid was applied directly through the exploitation casing. It turned out to be a success in connecting the first set of wells (No. 104 and No. 106). The salt extracted in these wells totalled 1.25 million tons from 1971 to 1981. It was a typical example for obtaining best results of hydraulic fracture in this area.

However, difficulties were met when popularizing this method. Fracturing fluid intruded into the roof of the rock salt in most of the 14 wells in which the hydraulic fracture method was tried from 1972 to 1974. The attempts at connecting in rock salt failed. Thus, we made another experiment—downhole directional fracture.

Directional Jetting Fracture

It was in 1974 that a downhole directional fracture experiment was first made at Changshan Rock Salt. The fracturing process was composed of downhole directing, jetting and fracturing. Elbow joint and inserted magnet were used for downhole direction. Three kinds of jetting fluids (clear water with sand, saturated brine and saturated brine with sand) were tried. The jetting speed was up to 220–250 m/sec. No instantaneous peak pressure was found when rock salt was fractured in the case of previous downhole directional jetting. Pressure was monitored during extending. The peak pressure of hydraulic fracture in rock salt at Changshan was 195–220 kg/cm^2, while the pressure during extending after the directional jetting was only 130–140 kg/cm^2. This proved that before fracturing, downhole directional jetting could make a crack in the predetermined part of the rock salt, preventing the fracturing fluid from intruding up into the roof. Figure 5 shows the characteristics of the method used in Well No. 118.

The field practice of hydraulic fracture in rock salt shows that not all the attempts at connecting of fracture in rock salt will succeed. There are several reasons, the most important one of which is the geological features. The fracturing in rock salt is a speedy and economical exploiting process when the extending direction of fracturing fluid is controlled. Therefore, it is necessary to further research it. To continue the production, we had to shift to the research and application of the oil pad method.

Oil Pad Method

In 1975, the single-well oil pad method was first tried in Well No. 120 of Changshan Rock Salt. The well was 935.21 m deep and the thickness of rock salt was 17 m. Ø5½" exploitation casing, Ø3" annular casing and Ø1½" tubing were used. The height of the cavity was 1.5 m and the volume of the cavity developed was 704 m^3 with the salt output of 50 t/d. Salinity of the brine reached 300 g/l. During the production period, the tubing was lifted six times for checking; no deformation and bending were detected. The salinity, yield and recovery rate were highly raised.

It was well-known long ago that rock salt should be exploited with the connected well system. In 1892, rock salt was discovered at Dawenbao and was exploited then. Several years later, some people poured water with rice-husk into the abandoned wells, and the husk was carried up with the brine produced in other wells. This method used in two or more wells to produce brine was a natural devel-

