

# Simultaneous Multiple Seam Exploitation of Halites by Separate Hydrofracturing

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## ABSTRACT

In the past, multiple sedimentary halite deposits were exploited individually. In this paper, the author studies a method of simultaneous multiple seam exploitation. Within the block located in the well-field, many well sets are sited, each of which has an active well and a passive well, and four salt beds — the first, second, third and fourth industrial exploitation salt beds (IESBs) — are drilled. Along the dip, the active well is sited at the lower part and the passive well at the upper part mainly based on the regularities of the approximate water-flood pressure differences and water absorption indexes in the adjacent salt beds in the same ore-body. Operations may then be carried out in the following five steps: 1. Perforation and troughing in the first, second, third and fourth IESBs, individually from bottom to top. 2. Interlayer packing of the ring-shaped space in the casing pipe to form two upper and lower circulation areas. 3. Fracturing and trough reaming in each of the four IESBs by separating water-flood. 4. Adjusting and testing water-flood pressure difference and water-flood volume by separate water-flooding. 5. Separate exploitation of brine by combination flooding; followed by simultaneous multiple-layer exploitation.

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## INTRODUCTION

Yingcheng Salt Mine in Hubei, China is one of many multiple sedimentary soluble saline deposit (see Fig. 1) having many industrial exploitation salt beds (IESBs). Their resource recovery ratio (RRR) and exploitation capacity (EC) were limited in the past because of mono-stratum exploitation technology. In recent years, mining experts have devoted every effort to finding a technology capable of simultaneous multiple-seam exploitation of the separate salt beds in order to increase the resource recovery ratio and exploitation capacity. After many years of study and experimenting with the water frac (hydrofracturing) method, simultaneous exploitation of two separate halite beds in the same well set (well pair) was successfully achieved in three well sets in Yingcheng Salt Mine in 1987. The method is described below.

## GEOLOGICAL CHARACTERISTICS AND EXPLOITATION CONDITIONS OF ORE DEPOSIT

Yingcheng halite is an ore deposit comprised of multiple-seam sediments of inland lake facies buried in the salt-bearing member of the gypsum-salt for-

mation of the Eocene System (Eyn<sub>2</sub>). The strata dip gently at an angle of 2–4°. Within the ore area, there is no interrupting fault structure. The strata are stable and their correlations are sharp in longitudinal and transverse directions. The wall rocks are not aquiferous; the hanging wall of the salt-bearing member is a good aquifuge. The buried depth of the ore-body ranges from 300 to 800 m; the thickness is 500 m; the ore-body has monostratum halite of about 240–320 beds with a total thickness of 110–170 m. According to the exploitation technical conditions, ten IESBs may be located in the ore area, at intervals of not less than 20 m; each with a thickness of 6–15 m. Each IESB consists of some interlayers of thin-bedded halites (NaCl), calc-mirabilites (Na<sub>2</sub>SO<sub>4</sub>·CaSO<sub>4</sub>), mudstones and anhydrites (CaSO<sub>4</sub>). The ore-bearing ratio in the IESB is 50–60%; the average content of NaCl in halite ores is 70%. There are other mineral components of mirabilites (Na<sub>2</sub>SO<sub>4</sub>), calc-mirabilites, anhydrites and magnesium sulfates. Most of the immediate hanging walls of the IESB are thick-bedded argillaceous anhydrites, the structures of which are stable with a compression strength of more than 35 MPa. The physical mechanics properties of the halite ores and the wall rocks in the ore deposit are detailed in Table 1.

Geological age	Stratome	Depth (m)	Column	IESB No.	Lithological description
Q		90			upper part: clay band
covers					middle part: argillites (thick-bedded mudstone)
		300			lower part: argillaceous calc-mirabilites interbedded with mudstone and gypsum
E	E <sub>yn2</sub>			10	within the salt-bearing member, there are 10 industrial exploitation salt beds (IESB) each of which consists of some interlayers of thinbedded salts, argillaceous calc-mirabilites and argillaceous anhydrites
				9	
				8	
				7	
				6	
				5	
				4	
				3	
				2	
				1	

Fig. 1. Comprehensive stratigraphic column from an ore area of Yingcheng Salt Mine, Hubei, China.

