Well Communication in Salt Formations

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ABSTRACT

A survey of hydrofracturing case histories was conducted by collecting available data from member companies of the Solution Mining Research Institute. The experience of almost two decades of hydrofracturing for well communication in salt deposits shows that little is understood of the mechanics of fracture initiation and propagation, fracture inclination and direction. Field results have been mixed: total successes, partial successes, complete failures. It appears that the success of a 'frac' job depends among others on two main factors: the geology of the salt formation, and the design of well location, well completion, and fracturing sequence. The survey has indicated that a thorough geological investigation could be the key to success in formations disturbed by folding, faulting or other discontinuities. The mode of deposition and crystallization and existing regional forces affect the fracture even in flat undisturbed beds. Preferred directions of fracture propagation are observed in almost all cases studied. Low pressure connections are obtained very quickly in target wells located in the preferred fracture direction. With regards to well completion, available data indicate that open holes in the salt zone stand a better chance of communicating than cased and perforated wells, although the latter have been known to produce satisfactory results in some fields. It is recommended that a carefully designed experimental hydrofracturing be carried out in every newly developed salt field, and its results thoroughly examined before planning the final layout of wells and the sequence of fracing. A group of four wells should be drilled, one in the center, with the others evenly spread around it at reasonable distances. The central well will be hydrofractured, with all four wells carefully monitored. The time elapsed to the formation of high and low pressure communications with each of three wells will determine fracture orientation and salt field well design.

INTRODUCTION

One of the most efficient ways of producing salt is by circulating water between wells, and one of the fastest, least expensive techniques of connecting wells has been hydraulic fracturing (hydrofracturing or fracing). The latter was introduced in 1948 as a method of stimulating oil well output. It was not originally intended to connect groups of wells, but rather to induce and extend a fracture from a well into the oil bearing formation for the purpose of artificially increasing its permeability. The salt industry adopted the method for the purpose of well communication which, when established, enables water pumped in through the 'injection' well to be extracted as brine from the 'target' well(s).

The hydrofracturing operation begins with the completion of the injection and target wells. That is when the decision is made whether the job will be run in open-hole or through casing. For safety reasons cased holes have been increasingly used for fracturing, although their usefulness as to the success of method may be questioned. Perforation or notching of the well at the depth where fracture initiation is sought are mandatory in cased holes, but only optional in open holes. Theoretically, mechanical notching should be preferred to explosive perforating because it controls the initial shape and inclination of the fracture. Perforations may cause uncontrolled fractures running in many directions. Open holes can also be hydrofractured without the help of a preliminary indentation.

Fracture connection between wells is attempted by pressurizing a packed-off interval in the injection well until the formation starts taking fluids. The well pressure drops and large amounts of water or brine are pumped in to extend the fracture towards the target well(s). The success of this operation in obtaining well communication has been consistent in some fields, erratic in most, and lacking in others.

The initial well communication, when obtained, is a high pressure connection, i.e., the pressure required to keep the fracture propped open is high. In case of horizontal fractures this pressure is slightly larger than the overburden stress. Regardless of the fluid used up to this stage, once the connection is made, water is pumped in and the process of brine production is commenced. When enough salt is removed from the planes parted by the fracture a self supporting gallery is usually created which does not necessitate a highly pressurized fluid to keep open. When this stage is reached, the final 'low-pressure connection' is achieved and the hydraulic fracturing process is completed. Unfortunately, high pressure connections do not ensure low pressure communications. Often this last stage lasts from a few hours to a number of days. Sometimes, however, it may take considerably longer or never be completed. Brine production by high pressure pumping is uneconomical and unless the low pressure connection is achieved the entire hydrofracturing job is often considered a failure.

The questions most often asked by those who have not had complete success in connecting wells are: How do fractures propagate in salt? How can fractures be controlled? What well completion ensures better success? What keeps a high pressure connection from yielding a low pressure one? These and many other questions cannot be answered in a definite way to date because of the lack of information with regard to the mechanical behavior of rock salt under hydraulic fracturing conditions. An investigation of this behavior has been planned by the author for quite sometime. However, prior to undertaking it, it was felt that a study of existing data on past jobs could identify more clearly the nature of the field problems, and yield conclusions that would be beneficial both to industry and to the planning of further research. Under the sponsorship of the Solution Mining Research Institute a case-history study was thus undertaken and some ten brine field hydrofracturing data were made available for analysis. The results of the study are detailed below. Because of management policies in some companies, no mention is made in this paper of salt field names or locations. However, all of the reported cases are authentic.

CASE HISTORY STUDY

The study of past experiences in hydrofracturing salt has been limited to flat or nearly flat bedded salt formations of the type encountered in Ohio, Michigan, Ontario, etc. The jobs analyzed span over a period of almost 20 years. The completeness of the records left varies considerably from job to job. The lack of documentation precluded a uniform type of study. Each analyzed case, however, contributed some to the general picture obtained of the hydrofracturing mechanism in salt.