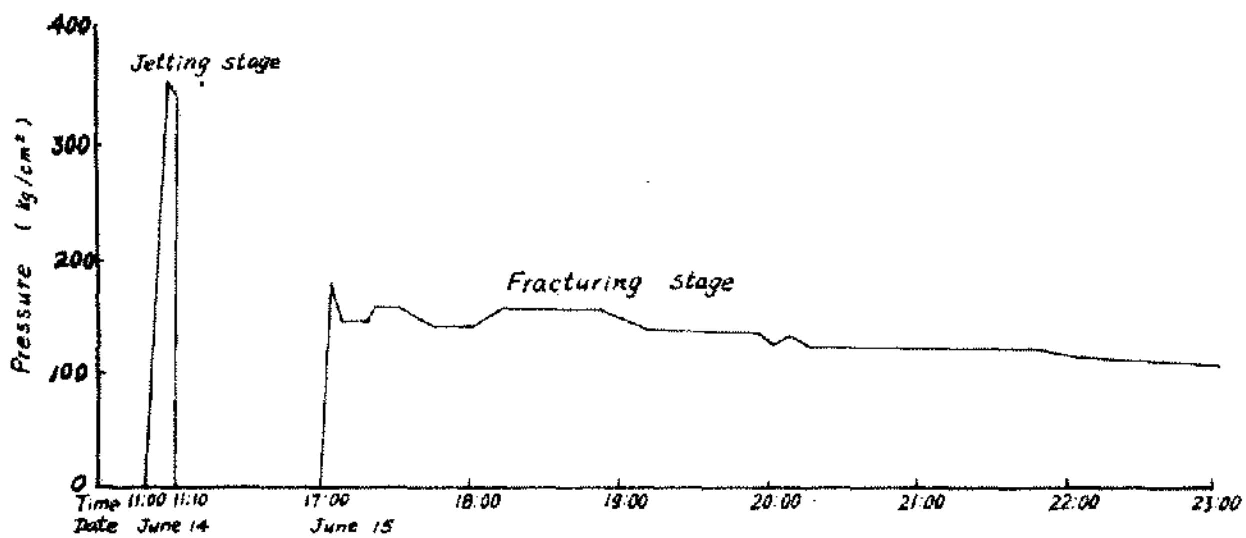

Figure 5. Pressure curve of directional jetting fracture.

opment. Based on this, exploitation of rock salt with wells connected was spread in this area, which was the earliest application of well connection in China. Therefore, we began the experiment of connecting exploitation in the dual-bore system with oil pad.

Dual-Bore Oil Pad Method

The dual-bore oil pad method makes it possible for the recovery rate to be highly raised and is suitable for the exploitation of thinly bedded rock salt layer. In addition to the remarkable economic benefits of the drilling work, it goes without saying that the simplification of facilities and engineering work for oil pad operation and pipe laying, and of the management of the well, is realized. For more detailed description of the art, examples are given below.

Case I. Wells No. 213 and No. 214 are a set of dual bores. The bottom (about 100 m high) of the exploitation casing was of thick wall, which was set into the rock salt (1-2 m deep). In the course of cementing, oil-well cement mixed with saturated brine was used for the bottom part of the exploitation casing while oil-well cement mixed with fresh water was used for the remaining part of the casing. The pressure within the casing and the shoe was tested to be 120 kg/cm^2 after the setting of the cement. Core drilling was conducted for the penetration of 1.2-1.6 m into the floor of the rock salt through the shoe, and the drilling process was completed. Table 2 and Table 3 show some of the parameters of the dual bore.

The whole process of developing and connecting the cavities in dual bores by oil pad can be divided into two stages as follows.

The Stage of Cavity Development. This stage is roughly subdivided into three stages as

1. The Stage of Low Salinity:

Injection Rate	6-10 m^3/h
Injection Pressure	10-20 kg/cm^2
Brine Concentration	Less than 100 g/l
Duration	40-50 days

2. The Stage of Salinity Increase:

Injection Rate	6-10 m^3/h
Injection Pressure	20-25 kg/cm^2
Brine Concentration	100-298 g/l
Duration	100-110 days

TABLE 2

Maximum Dip Angle, Azimuth and Downhole Spacing of Wells No. 213 and No. 214

	Item			
Well No.	Max. Dip Angle	Azimuth of Closure	Distance of Closure (m)	Downhole Spacing (m)
213	7.4°	129°	69.3	71.7
214	3°	47.5°	35	

TABLE 3

Bore parameters of Wells No. 213 and No. 214

	Well No.	
Item	213	214
Drilling Depth (m)	1,042.66	1,042.37
Roof Depth (m)	1,024.36	1,020.91
Floor Depth (m)	1,041.46	1,040.77
Visual Thickness of Rock Salt (m)	17.1	19.86
Setting Depth of Exploitation Casing (m)	06$^5/_8$" × 1,025.69	06$^5/_8$" × 1,022.81
Depth of Exploitation Casing in Salt (m)	1.33	1.90
Setting Depth of Annular Tube (m)	04" × 1,037.44	04" × 1,037.29
Setting Depth of Tubing (m)	02" × 1,039.44	02" × 1,039.19
Height of Cavity (m)	2.00	1.90

3. The Stage of Stable Salinity:

Injection Rate	6-10 m^3/h
Injection Pressure	25-35 kg/cm^2
Brine Concentration	Stable at 250 g/l
Duration	70-75 days before connection

Figure 6 shows the salinity curves before the connection of the cavities in the dual bores by oil pad, from which it can be seen that when the height of the cavity is less than 2 m the cavity development in thinly bedded rock salt is characterized by stable increase of the salinity and quick development of the cavity. Salinity was stabilized in the later stage.

The Stage of Cavity Connection. The connection of cavities can be measured by echo log with the calculation of the volume dissolved out, the salt exploited and the comprehensive analysis of the initial data obtained during the oil pad operation.