TABLE 1

Physical mechanics properties of halite ores and wall rocks

Lithology	SG (t/m <sup>3</sup> )	Compression strength (MPa)	Shear strength (MPa)	Form of ore bed
White crystallized halites	2.10	20.0-25.0	2.0	Stratiform
Mud-bearing grey halites	2.20	15.0-20.0	2.0	Stratiform
Argillaceous shales	2.30	25.0-30.0	2.5	Stratiform
Argillaceous calc-mirabilites	2.25	30.0-35.0	2.5	Stratiform
Argillaceous anhydrites	2.60	35.0-55.0	4.0	Thick-bedded

CONSTRUCTION OF A BRINE WELL

(a) Brine well pattern (siting or spacing)

Many well sets, each having an active well and a passive well, are sited within the block located in the well-field (Fig. 2). Along the dip, the active well (uneven numbers) is sited in the lower part, and the passive well (even numbers) is sited in the upper part to achieve an optimum fracturing connection direction. The distance between two wells in the same set is 150 m, and that between two well sets is 300 m.

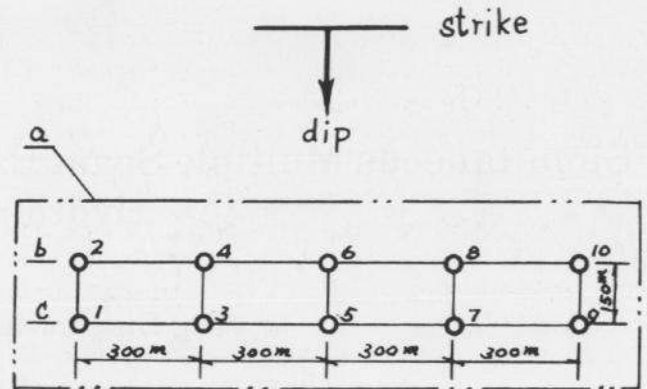


Fig. 2. Well set pattern of halite exploitation by the waterfrac method. (a) Active wells with uneven numbers, 1, 3, 5, etc. (b) Passive wells with even numbers, 2, 4, 6, etc. (c) Block boundary located in the well field.

(b) Brine well structure and well building operation (Fig. 3)

Based on the well structure, a 8.75 inch diameter superficial casing pipe is placed in the aquifer and soft beds in the upper sector. When the brine well is drilled to the basal plane of the foot wall at the bottom of the first IESB, a 5.5 inch diameter production casing pipe is sent down the first IESB of the active well to a depth 2 m above the basal plane of the foot wall, and the production casing pipe in the passive well is sent down the first IESB to a depth 2 m below the basal plane of the hanging wall. After completion, a bare sector is formed at the lower part of the well. Casing and cementing of the well is carried out through the superficial and the production casing pipes using cement slurry which is

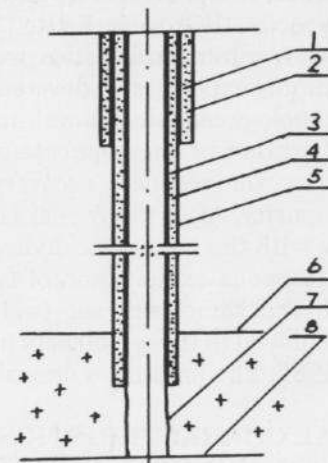


Fig. 3. Section of brine well structure. 1. Superficial casing pipe (SCP). 2. Cement ring in SCP used for casing and cementing. 3. Production casing pipe (PCP). 4. Cement ring in PCP used for casing and cementing. 5. Rock walls. 6. Hanging wall of the 1st industrial exploitation salt bed (IESB) at the bottom. 7. Naked well sector. 8. Foot wall of the 1st IESB.

stirred and combined with saturated brine with an SG of 1.7–1.9; the cement slurry must be returned to the surface. The maintenance duration of casing and cementing is not less than 72 hours. Within the well, the pressure test is 20 MPa with no detectable leakage. The preset cement plug is then drilled off; the well is cleaned to the basal plane of the foot wall in the first IESB and is then circularly flushed by pumping clean water until the remaining cuttings are washed out.