The first important conclusion of the study is that field results have been mixed. Total successes, total failures and partial successes (or partial failures) have all been experienced within the limited number of cases studied. Each of these field results will now be described. Figure 1 is a legend defining the convention used in the diagramatic sketches that accompany most of the case histories.

Case 1—the success story

The mined salt layer is 40–50 m thick at a depth of approximately 700 m. Salt extraction is routinely performed by brining through two-well groups. Each group is connected by hydraulic fracturing. Figure 2 diagramatically depicts a typical fracturing operation and results. Both the injection and the target wells are drilled to about 15 m above the bottom of the salt. The wells are 120 m apart with the target well always updip of the fracturing well. The segment of the wells within the salt layer is left uncased and an open-hole packer is placed in the fracturing well, some 15 m from its end. The packer is connected to pumps on the surface through 14 cm tubing.

The hydraulic fracturing of this system has been consistently successful (more than 90% in some 20 attempts). Caliper logging has identified the well portion immedi-

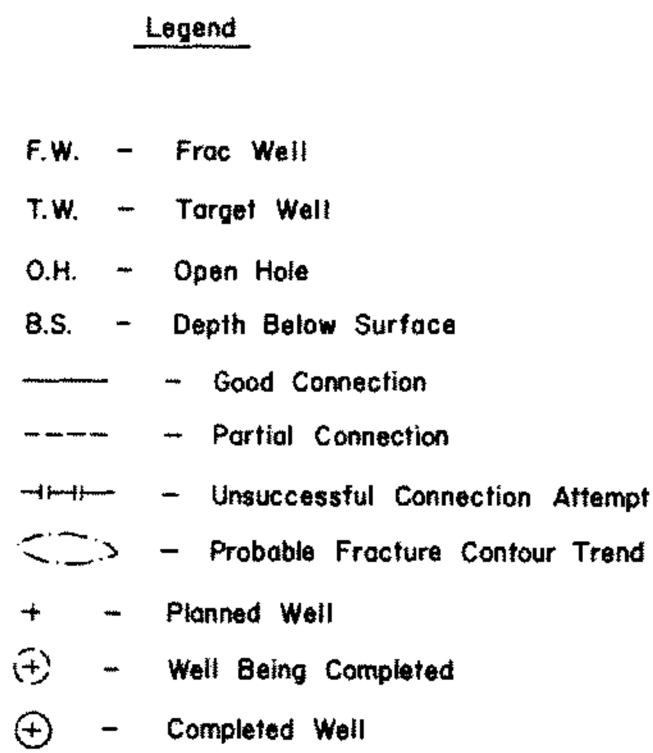

Figure 1. Legend of symbols used in the illustrations accompanying this paper.

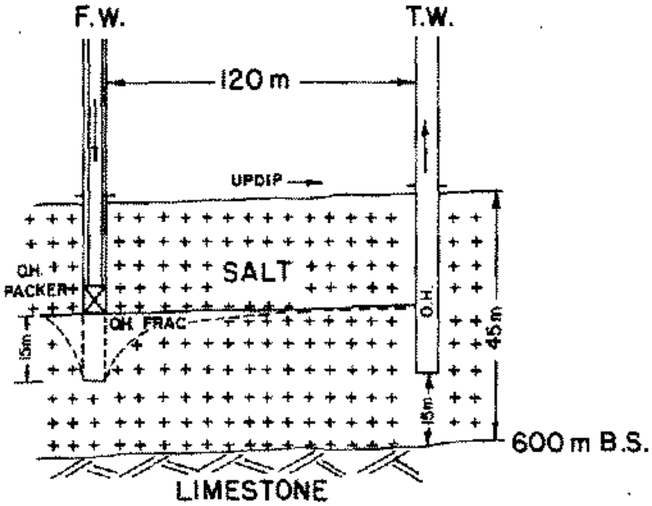

Figure 2. Case 1—Typical well layout, completion and fracturing results.

ately below the open-hole packer as being the zone of fracture initiation. Similar logging of the target well has found the fracture to hit it at about the same elevation as where it originated. Only 150–500 m^3 of brine are consumed to establish communication, an operation that typically lasts 1–2 hours. Switching to water occurs when a reasonable flow is established (.2–.4 m^3/min). Normal brining operations are started as soon as the low-pressure connection is obtained (within 12–16 hrs).

Very little if any fluid loss is experienced and this is attributed mainly to the rather high elevation of the well bottom (15 m above the interface with a limestone zone). Salt has a tendency of healing, while other formations are often traversed by discontinuities like joints, faults, partings. By removing the potential fracture plane from such natural channels the danger of fluid losses is minimized and quicker communication is ensured. However, it is well known that the process of brining removes salt mainly from the hanging wall of the hydrofracture. To salvage the salt left in the 15 m layer between well-bottom and limestone, the fracturing well is deepened at a later stage.