Generally, the variations of flowrate, pressure and water temperature may show the connection of the cavities. There was a period from the connection to the formal production, the length of which depended on the geological features of the rock salt deposit, the location of the connection, the difference between the elevations of the two wells, the well spacing, the injection rate and pressure. Taking the Dual Bores No. 213 and No. 214 as an example, it lasted several months from the connection to the formal production. Therefore, it would take 450-500 days on the whole for dual bores to be put into formal production when the cavities had been connected by the control of oil pad. Injection rate might be increased because the pressure would drop gradually after the connection of the cavities.

Case II. Wells No. 201 and No. 202 are another set of dual bores. The downhole spacing between the two bores is 68.20 m. The oil pad operation lasted for 180 days. The

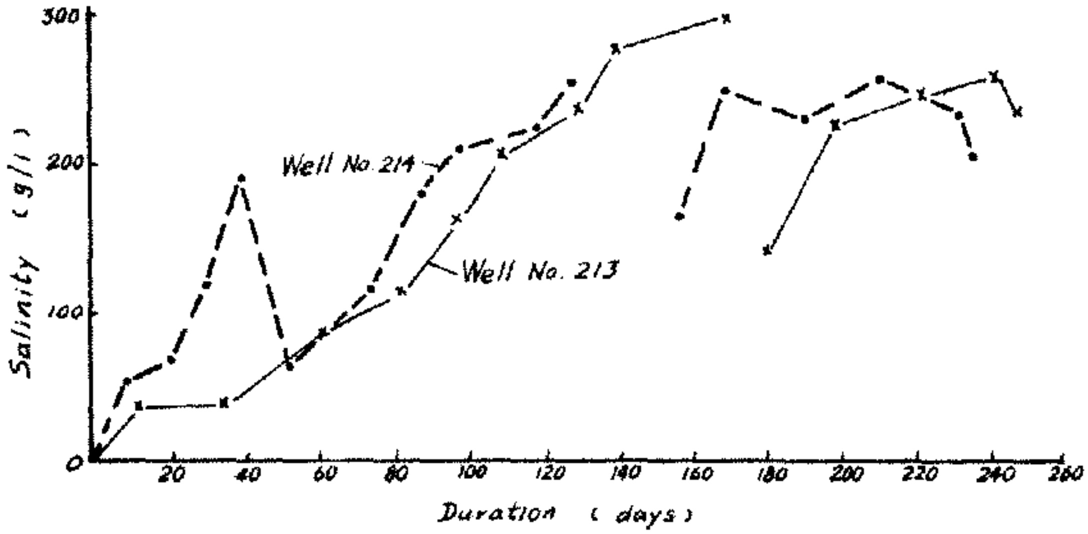

Figure 6. Salinity curves of Wells No. 213 and No. 214 during the stage of cavity development.

oil injected amounted to 110 m^3. The salt production converted from brine during the period of the cavity development was 25,980 tons. Injection pressure during the connection of the cavities was 30–40 kg/cm^2, flowrate was greater than 40 m^3/h and the average content of salt in brine was 310 g/l. Daily output of salt was 300–400 t/d. The drilling and technical parameters of this set of dual bores are shown in Table 4 and Table 5.

In order to effectively control the cavities dissolved and to speed up the development of cavities, the geological features of the thinly bedded rock salt deposit in the area had to be considered. We thought that the following points must be paid attention to:

- Selection of injection flowrate and circulation (reverse or direct)
- Thickness of the oil pad, oil amount injected and the oil injection method
- Measurement of cavity diameter and calculation of lateral dissolving speed and
- Prediction and observation of connection of the cavities.

To exploit the thinly bedded rock salt layer at Weixi by the oil pad method, upward dissolution must be effectively controlled. If the upward dissolution had not been controlled, the caprock of the rock salt would have been exposed, and the black brine and hydrogen sulfide in the extremely thin caprock would have been cause to come down into the cavity. Therefore, it was effective that the reverse circulation of injection water (top injection-bottom production) with proper rate was conducted in the course of cavity development.

The oil pad was too thin as a stable film that could prevent fresh water from dissolving the salt upwardly. According to the calculation of actual oil injected, the average thickness of the oil pad was 1.5–2.0 cm. The irregular cavity measured by echo log (manufactured by Sichuan Salt Company) might result from the non-uniformity of the rock salt and the influence of the occurrence. For example, the cavity of Wells No. 201 and No. 202 looked like a trumpet with its opening upside down. About 40–50% of the oil injected was stored here, the rest being distributed like a thin film with the thickness of about 1.5 cm.