**SIMULTANEOUS MULTIPLE-SEAM EXPLOITATION OF HALITES BY SEPARATE HYDROFRACTURING**

**(a) Exploitation operation of the first IESB**

When the brine wells are constructed, the well-field technical lines, water-flood control apparatus, fracturing, trough reaming and water-flood equipment is installed, and the water-flooding site within the well is established in order that the continuous running of the brine well-set can begin at any time. After this, operation of the first IESB may be started by water frac and trough reaming in accordance with the technological standards for halite exploitation by the water frac method. Based on the variation characteristics of water-flooding pressure, the exploitation operation of the first IESB includes three stages: fracturing, trough reaming and brine recovery (see Fig. 4). During the fracturing stage, the instantaneous breaking strength (IBS) is 12 MPa; the stable water-flood pressure is 7.5 MPa; the fracturing duration is 4 hours; and the total water-flood volume is 48 m<sup>3</sup>. During the trough reaming stage, the stable water-flood pressure is 7.5 MPa; the water-flood duration is 96 hours; and the total water-

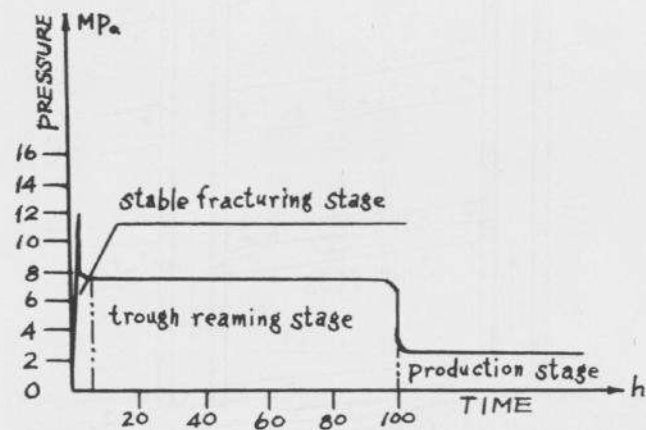


Fig. 4. Variation curve of water-flood pressure in the stages of fracturing, trough reaming, and brine recovery within the first IESB.

flood volume is 3840 m<sup>2</sup>. During the brine recovery stage, the running water-flood pressure is 2.8 MPa; the per unit time water-flood volume is 60 m<sup>3</sup>/h; per unit time brine output is 45 m<sup>3</sup>/h. When the water-flood pressure drops from 7.5 MPa to 3 MPa, trough reaming in the brine well is accomplished. When the brine well is put into normal brine recovery production, water-flooding must continue for not less than 30 days in order to ream the soluble chamber to the extent that the two wells are connected. Water-flooding in the first IESB is then stopped, and separate operations can commence in the second, third and fourth IESBs. This is the key operation of simultaneous exploitation technology.

**(b) Separate operation in the second IESB (Fig. 5)**

This operation, the most important part of the present technology, comprises four steps:

**1. Perforation and troughing**

The perforator is sent down the well, using surface hoisting equipment, to the site selected in the second IESB for perforation by blasting in order to shoot through the walls of the production casing pipe (PCP) and the cement ring (used for casing and cementing). This causes the channel between the salt bed and the PCP to form a certain sectional area.

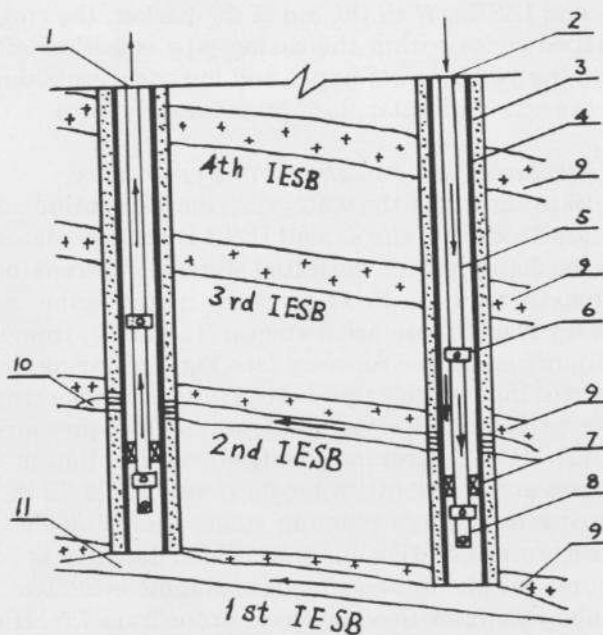


Fig. 5. Technology of separate water fracturing. 1. Passive well. 2. Active well. 3. Cement ring used for casing and cementing. 4. Production casing pipe. 5. Central pipe. 6. Distributor. 7. Packer. 8. Tail valve (valve ball). 9. 1st, 2nd, 3rd and 4th IESBs. 10. 2nd IESB being trough reamed and chamber solubilized. 11. 1st IESB being exploited and chamber solubilized.