The success of hydraulic fracturing in this field has not come overnight. It was predated by some not-too-successful jobs, but the operators apparently managed to learn from their mistakes and perfected the method to an almost routine undertaking. This is also, perhaps, partly due to a rather homogeneous, predictable salt layer which takes the guessing out of the game.

In addition to the well-bottom elevation, the type of well completion should be noted. An open-hole fracturing job (without perforating or notching) allows the fracture to initiate where a weakness exists and to extend and reach the target well in the most natural way. Whether or not the updip position of the target well contributed to the successful results could not be established. The dip is very gentle, practically negligible, and cannot be considered a major factor.

Cases 2, 3, 4—complete failures

Cases of complete failure are considered those in which no apparent communication between wells has been established. Curiously, the reported cases represent three unrelated attempts in three different fields to connect wells in the "D" salt zone of the Salina (after classification by Landis).

Case 2 is a field, or a portion of, locked in between a highway and a railroad track, forming a long and narrow stretch. It is apparent that the layout of the wells was mainly dictated by the surface geometry and not by fracturing considerations. The efforts of numerous attempts (Fig. 3) to connect groups of wells in the "D" salt zone, using different permutations, were unsuccessful. The four frac jobs performed in well No. 1 are shown schematically in Fig. 4. Well No. 2 was never hit by any of the fractures induced in No. 1. Each of the four attempts represents a different well completion. None appeared to yield desired results.

Cases 3 and 4 represent groups of two wells in two separate fields in which considerable amounts of money and time (many months in each case) were spent on every

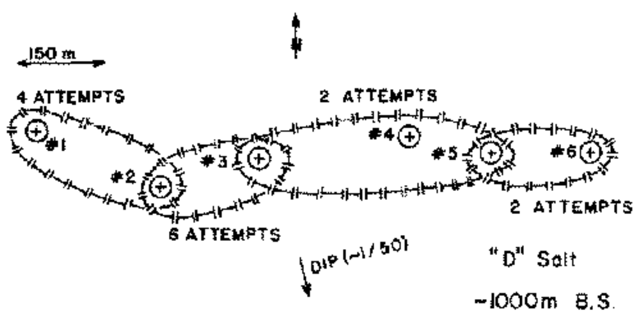

Figure 3. Case 2—Unsuccessful fracture connection attempts in the "D" salt zone.

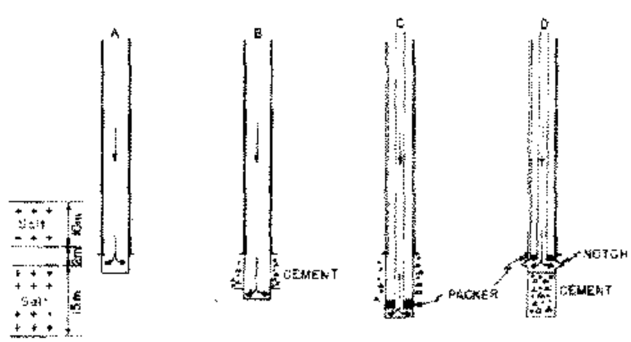

Figure 4. The sequence of unsuccessful fracturing attempts in well No. 1 (Case 2).

feasible hydraulic fracturing configuration with no apparent success.

Several explanations can be given to describe the consistent failures in the 'D' salt. They are all speculative since available data on the properties of this salt zone are scarce at best. One explanation is based on the fact that the salt layers in the sites under consideration are relatively thin (of the order of 1–20 m) and are separated by anhydrite, dolomite or mudstone. It is almost inconceivable that in such thin layers of salt a hydraulic fracture could be isolated from the neighboring rock layers. These rocks are substantially more brittle than halite, and show no tendency of healing existing fractures. The possibility exists that these intermittent layers are indeed precracked, and that once the hydrofrac reaches them their high permeability will direct most of the flow out of the salt. Since the target wells in most of the described cases were completed so that only a very restricted segment was left for fracture connection it is not unrealistic that the flow of brine or water through the fracture of the neighboring layers went unnoticed.

Another theory related to the persistent failures is that the salt layers themselves, independently, or as a result of the intermittent strata of the more brittle rocks, are traversed by faults or other discontinuities which deflect the direction of fluid flow and disrupt the otherwise probable communication. Faults and fractures in halite are expected to heal with time and are generally considered non-existent, but many observations in underground mines confirm that discontinuities in salt are sometimes clearly detected.

