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GEOTHERMAL RESERVOIR WELL STIMULATION
PROGRAM: TECHNOLOGY TRANSFER

May 1980

Work Performed Under Contract No. AC32-79AL10563

Republic Geothermal, Inc.
Santa Fe Springs, California

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U. S. DEPARTMENT OF ENERGY
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GEOHERMAL RESERVOIR WELL
STIMULATION PROGRAM

TECHNOLOGY TRANSFER

VOLUME I

Prepared for:

U.S. Department of Energy

Contract No. DE-AC32-79AL10563

by: Petroleum Training and Technical Services

May 1980

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1.0 INTRODUCTION

In the first phase of this contract, a comprehensive search of all available sources was made to assess the state of the art technology in stimulation operations. This assessment was carried out by several of the participating subcontractors. Included are:

- (1) Petroleum Training and Technical Services
- (2) Maurer Engineering
- (3) Vetter Research
- (4) Republic Geothermal, Inc.

To accomplish this overall assessment, several avenues have been explored and the information from all these sources collected, compiled and correlated. The primary sources of information were obtained as a result of:

- (1) On line literature searches of available databases. The principal areas used were:

TULSA Abstracts: Petroleum literature
NTIS: Government Reports
COMPENDEX
GEOREF
CONFERENCE PAPERS

Service Company

- (2) Discussions on stimulation operations, especially with those groups that have been developing and performing stimulation operations. Those discussions included the following companies:

BYRON JACKSON
HALLIBURTON
DOWELL
WESTERN COMPANY

- (3) Operator Companies, meeting and discussing stimulation operations with those companies who have been actively involved in successful stimulation operations.

(4) Government Funded Research, met and discussed fracture stimulation operations with those companies who are actively pursuing funded research in this area.

(5) Personal experiences of the members of the contractor and sub-contractor group. The collective experiences of the project team in the area of stimulation operations have been documented. Many of the group have extensive operational and analytic experiences in stimulation work.

1.1.1 Review of Available Data from Previous Fracturing Stimulation Operations

Several sources were explored to compile the data and it was found that the "goodness of information" varied with the source. The main criticisms reported in this effort which were related to the information were:

- (1) Sources provided incomplete information.
- (2) Sources were several years behind on reporting the information after the operation had been done.
- (3) Information was proprietary and could not be released.
- (4) Information did not exist.

By far the most productive phase of this effort in terms of good information received for time invested was the personal contacts with the service companies and the operators. The other sources provided data in varied degrees of goodness.

2.0 STIMULATION PROCESS VARIABLES

There are several variables that affect the stimulation process. However, the variables can be divided into 2 basic categories.

- (A) Controllable - these are those variables that the engineer can control to affect the process outcome, e.g., treatment size
- (B) Non-Controllable - these are those variables that cannot be controlled as modified, e.g., formation depth and porosity.

A further distinction may be made to indicate a special category of parameters which have limited controllability. These parameters are theoretically controllable but limitations imposed by prior operating or design actions limit the range of variation possible in these particular cases. An example is the pumping rate during the treatment, this may be limited due to the wellbore dimensions which can cause excessive pressure loss at high flow rates.

The Controllable Variables generally represent operational and fluid parameters. These are as follows:

1. Treating Pressure
2. Injection Rate
3. Stimulation Volumes
4. Treatment Sequencing
5. Proppant Volume
6. Proppant Distribution
7. Fluid Loss Additives
8. Frictional Losses
9. Mobility Control and Degradation
10. Breaking characteristics
11. Fluid Temperature Response
12. Viscosity
13. Frac Fluid Type
14. Fracture Fluid Chemistry

The Non-Controllable Variables are usually associated with the formation and its fluids.

1. Permeability
2. Porosity
3. Reservoir Pressure
4. Pay Thickness
5. Clay Content
6. Depth
7. Shale Content

8. Heterogeneity
9. Isotropy
10. In Situ Rock Stresses
11. Reservoir Temperature
12. Adsorption Phenomena
13. Wellbore Damage
14. Rock Hardness

In reviewing the work done on stimulation it has been noted that there have been several reasons indicated for failure of stimulation jobs.