TABLE 4

Maximum Dip Angle, Azimuth and Downhole Spacing of Wells No. 201 and No. 202

	Item			
Well No.	**Max. Dip Angle**	**Azimuth of Closure**	**Distance of Closure (m)**	**Downhole Spacing (m)**
201	5.3°	120°	29.40	68.20
202	4.9°	340°	42.10	

TABLE 5

Bore Parameters of Wells No. 201 and No. 202

	Well No.	
Item	**201**	**202**
Drilling Depth (m)	1,003.09	1,004.59
Roof Depth (m)	985.49	987.89
Floor Depth (m)	1,001.50	1,003.39
Visual Thickness of Rock Salt (m)	16.01	15.50
Setting Depth of Exploitation Casing (m)	07″ × 987.12	07″ × 989.08
Setting Depth of Annular Tube (m)	05″ × 998.30	05″ × 1,000.46
Setting Depth of Tubing (m)	02½″ × 1,000.30	02½″ × 1,002.46

Excess oil was injected, i.e., the injection of the oil did not stop until oil came out to the surface. Generally, oil injection was made once a day in the first month, once every two days in the second month, and once every three days from the third month on. The actual oil consumption was by no means large. The accumulated amount of oil injected in Wells No. 201 and No. 202 was 110 m^3, and 140 m^3 in Wells No. 213 and No. 214. Based on the analysis of the oil amount injected, it can be seen that the oil injected in the first stage is 60–70% of the total oil consumption. The oil injected in Wells No. 213 and No. 214 is tabulated in Table 6 and Table 7.

The lateral dissolving speed was 0.16–0.19 m/d according to the measurement by echo log and the actual data of each well (exclusive of the period of extending the connection), which is shown in Table 8.

Presently, echo log is used to measure the diameter of the cavity, the cavity form and the speed of lateral dissolution, and to predict the connection of cavities. The initial data obtained during the oil pad operation is also taken into account. The cavity in Wells No. 201 and No. 202 measured by echo log is depicted in Figure 7.

Though we lacked the systematic experiment of the dissolving speeds in different directions in the well, we made a partially simulated test in the laboratory by using the core from the well. Values of temperature and dissolving speeds during static dissolution were measured and were shown in Table 9 and Table 10.

It is obvious that the lower the concentration, the higher the dissolving speed, as is in conformity with the actual conditions of the oil pad operation. The oil injected in the first stage is 60–70% of the total oil consumption in the whole process of the oil pad operation. Therefore, it is essential that the oil injection during the first stage be conducted successively and that excess oil be injected so as to prevent the thin layer of rock salt from being dissolved upwardly. We see clearly from the above tables that the upward dissolving speed is about 2 times as fast as the lateral dissolving speed.

TABLE 8

Parameters of the Two sets of Dual Bores During Cavity Development

Item	Well No.	
	Dual Bores No. 213 & No. 214	Dual Bores No. 201 & No. 202
Duration of Cavity Development (days)	180	222
Diameter of Cavity (m)	68.2	71.7
Average Speed of Lateral Dissolution (m/d)	0.19	0.16

From what has been described above, we can conclude that the key to exploit the thinly bedded rock salt by the oil pad method is to avoid the upward dissolution. Its shortcoming is the longer duration of cavity development and connection. However, it is liable to produce saturated brine (the daily output of dual bores is 300–400 tons) from the thinly bedded rock salt.

EXPLOITATION IN EXTREMELY THIN MONO-LAYER

In Ziliujing, there has long been the exploitation in extremely thinly bedded mono-layer of rock salt at the depth

TABLE 6

Oil Injected in Well No. 213 During Cavity Development

Stage of Cavity Development	Oil Injected (m^3)		Oil Out of the Well (m^3)	Oil in Well (m^3)
	Oil Injected in Each Stage	Percentage of the Total		
1	48.6	60.2	10.35	38.25
2	11.0	13.6	—	11.00
3	21.14	26.2	—	21.14
Total	80.74	100	10.35	70.39