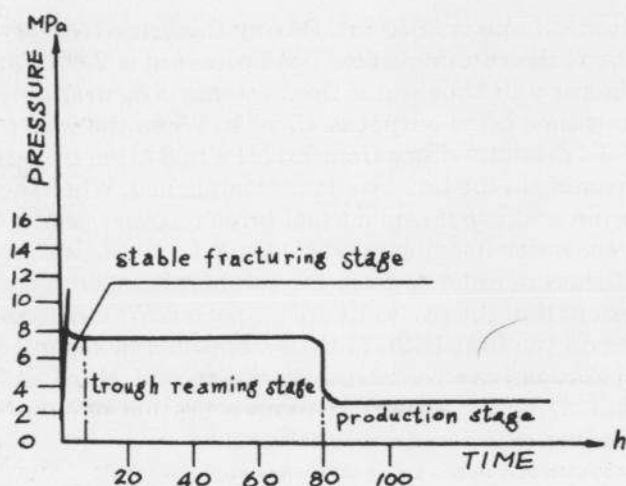


Fig. 6. Variation curve of water-flood pressure in the stages of fracturing, trough reaming, and brine recovery within the 2nd IESB.

The total sectional area of perforation should not be less than  $20 \text{ cm}^2$ .

## 2. Interlayer pack off

The central separable recovery string (CSRS) comprises such principal tools as a packer (hydraulic pressure differential type), water distributor, etc., which is connected to the central pipe and sent down the brine well to the section between the first and second IESBs. With the aid of the packer, the ring-shaped space within the casing pipe is packed off, forming two areas of upper and lower currents due to the action of water-flood pressure difference.

## 3. Fracturing and trough reaming operations

With the aid of the water distributor, continuous water-flooding of the second IESB is started. Based on the displays from the initial water-flood breaking strength to water-flood pressure in the brine recovery stage, there are 3 stages: fracturing, trough reaming and brine recovery (see Fig. 6). During the fracturing stage, the instantaneous breaking strength is 11 MPa; the stable water-flood pressure is 7.5 MPa; the running water-flood duration is 6 hours; and the total water-flood volume is  $72 \text{ m}^3$ . During the trough reaming stage, the water-flood pressure is 7.5 MPa; the water-flood duration is 74 hours; and the total water-flood volume is  $2220 \text{ m}^3$ . When the water-flood pressure drops from 7.5 MPa to 3.0 MPa, this indicates the commencement of the brine recovery stage. During this stage, the stable water-flood pressure is 2.8–3.0 MPa; per unit time water-flood pressure is  $50 \text{ m}^3/\text{h}$ ; and the per unit time brine output is  $40 \text{ m}^3/\text{h}$ .

## 4. Separate operation of distribution water-flooding in the first and second IESBs

After trough reaming in the second IESB is accomplished, through the adjustment of the current section by two water distributors in the central separable recovery string (CSRS), simultaneous exploitation of the first and second IESBs may be carried out with adjustment of distribution water-flood by maintaining a balance between the water-flood pressure difference and water-flood volume. At this stage, the optimum water-flood equipment is a high-pressure centrifugal pump and a plugger pump.

According to the technological operation order and standard mentioned above, the separating operation of the third and fourth IESBs is accomplished, from bottom to top.