A third explanation is based on the author's laboratory experimental results of hydraulic fracturing in salt. Unlike any other previously tested rock, hydraulic fracturing of salt specimens obtained from the Detroit mine yielded not one but a band of fractures. These looked more like a band of flow channels along grain boundaries, with the general orientation being vertical. Because of the limited number of tests, using only one type of coarsely crystalline salt, it is impossible to extrapolate as to the generality of the results. However, if the 'D' salt happened to behave in a similar manner, it is then conceivable that the oriented flow through the crystal boundaries could have missed the target well.

Cases 5–10—partial failures

Probably the most interesting cases are those of partial failures or partial success. They show how such parameters as geology, well layout, completion, and design can affect the results of a frac job.

One of the most fully documented cases is No. 5. A group of eighteen wells were planned to be connected by hydraulic fracturing into six galleries as shown in Fig. 5. No apparent consideration was given to fracture direction preference in the area. Surface considerations called for the six galleries to be north-south oriented, and to accomplish that the distance between wells in the N-S direction was kept at 150 m, while the span between E-W wells was set at 250 m. All wells were to be completed with casing and perforations at the depths desired for fracture connection.

The first designated group to be connected was B1–3, (Fig. 5) with the central well (B2) acting as the fracturing hole and the other two as the target holes. The only other hole drilled at the time was C3. Three and one half hours of pumping into well B2 (325 m^3) produced a connection, but with the 'wrong' well, i.e., C3 (Fig. 6). Caliper and

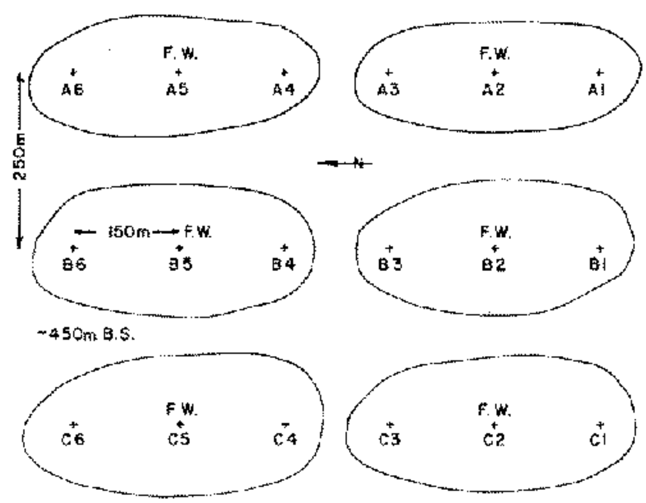

Figure 5. Case 5—Planned well layout and cavity pattern.

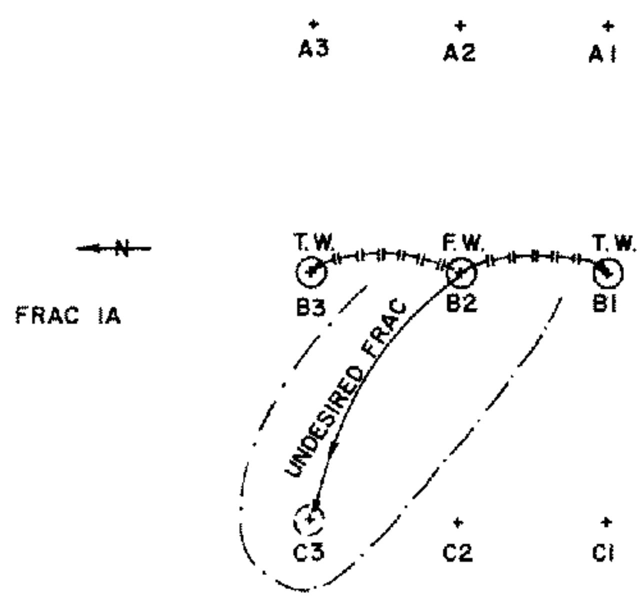

Figure 6. Case 5—First unsuccessful attempt to connect B2 to B1 and B3.

radioactivity logs showed that the fracture hit well C3 at the same level that it initiated at B2.

After casing, cementing and shutting-in well C3, fracing was resumed on B2 (at 1.2 m^3/min). Some 20 hours later partial flow was detected in well B3 (.3 m^3/min) and in B1 (.004 m^3/min). Soon, however, well A3, which was being drilled at the time, ran into a high pressure flow of brine, and fracing was stopped again (Fig. 7). Later on, when all 9 wells shown in Fig. 6 had been drilled and completed all but B2 and B3 were shut-in to allow a new attempt to connect the two wells. C2 had erroneously been left open, however, and the full flow of brine was coming its way. Only after plugging C2 an eventual full flow connection B2–B3 was established. This was four months after the first frac attempt!

The above sequence of events shows beyond any doubt that the salt formation in case 5 had a preferred fracture and fluid flow direction which affected not only well communication but also the transition to low pressure connection. It so happened that the preferred direction was east-west, while the design called for north-south well connections. The result was a large consumption of fluids and eventual drastic redesign of galleries.