TABLE 7

Oil Injected in Well No. 214 During Cavity Development

Stage of Cavity Development	Oil Injected (m^3)		Oil Out of the Well (m^3)	Oil in Well (m^3)
	Oil Injected in Each Stage	Percentage of the Total		
1	67.81	69.7	22.65	45.16
2	10.71	11.0	7.10	3.62
3	18.76	19.3	—	18.76
Total	97.29	100	29.75	67.54

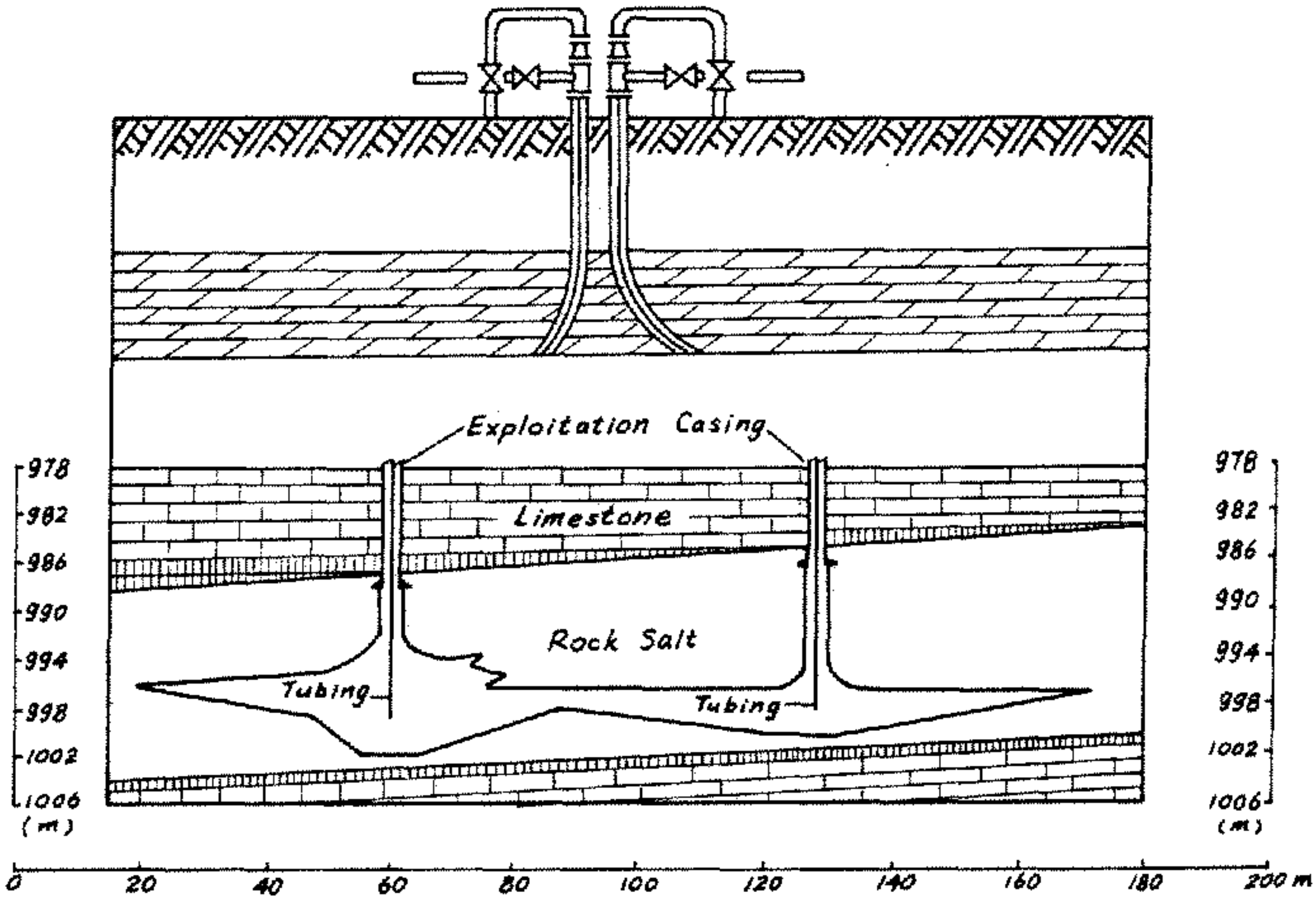

Figure 7. Cross section of Wells No. 201 and No. 202 cavity.