1. Fracture not confined to target formation
2. Fracture fluid communication at the wellbore produces stimulation of non-target zone
3. Premature stimulation treatment termination
4. Incorrect proppant
5. Frac fluid incompatibility with formation fluids
6. Improper proppant volumes
7. Improper perforating program
8. Incomplete return of treating fluids.

On the positive side several reasons for demonstrated success in stimulation jobs have been reported.

1. Use of water as a frac fluid
2. Overdisplacement - at low rate - helps to minimize back production of frac sand
3. Use of spacers to reduce proppant concentration has reduced screen outs
4. Reduced pumping rate near end of job enhances prop pack and conductivity
5. Energizing the last portion of its injected fluid speeds cleanup and improves productivity
6. Use of surfactant to lower surface and interfacial tension has helped frac fluid recovery

Observation of the results and analysis of the pressure and flow data have provided differing interpretations. The conclusions reached usually depend somewhat subjectively on the author's perspective. Stimulation treatments have ranged from:

- I. Phenomenal successes - predicted fracture geometry agrees with actual post fracture analysis and production increase close to predicted
- II. Engineering successes - the predicted fracture agrees with the post fracture analysis but there was no production/reserves increase due to an inadequate reservoir
- III. Marginal - no change in reservoir production/reserve picture
- IV. Abysmal Failures - a totally "no answers exist" situation where no trace of stimulation can be determined even after enormous amounts of fluid and proppant have been pumped into the formation

The underlying theme of most of the post mortem analysis of fractures is that good stimulation can be accounted for by the known post frac analysis techniques. However, the statistic that 25% of all jobs fail and some indicate that this percent may be even higher points to one salient conclusion:

1. A BETTER DIAGNOSTIC TOOL OR SUITE OF TOOLS IS NEEDED TO DETERMINE WHAT WENT WRONG ON THE FAILURES AND TO APPLY THIS KNOWLEDGE TO OTHER JOBS.

Sufficient detailed analysis of the failures has not occurred. Usually this is a conscious subjective decision by the individual to not to dwell on the bad news or to explain it away as rapidly as possible.

3.0 FRACTURING FLUID DESIGN

3.1 Effect of Fracturing Fluid Interactions

The fracturing fluids can interact with both the formation itself and with the proppant within the fracture itself. These interactions directly affect matrix permeability and fracture conductivity, two parameters which seriously modify the post-fracture productivity of the reservoir. It is imperative the fracture fluid damage be incorporated into detailed design and analysis of the stimulation treatment.

3.2 Interaction with Formation

The loss of fracture fluid to the formation opposite to the fracture face creates a zone of immobile fluid within the pore space. This fluid saturation decreases the relative permeability to the mobile phase--usually gas--and thus decreases the deliverability. A secondary problem associated with fracture fluid invasion is the reduction in matrix permeability due to the swelling of clays. This factor can cause a several fold decrease in matrix permeability which may not fully recover after cleanup.

The percentage of permeability damage is dependent on the initial insitu permeability and the type of fluid. As a general rule, higher permeability samples show a greater degree of damage. Laboratory studies have shown that after cleanup the permeability damage is still significant and the remaining degree of damage is a function of the original permeability.

3.2.1 Interaction in the Fracture

The fracture fluid leaves behind liquid and solid residues in the fracture. In addition, softening of the fracture face can cause proppant embedment and decreased conductivity. The effect of this damage is more dramatically shown when the fracture conductivity is investigated as a function of effective insitu stress. Referring to Figure 1, the initial gentle slope of the curve indicates the packing of the proppant with increasing stress, for the three samples shown points B, C, D represent the stabilized fracture conductivity with no fracturing fluid damage while points B', C', D' represent the lowest fracture conductivity equal to or higher than packed fractures at the same applied stresses. Upon interaction with the fracture fluid the damage to the propped mono-layer fracture is greater than that to the propped fracture. The contributing factors to a reduction in fracture conductivity are:

1. Packing of proppant which is predominant in fully packed layers.
2. Proppant embedment due to softening of fracture face.
3. Proppant crushing which is predominant in a partial layer.
4. Fracture fluid residue clogging of channels in packed layers.