## (c) Simultaneous exploitation by combination water-flooding

After the separate operations are accomplished in the first, second, third and fourth IESBs, the CSRS is hoisted out of the well and all the IESBs are simultaneously exploited by combination water-flooding from the casing pipe (see Fig. 7). This is the key to the present technology and is based mainly on the regularities of the approximate water-flood pressure differences and water-absorption indexes ( $0.12\text{--}0.16 \text{ m}^3/\text{s}$ ) in the adjacent salt beds in the same ore body. This operation is the result of comprehensive study and analysis, which aims at retrieving the CSRS from the well to increase the

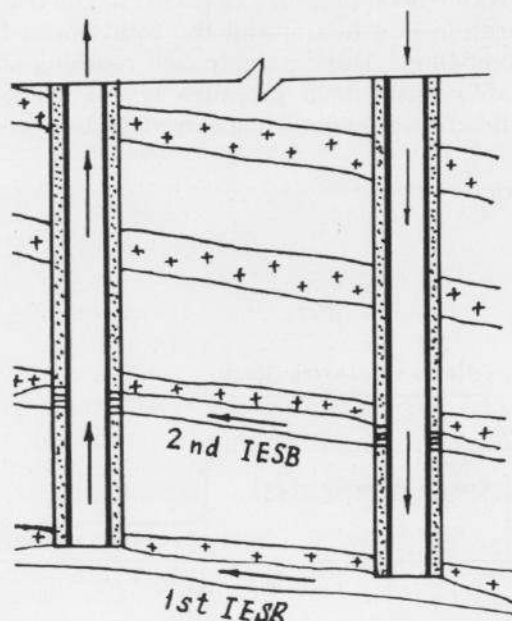


Fig. 7. Simultaneous exploitation of the 1st and 2nd IESBs by combination water-flooding.

sectional area through which to pass the current and to raise the total water-flood volume and separating water-flood volume in order to achieve a greater brine output.

#### (d) Regular examination during simultaneous exploitation by combination water-flood

Based on the parameters of water-flood pressure difference and of separating distribution water-flood and monostratum water-flood exploitation in all IESBs, the CSRS is sent down the brine well every 180 days to examine the variation of such parameters as water-flood pressure difference, water-flood volume, brine output, etc. This is done in each IESB to test and adjust the separating water-flood properly and in isolation in order to prevent any potential stoppage. Thus, the technology is all accomplished.

TABLE 2

Comparison of the results of simultaneous exploitation of two halite beds with those of one bed

Item for comparison	One bed	Two beds
Resource recovery ratio of brine well (%)	30	60
Exploitation capacity of brine well (m <sup>3</sup> /h)	45	70-90
Engineering investment* (million)	12.70	7.00

\*Engineering investment of brine well of 0.3 million tons of salt output per year

#### VALUE OF THE TECHNOLOGY

Based on the applied results, the merits of the present technology may be compared with those of monostratum exploitation (see Table 2):

(a) The resource recovery rate of the brine well increases by more than 100%, and the exploitation capacity by 80-100%.

(b) When the mining area is built on the same scale, the comparison is as follows: the cost of the engineering and investment in the brine well may be reduced by 46%; the engineering materials and occupied land decreases by 56%, the duration of the engineering operation decreases by 45%; after being put into production, the brine cost decreases by 34%, and the output value increases by more than 56%.

(c) Because of the decrease in brine-well engineering, the corresponding environmental pollution should be reduced.

#### CONCLUSIONS

(a) Multiple sedimentary halite deposits are distributed worldwide, and are vast in area and rich in reserves. This type of deposit has multiple beds, each of which are thin, and generally possesses from several tens to several hundred monostrata in which some IESBs may be located. However, each IESB is very thin in monostratum, multiple in intercalated beds and low in ore-bearing ratio. Based on the analytical data of monostratum exploitation technology applied to Yunying Salt Ore Area in recent years, the resource recovery rate of monostratum is only 30% and that of the ore deposit is only 3-5%. Therefore, this type of ore deposit could be reasonably exploited only by simultaneous multiple-seam exploitation of the salt beds in order to exploit more resources, to raise the resource recovery ratio and exploitation capacity in the brine well, and to increase the mine benefit.

(b) Based on the water-flood volume characteristics (10-20 times as much as that of the oilfield) of the soluble halite exploitation, the technological operation of hoisting out the CSRS is used to increase the water-flood volume. Regularly sending the CSRS down the well to examine and process stoppages in the separating soluble chamber is an essential means of correcting the separating measurement. It is important that the operating groundrules be strictly complied with in order for the technology to prove effective.

(c) Further studies of this technology will be made to optimise its well structure. At the same time, multiple halite deposits must be fully researched as to the movement regularities of the overlying strata caused by solution mining, and the reasonable exploitation interval between salt beds must be determined both to exploit the maximum resources and to control the minimum movement of the surface.

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