TABLE 9

Dissolving Speeds of Rock Salt During Static Dissolution ($kg/M^2 \cdot h$)

Dissolving Speed and Direction	Concentration		
	9° Bé	10° Bé	20° Bé
Upward Dissolution	41.4	26.0	4.1
Lateral Dissolution	21.2	14.0	2.5
Downward Dissolution	6.0	—	—

TABLE 10

Lateral Dissolving Speeds at Different Temperatures During Static Dissolution

Concentration °Bé	Lateral Dissolving Speeds ($kg/M^2 \cdot h$)		
	30°C	35°C	40°C
0	27.4	29.9	32.3
5	24.4	26.4	38.6
10	17.6	19.3	20.9
15	14.7	16.1	17.4
20	3.4	3.2	3.5
23.5	1.1	1.2	1.3

of over 1,000 m, so we now give a particular example to show how the extremely thin rock salt layer is solution-mined.

Dashanpu Rock Salt body lies under T_1j^{4-4}, which includes Layers A1 and A2 of the lenticular deposit (See Figure 8). There are 8 wells drilled in the body (5 test wells and 3 production wells) with a well spacing of 300–400 m. Six wells have penetrated Layer A1. It has been proved according to the data of coring, drilling and electric logging that the thickness of the salt layer in Well No. 13 is 6 m, the thickness of the salt layer in the rest of the Wells is only 1–1.5 m. Layer A2 is tapped by drilling only in Wells No. 13 and No. 14, with a thickness of 0.3–1 m. The two layers lie in the depth of 1,300–1,430 m, with an area of 0.51 km^2 and ore grade of NaCl $\geq$ 90%. Layer A1 is now being exploited. Table 11 shows the profile of Layer A1, taking Well No. L25 as an example.

Well No. L.25 was drilled as a test well. Core drilling was 141 m from the top of the bottom of the saliferous well bore and the average core recovery was 73%. The pure rock salt was 1.05 m thick, the rest being anhydrite with saliferous lumps with the thickness of 1.85 m. 05″ exploi-

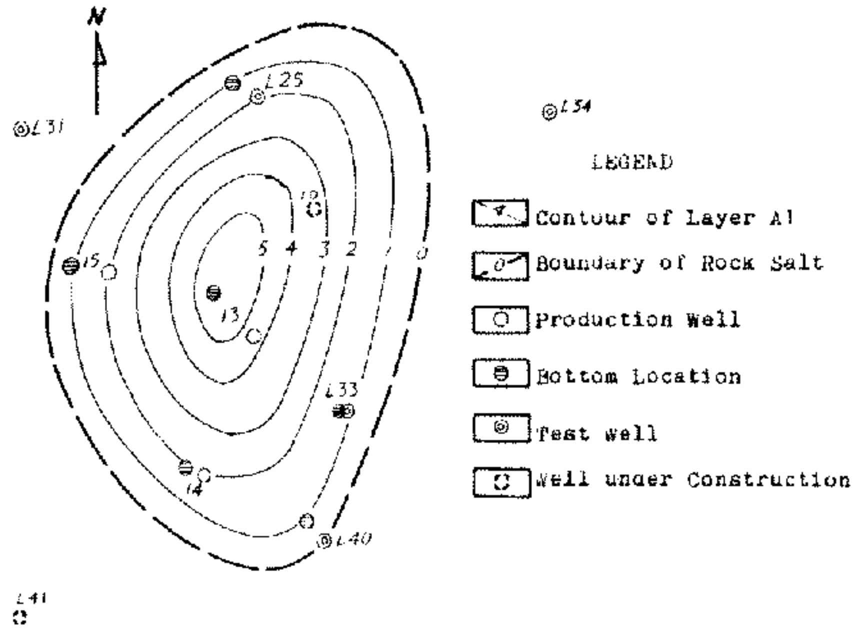

Figure 8. Location of wells in Dashanpu Rock Salt A1.