Fig. 1: Fracture Conductivity - effective stress relationship

5. Clogging of channels due to release of fines.
6. Clay flocculation especially at proppant embedment locations.

5.3 SUMMARY

The problems caused by fluid interactions are severe and must be accounted for in geothermal stimulation situations. The effects of insitu stresses and temperature, particularly the latter, must be rigorously explored in the design of the geothermal projects. The following problems may be associated with fluid interactions:

(A) PROBLEM

Matrix Permeability Reduction

CAUSE

Immobile zone in fracture fluid
Clay swelling

REMEDY

Proper design for leak off control
Effective cleanup operations
Proper selection of fracture fluid to minimize clay interaction

(B) PROBLEM

Fracture Conductivity Impairment

CAUSE

Solid and liquid residue
Proppant embedment
Proppant crushing to produce fines

REMEDY

More effective cleanup operations
Minimize fluid effects on fracture face by appropriate selection of fluid
Better selection of proppant

4.0 HYDRAULIC FRACTURE DESIGN

4.1 Problems Associated with Hydraulic Fracturing

(A) PROBLEM:

Fracture not confined to productive interval

CAUSES:

Improper identification of effective barriers

Lenticular structure of sands

Non-continuity of sand away from wellbore

SOLUTION:

Lab core studies to predict capability of sands to sustain fractures

More comprehensive logging program to delineate zones

Better geological control to define productive sands away from wellbore

(B) PROBLEM:

Breakdown of horizontal barriers of reservoir

CAUSES:

Too large an injection rate puts excessive stress on barrier

SOLUTION:

Constrain the injection rate to produce stresses below the limit to fracture barrier

(C) PROBLEM:

Fracture generation outside of desired interval

CAUSES:

Incorrect perforating program caused propagation out of zone

SOLUTION:

Especially in large vertical zones, use limited entry techniques

Use of hole opener treatment to assure adequate entry in all perforations

(D) PROBLEM:

Premature termination of treatment

CAUSES:

Screen out due to inadequate leakoff control

SOLUTION:

Minimize leakoff problems by adequate fluids

Use of 100 mesh sand to control leakoff into formation by bridging in hairline fractures

(E) PROBLEM:

Equipment breaks down prior to completion of treatment

CAUSES:

Equipment failure

SOLUTION:

Adequate maintenance of equipment and tubular goods

(F) PROBLEM:
Poor stimulation results

CAUSES:
Incorrect proppant size

SOLUTION:
Proper design of proppant to sustain closure stresses

(G) PROBLEM:
Poor stimulation results

CAUSES:
Improper fluid selection and fluid incompatibility

SOLUTION:
Comprehensive laboratory and analytical testing with cores and reservoir fluids

(H) PROBLEM:
Poor stimulation results

CAUSES:
Improper proppant volume and scheduling

SOLUTION:
Proper design of proppant volume and pumping schedule to provide efficient transport and placement of sand during treatment and effective packing

(I) PROBLEM:
Poor stimulation results

CAUSES:
Shut-in of wellbore and treating fluid returned to surface

SOLUTION:
Allow sufficient time to recover treating fluid and proper cleanup

4.2 Effect of Temperature in Fracture Design

Until the middle 1960's, the classical assumption that the fracture fluid immediately reaches the temperature of the reservoir matrix was universal. At this time several works were published showing that the assumption was erroneous and could lead to inefficient fracture design and subsequent errors in predicting post-fracture reservoir response.