The same trend of preferred fracture direction can be observed in the second 9 well group. The sample shown in Fig. 8 is of an attempted connection A6–A5. Pumping into A6 yielded a connection with B6 after 10 hours and 600 m^3 of flow. Shutting-in well B6 still did not result in the desired connection. Rather B5 was communicated with.

It is strongly felt that in such a large hydrofracturing operation involving eighteen wells, more emphasis should have been placed on studying the mechanical reaction to fracturing of the formation involved before planning well location and gallery layout. One recommended method of initial fracing to determine trends and preferred directions in a salt layer is described elsewhere in this paper.

Case 6 involves the first three wells (A1–3) to be connected by hydraulic fracturing in a new salt field, as shown in Figs. 9 and 10. The wells were 300 m apart, and about 750 m deep. They were aligned in an east-west direction. After completing wells A2 and A3 an attempt was made to connect them by fracturing A2. Twenty-four hours of pumping resulted not in a connection with A3 but in a brine flow out of a gas well some 2500 m to the west (Fig. 9). Prior to discontinuing fracturing operations some

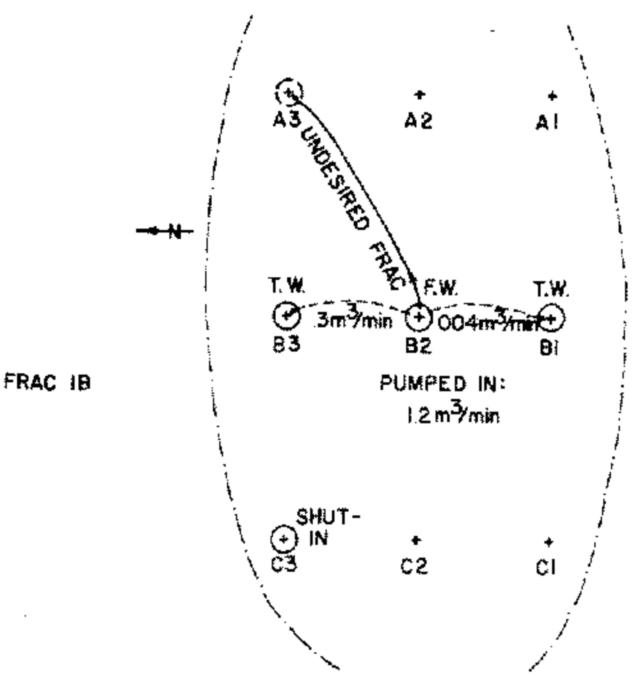

Figure 7. Case 5—Second unsuccessful attempt to connect B2 to B1 and B3.

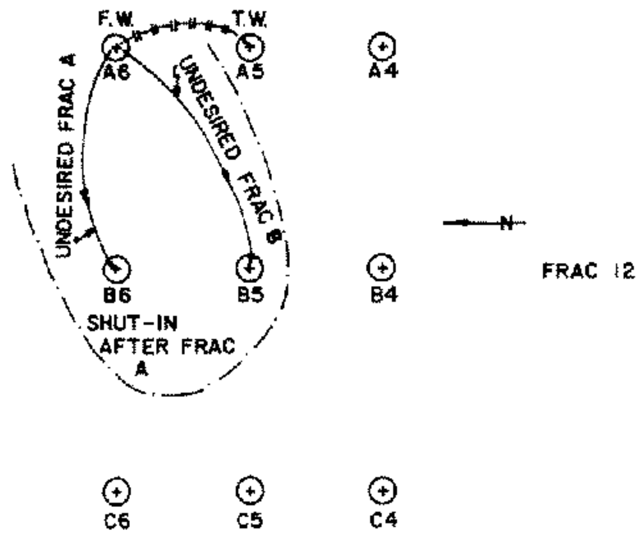

Figure 8. Case 5—Two unsuccessful attempts to connect A6 to A5.

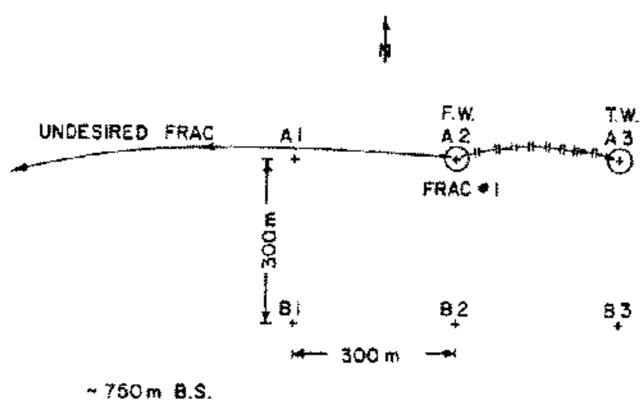

Figure 9. Case 6—Unsuccessful attempt to connect well A2 to A3 due to strong flow tendency to the west.