TABLE 11

Profile of A1, Well No. L25

Well Depth (m)	Lithology	Thickness (m)
1,327.68–1,328.41	Intercalation of pelitic dolomite and anhydrite with rock salt lumps	0.73
1,328.41–1,328.56	Pure rock salt, NaCl 90.24%	0.15
1,328.56–1,328.98	Dolomite and anhydrite with rock salt lumps	0.42
1,328.98–1,329.80	Pure rock salt and lumps of anhydrite	0.82
1,329.80–1,329.89	Anhydrite and dolomite with pelitic dolomite	0.09
1,329.89–1,329.99	Pure rock salt	0.11
1,329.99–1,330.69	Dolomite, anhydrite and lumps of rock salt	0.70
1,330.69–1,331.10	Anhydrite and dolomite	0.41
1,331.10–1,339.92	Dolomitic anhydrite and anhydrite	8.83

tation casing was set at the point of 27 m on top of the saliferous layer and 2½" tubing was set to the bottom of the rock salt. Then the well was put into service. The single-well convection method was practised according to the fact that the caprock of the salt layer was stable and the salt layer was extremely thin. Remarkable benefits have been obtained. The well has operated for 14 years since October, 1967. The accumulated output of salt is 410,000 tons and its daily capacity still remains 150–200 tons of salt per day.

Table 12 shows the capacity of each well in the extremely thin layer of rock salt.

Taking Well No. L33 as another example, the drilled thickness of the rock salt was 1.13 m. The total salt output in 118 months from 1972 to 1981 was 432,000 tons. Its present daily capacity can reach 120–170 t/d. Figure 9 depicts the characteristics of solution mining in an extremely thinly bedded rock salt deposit.

It can be seen from Table 12 that the service lives of these wells were comparatively long though the single-well convection method was used in production. In the course of production, the tubing was stable and did not break easily because of the extremely thin salt layer, the stable roof and floor and the small height of the cavity. We successively summed up the experiences and took various measures, which mainly include:

- The increase of injection pressure from 30 kg/cm^2 to 60–70 kg/cm^2 to speed up the lateral dissolution. The injection rate of 40–60 m^3/h and the velocity of 3–5 m/sec in the tubing helped to carry the insolubles up to the surface; thus the well was purified successfully.
- Direct circulation with higher injection rate helped to raise the brine concentration.
- The setting depth of exploitation casing and tubing had to be as exact as possible because the salt layer was extremely thin. The tubing had to be set to the bottom of the salt layer.
- Brine concentration was low during the later stage of the well. Intermittent production was conducted so as to enable the concentration to be raised at static dissolution; thus the recovery rate was raised.

TABLE 12

Capacity of Each Well in the Extremely Thin Layer of Rock Salt

Item	Well No.					
	L25	L33	I3	I4	I5	L40
Period of Production	Oct. 1967 to Dec. 1981	Jan. 1972 to Dec. 1981	May 1976 to Dec. 1981	Sept. 1978 to Dec. 1981	May 1979 to Dec. 1981	Jan. 1981 to Dec. 1981
Duration of Service (Months)	170	118	67	39	31	12
Accumulated Output (t)	410,680	432,566	368,644	145,672	26,000	28,053
Normal Daily Capacity (t/d)	150–200	120–170	150–250	170–200	60–80	80–120