The approaches to solving the problem have one unifying theme; the transient heating by conductive and convective heat flow has to be incorporated in the design process. The successful addition of those processes have resulted in the development of analytical tools which have indicated the following:

- Heat blockage is caused by flow of cool fracture fluid into the reservoir counter to the flow of heat into the fracture
- This heat blockage is significant and significantly affected by leakage rates and to a lesser degree by fracture dimensions, rock and fluid properties
- In temperature sensitive fracture fluids, there is a marked difference between the design parameters based on no temperature effects as compared to those that include the heat blockage effects
- In general, inclusion of heat effects in the fracture provide more optimistic fracture geometries since fluids have greater carrying power, produce greater fracture conductivities and consequently greater productivity increases

4.2.1 Whitsitt-Dysart Model

This model is designed to handle temperature effects.

$$T = T_w + (T_i - T_w)(1 - e^{-\beta}) \quad (1)$$

$$\beta = \frac{2.37I(K\sqrt{t} x_D)}{(1 - \phi)K\sqrt{t}} \quad (2)$$

$$K = \frac{2.1 W_t C_f}{hL(1 - \phi)\sqrt{MK}} \quad (3)$$

Assumptions: (1) Non uniform leak off along fracture - greatest near tip, least at wellbore

(2) No wellbore fluid heating

Conclusions: (1) Fluid temperatures much lower than reservoir temperatures

(2) Higher viscosity and proppant carrying capacity can lead to better and more conductive fractures

Nomenclature: T_i = initial reservoir temperature

T = temperature of fluid in fracture

T_w = temperature of fluid leaving wellbore

W_t = total mass flow rate of fluid into one side of fracture

C_f = specific heat of fracture fluid

h = height of fracture

L = length of fracture

ϕ = porosity

M = volumetric heat capacity of matrix

k = thermal conductivity of rock

I = integral defined in original paper

4.2.2 Sinclair Model

This model is designed to handle temperature effects.

$$T_{Db} = \frac{1}{2} U(\tau - \delta M_D) \left\{ \exp[2\alpha(\delta + \xi)] \operatorname{erf} \left(\frac{\delta + \xi}{2\sqrt{\tau - \delta M_D}} + \alpha\sqrt{\tau - \delta M_D} \right) \right. \\ \left. + \operatorname{erf} \left(\frac{\delta + \xi}{2\sqrt{\tau - \delta M_D}} - \alpha\sqrt{\tau - \delta M_D} \right) \right\} \quad (1)$$

$$\delta = \frac{1}{2\alpha} \ln \left| \frac{i_D}{i_D - 2\alpha x_D} \right| \quad (2)$$

- Assumptions:
- (1) Constant leak off rate along fracture
 - (2) Conductive and convective heat loss included
 - (3) Constant fracture width
 - (4) Constant fluid and formation properties

- Conclusions:
- (1) Heat blockage produces significant effect on the fracture fluid temperature
 - (2) Higher leak off rate causes more heat blockage and provides more effective insulation

Nomenclature: U = step function
 τ = $K_1 t / H^2 \rho_1 C_1$
 M = $\rho c w / \rho_1 C_1 H$
 i_D = injection rate term
 α = $\rho_f C_f V_f H / 2 K_1$

4.2.3 Modified Carter Equation (Pattillo Equation) Model

This model describes fracture area growth,

$$A(t) = \frac{iw_0}{2c^2\pi} \left\{ \frac{1}{K_1 - K_2} [K_1 e^{K_2^2 t} \operatorname{erfc}(K_2 \sqrt{t}) - K_2 e^{K_1^2 t} \operatorname{erfc}(K_1 \sqrt{t})] + \frac{2c}{w_0} \sqrt{t} - 1 \right\} \quad (1)$$

$$K_1, K_2 = \frac{kw_0}{2c\sqrt{\pi}} \pm \sqrt{\left(\frac{kw_0}{2c\sqrt{\pi}} \right)^2 - k} \quad (2)$$

$$w(t) = w_0 [1 - e^{-kt}] \quad (3)$$

Assumptions: Same as Carter except:

- (1) Non-uniform width of fracture
- (2) Greatest width is at the wellbore

Nomenclature: $A(t)$ = Area of 1/2 fracture at time t

C = fluid loss coefficient

i = volumetric flow rate into the fracture

k = fracture width growth parameter

K_1, K_2 = constants defined by Equation (2)

w_0 = fracture width at wellbore

t = time

- Conclusions:
- (1) Allows variation of fracture width with time
 - (2) Incorporates static or dynamic fluid loss functions

4.3 Fracture Evaluation

4.3.1 Introduction

The evaluation of the fracture treatment and specifically the determination of the fracture geometry and properties has been the subject of considerable debate and discussion throughout the literature. There are two basic approaches:

- (1) Pressure transient analysis
- (2) History matching using reservoir simulators

4.3.2 Pressure Transient Analysis

Literally hundreds of articles have been published on pressure transient analysis in fractured wells. Many of these articles have been reinterpretations of the same basic theme with very slightly modified boundary conditions. An analysis of all this literature brings to focus four possible situations of any real interest:

Fracture Orientation:

1. Vertical Fractures
2. Horizontal Fractures

Fracture Conductivity:

1. Infinite conductivity--no pressure drop along the fracture
2. Uniform flux--high conductivity but not infinite, implying a pressure drop along the fracture

A comparison of measured field data and analytical studies indicates:

Wells intersecting natural fractures tend to fit the uniform-flux mold.

Hydraulically fractured and propped wells tend to fit the infinite conductivity case.

The two frequently used techniques for pressure transient analysis of fractured systems are indicated below.

- (1) Semilog Plots - Horner
 - Miller-Dyes-Hutchinson
 - Muskat

These methods are severely limited in their applicability to determine fracture parameters and reservoir permeability data since trial and error techniques are necessary.

(2) Log-Log Plot - These are generically called the type curve approach. It involves a plot on log-log paper of the pressure response function and a subsequent curve-matching to determine the fracture and reservoir parameters.

It is the general opinion of most reservoir engineers that the type curve approach is superior to the other presently available means of analytical analysis of fractured well data.

4.3.3 Assumptions to Pressure Analysis in Fractured Systems

- Homogeneous systems
- Isotropic
- Slightly compressible fluids
- Single phase
- Constant viscosity
- Pressure gradients are small
- Gravity effects neglected
- Fractures symmetric
- Fracture penetrates total interval
- Production only occurs through the fracture

4.4 History Matching

This is the more elegant and expensive technique for analysis of post-frac data. Essentially, the performance of the well is simulated using the known rock and fluid properties and the estimated fracture parameters. The pressure test is then simulated and a comparison made with the field measured pressure data. The estimated fracture parameters are modified until a match of the complete build-up or draw-down curve is obtained.

It should be noted, however, that a match of both the historical production/pressure data and the pressure test must be obtained to guarantee an unique set of fracture parameters.

4.5 Post Fracture Analysis

The most fruitful technique for post-frac analysis involves a combination of Type curve matching and reservoir simulation of the build-up or drawdown test. The inclusion of the reservoir simulation phase into the post-frac analysis is recommended because of the possible non-uniqueness of the type curve match. The simulator then affords an approach for determination of the acceptability of a given set of parameters.

In any study, some concerted effort should be made to limit the degrees of freedom in the type curve matching. A determination of the pre-frac "kh" value can fix the y-axis on the log-log plot and thus limit variations to the x-axis only.

This precaution simplifies the analysis and reduces the cost of trial and error simulation studies of the post fracture performance (See Figure 6-1).

Fig. 1: Pressure Transient Analysis for Fractured Wells

4.5.1 Vertical Fracture - Well in Square - Uniform Flux - Constant Pressure Model

Equation: Dimensionless Pressure Relation

$$P_D(x_D, y_D, t_D) = \frac{kh}{141.2q_{\mu B}} [P_i - P(x, y, t)]$$

P_D is calculated or determined from tabulated values.