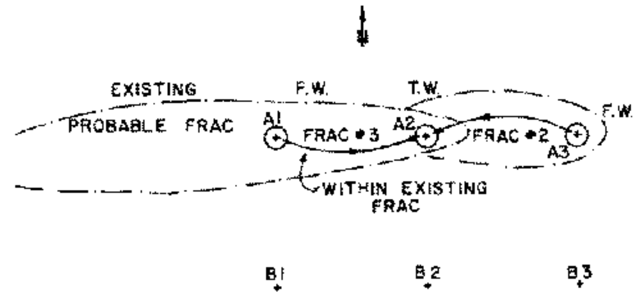

Figure 10. Case 6—Good connections A3 to A2 and A1 to A2.

10,000 m^3 of water were pumped into A2, 1000 m^3 were recovered from the gas well, and no flow was detected at A3. A strong case of preferred fracture direction to the west! The tremendous distance to the gas well could indicate that the advancement of the pumped water through the underground strata was not wholly due to fracturing but possibly a result of running into existing discontinuities. The fact remains, however, that the hydraulic fracture did not spread uniformly in all directions as theoretically assumed.

An attempt to fracture A3 into A2 was subsequently successful, supporting the hypothesis that hydrofracture development had strong tendencies to the west in this field (Fig. 10). Fracing A1 and A2 also yielded an easy connection, but this result is most probably due to an existing fracture created when A2 had been fraced.

Case 7 (Fig. 11) is another example of cavity and well layout design based on surface consideration rather than on underground fracture trends. Six wells were to be drilled that would form two north-south galleries at about 750 m below surface, one connecting the A wells, another

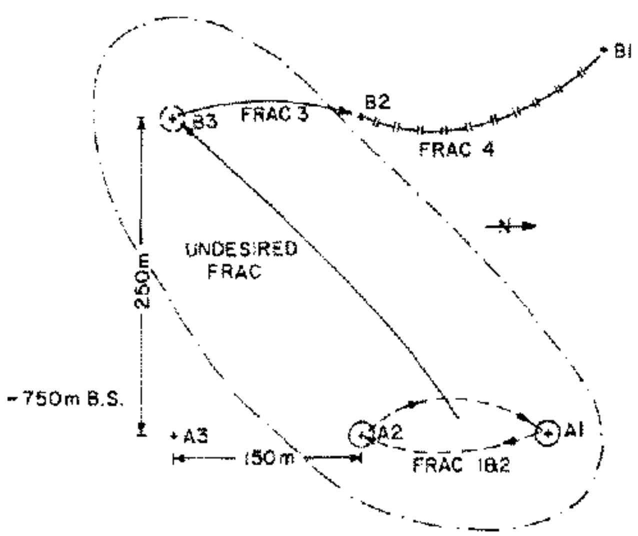

Figure 11. Case 7—High pressure connection A2 to A1 and no connection B2 to B1 due to strong frac preference to the southwest. Well completion shown at the time of fracs 1 and 2.

connecting the B wells. To 'ensure' that the fracture would not connect the wrong wells, a distance of 250 m was kept between the two groups, while only 150 m separated wells within a group. All wells were cased and perforated at the levels where fracturing was to be initiated or expected to connect.

The first attempt was to connect A2 to A1. Pumping in excess of 8000 m^3 of water yielded only a high-pressure connection with very little flow. During deepening operations in well B3, however, a full flow of brine was encountered. Moreover, shutting-in B3 raised the pressure in the well to a level equal to that in A1–A2. It was beyond doubt that the large volumes of water pumped into A1–A2 were actually flowing in a southwestern direction.

The attempt to connect B3 to B2 is an excellent example of the superiority of open-hole fracturing. Large quantities of fluid pumped into B3 appeared to yield no connection with B2. However, by cleaning out a few feet of cement that had previously been used to fill the bottom of B2 during casing a rapid inflow of brine was encountered and the connection to B3 was established. Were B2 open-hole in the salt zone the connection would have been made a number of days earlier.

The attempted connection B2 to B1 was a complete failure. Apparently, most of the water pumped into B2 went into the probable fracture shown in Fig. 11.

It should be noted again that the preferred direction of a fracture appears to control not only the actual connection between wells, but also the transition from high to low-pressure communication. The A2–A1 connection was finally achieved, although the wells were not ideally situated, because enough water was pumped in A2 to extend the fracture not only in the preferred direction, but also laterally towards A1. But the connection persisted at its high pressure level and partial flow in spite of additional large quantities of fluid. It was apparently more natural for the fluid to flow in the preferred fracture direction, at one point bringing the output at A1 to an almost complete halt.