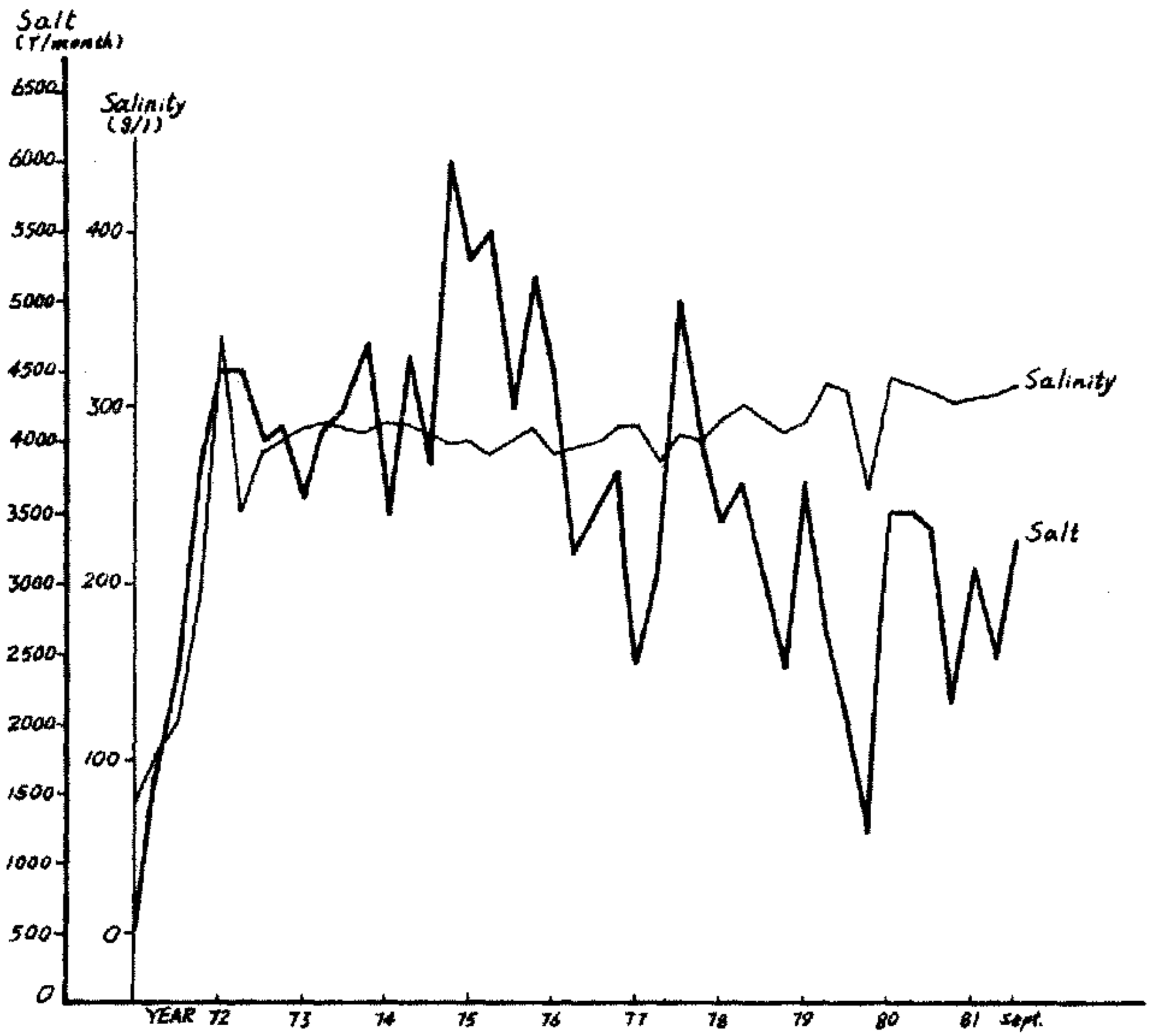

Figure 9. Characteristics of solution mining in exremely thinly bedded rock salt (Well No. L33).

- Careful maintenance of the well was necessary for safe production, including periodic check of the tubing, avoidance of water hammer during lifting the pump and stable downhole pressure during shutting in the well.

The accumulated salt output of these wells had reached 1.412 million tons since the beginning of exploitation in 1967, and the recovery rate was over 50% according to the actual drilling and geological data of the wells in this small rock salt deposit. This is a rare case in solution mining in the extremely thinly bedded rock salt deposit.

The main technical and economic index is as follows:

Brine cost	RMB Y5-6/ton of salt
Productivity	2,200–2,500 ton of salt/ man. year
Power consumption	24–26 KWH/ton of salt.

SUMMARY

Sichuan is situated in Southwest China, the population including that of the adjacent provinces Yunnan and Guizhou being more than 100 million. The well salt produced in Sichuan has long met the demand of the chemical industry and human needs in Southwest China. The necessity of exploiting the thinly bedded rock salt deposits of Ziliujing is determined by the fact that Ziliujing is rich in the resources of salt, brine and natural gas and has a long history of exploitation. Now Ziliujing has become a new city (named Zigong) where a chemical industry based on salt is developing rapidly.

The exploitation of thinly bedded rock salt deposits is carried out through several years' research and practice, and through the comparison of the pros and cons of different exploiting techniques used in this region. We take it for granted that the selection of an exploiting technique must be in accordance with the characteristics of the individual rock salt deposit and further development and improvement of the conventional techniques is necessary. This paper has mainly described the recent development of solution mining in thinly bedded rock salt deposits of Ziliujing. Undoubtedly, the investigation of the mechanism of solution mining and the improvement of the exploiting techniques are still the urgent tasks for us to accomplish.

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