Case 8 is an additional example of preferred fracture direction. This is a field where due to legal restrictions the wells must be drilled close to existing roads (Fig. 12). Hydraulic fracturing connections are also expected to follow road directions irrespective of their natural trends. To prevent any problems the wells to be connected are drilled within 30–80 m from each other. Because of the close distance most of the planned connections are eventually made, often at the expense of large quantities of flow and extended time. The part of the field shown in Fig. 12 appears to have a preferred fracture direction to the northeast, which unfortunately is not followed by the roads, resulting in long undesired connections.

Case 9 provides information on the importance of hydraulic fracturing depth and well completion. The first group of wells was drilled down to the bottom of the salt

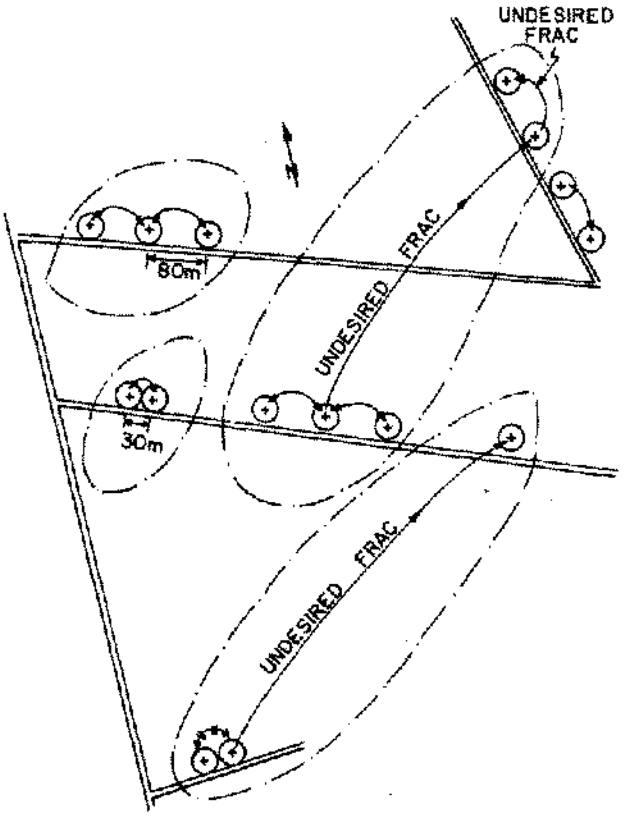

Figure 12. Case 8—Well layout following existing roads. Fracture preference to the north-east.

hoping that the interface with the underlying limestone would promote a horizontal fracture extension, and thus the entire salt zone would be brined (Fig. 13). What was overlooked was the condition of the limestone which is fractured and ruptured in that field. The result was a huge consumption of water and tremendous time loss (several months) before low-pressure connection was established.

In the second group of wells precautions were taken. The wells were drilled to some 2.5 m above the bottom of the salt and the fracturing which had previously been done through perforations was now initiated by the more precise way of notching. The results were almost perfect. Connection was immediately established and fluid losses were nil (Fig. 14). The small amount of salt under the fracture level which may not be completely recovered is just a small price to pay for a much improved frac job.

Case 10 is a similar example of connection failure in which fracing was done through perforations at the very bottom of a 75 m thick salt layer. In addition to the possibility that the underlying strata was prefractured and swallowed most of the pumped-in water, the perforations (like in case 9) could have caused formation damage and contributed to the failure of the job. A second fracture attempt some 20 m higher, and adjacent to a stringer, finally resulted in a good low-pressure connection.

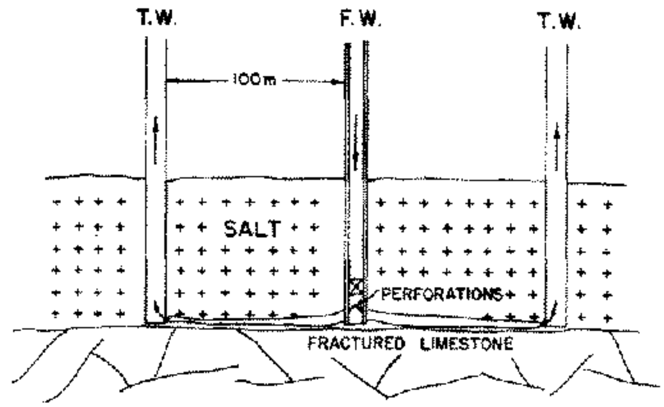

Figure 13. Case 9—Fracturing the portion of the well that came in contact with or was dangerously close to a fractured limestone formation resulted in huge quantities of pumped-in fluids and months of work before a low-pressure connection was established.

DISCUSSION AND RECOMMENDATIONS

In the above review of ten case histories no attempt was made to provide detailed descriptions of each frac job. Rather, the more important aspects were singled out in an attempt to expose some of the fundamental reasons behind fracturing partial or complete failures.

The major conclusion of the study is, perhaps, that hydraulic fracturing in salt is not as erratic as it appears at first sight. What contributes to its unpredictable behavior is the fact that not enough emphasis is being placed on understanding the geology of each location. For example, a thorough investigation of the permeability (due to both pores and fractures) of neighboring rock strata could assist in planning hydraulic fracturing depths away from dangerous zones which would absorb most of the pumped-in fluids. A study of the mechanical reaction to fracturing of the major salt formations could provide answers to such questions as why frac attempts in the "D" salt have been consistently unsuccessful, or why some fractures prefer particular directions of propagation.

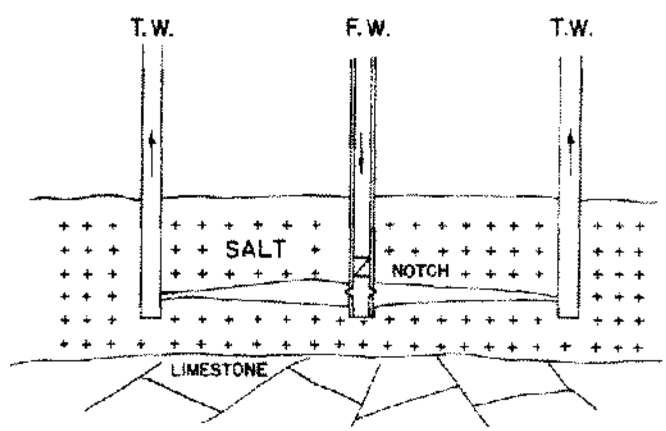

Figure 14. Case 9—Raising the bottom of the wells by 2.5 m resulted in near perfect fracturing and rapid low-pressure connection.

Improved recording of fracturing events is a prerequisite to better understanding of frac mechanism. Although considerable improvements have been made over the years there are still cases where pressure or flow records are inadequate. Continuous recording of these two parameters in both the injection and the target wells are strongly recommended. Accurate logging of wells to determine depth of connection could assist in estimating fracture inclination.

Well completion depends on different factors and may vary from site to site. Whenever structurally feasible, however, open-hole completion in the hydrofractured salt zone is recommended. Casing and perforating can be detrimental both to the injection well because perforations may induce fractures in undesired directions, and to the output well because the target area to the approaching frac is thus thoroughly limited.

Probably the factor most directly responsible for the success or failure of a frac job is the design of well location. When the geology, mechanical behavior, in situ stresses, or past experience related to a field are not well known there is not enough information to rationally plan well layout. This is, unfortunately, the case in most new salt fields, or new salt formations in old fields. One possible frac procedure to be followed in new fields is shown in Fig. 15. A group of wells (at least four) are drilled such that one is in the center and the others are evenly spread around it at reasonable distances for fracture connection. The central well is the fracturing hole. All wells are instrumented for pressure and fluid flow monitoring. As the hydraulic fracture is initiated and fluid is pumped-in the instruments are carefully watched. At some point one of the circumferential wells will show a sudden pressure increase signaling a high-pressure connection. At a later stage another well may indicate connection. Continued pumping will finally yield a low-pressure communication with one or more of the wells. This entire sequence of events, diagramatically depicted in Fig. 15, would not only yield a successful connection at least between some of the wells drilled, but, in particular, will provide enough data on fracture and flow preferred directions to render a rational layout of future galleries in the field.

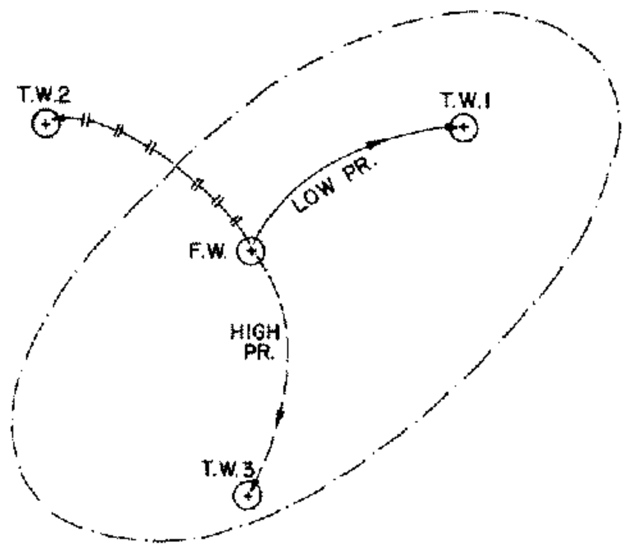

Figure 15. Recommended hydrofracture procedure prior to brine field design.