For Uniform Flux Case:

Use $x_D = 0.5$

$y_D = 0.5$

Pressure Function:

Figure 2

4.5.2 Vertical Fracture - Well in Square - Infinite Conductivity - Constant Pressure Model

Equation: Dimensionless pressure relation

$$P_D(x_D, y_D, t_D) = \frac{kh}{141.2 q_{\mu B}} [P_i - P(x, y, t)]$$

P_D is calculated or determined from tabulated data.

For Infinite Conductivity Case:

Use $x_D = 0.5 + 0.732x_{fD}$

$$y_D = 0.5$$

Pressure Function:

DIMENSIONLESS PRESSURE DROP VS DIMENSIONLESS TIME
FOR AN INFINITE CONDUCTIVITY VERTICAL FRACTURE.

FIGURE 3

Nomenclature:

P_{wD}	= dimensionless well bore pressure at fracture axis
t_D	= dimensionless time
x_f	= fracture length
x_e	= distance from outer of well to drainage radius
μ	= viscosity
A	= area
D	= dimensionless
w	= well
t	= producing time
Δt	= shut in time

4.5.3 Horner Model

Application: Plot shut in pressure P_w vs $\log \frac{t + \Delta t}{\Delta t}$

Plot Type:

Figure 4

HORNER GRAPH FOR VERTICALLY
FRACTURED WELL IN THE CENTER OF A
CONSTANT PRESSURE SQUARE.

Figure 5

4.5.4 Miller-Dyes-Hutchinson (MDH) Model

Application: Plot shut-in pressure P_{ws} vs log shut in time

Plot Type:

MILLER-DYES-HUTCHINSON BUILDUP
GRAPH FOR VERTICALLY FRACTURED WELL
IN A CONSTANT PRESSURE SQUARE.

Figure 6

4.5.5 Muskat Model

Application: Plot $\log$ of $(\bar{P} - P_{ws})$ vs the shut in time

Plot Type:

MUSKAT GRAPH FOR A
VERTICALLY FRACTURED WELL IN
A CONSTANT PRESSURE SQUARE.

Figure 7

4.5.6 Type-Curve Analysis Model

Figure 8

5.0 Stimulation Case Histories

5.1 RioBlanco Well, RB-0-4, Piceance Basin, Colorado

Preliminary Information

1.	Location	Piceance Basin
2.	Field Name	Rio Blanco Well RB-U-4
3.	State	Colorado
4.	County	Rio Blanco
5.	Formation Name	Fort Union Sands
6.	Hydrocarbon Type	Gas
7.	Cumulative	The well is a gas reservoir evaluation well. The goal is for commercial development of low-permeability gas reservoirs by nuclear explosive stimulation. However, hydraulic fracturing of the well is also performed, which is described here.

Formation Description

8.	Rock Type
9.	Geologic Information

Formation Characteristics

10.	Permeability	
11.	Porosity	
12.	Matrix porosity	
13.	Frac. porosity	
14.	B.H. Temp.	
15.	Avg. Res. Press.	
16.	Depth D.	7,000 ft.
17.	Thickness (h)	
18.	Clay Content	
19.	Heterogeneity	
20.	Isotropic	
21.	Anisotropic	
22.	Shale content	
23.	Initial potential	

Methods of Analysis

24.	Design Criteria	
25.	Post Frac. Analysis	Flow test
26.	Deliverability	
27.	Interpretations	

Productivity Modification

28.	Initial Potential	The well failed to produce after perforating and swabbing
29.	Post Frac: Production	53 MSCF/D @ BHP 1,700 psig; 7 MSCF/D/at termination of testing, BHP 97 psig
30.	Decline Ratio	
31.	Productivity Increase	
32.	Kh, prefractured	
33.	Kh, post fractured	
	Permeability	0.5 μ - Darcies in the fractured interval

Fluid Characteristics and Properties

34.	Formation Fluids	
35.	Viscosity	
36.	F. V. F.	
37.	Hydrocarbon Sat.	
38.	API Gravity	
39.	Treating Fluids	Water base solution with 2% KCL and 40% methanol plus the following Halliburton additives:
WG7 (Alcogel) - 20 lbs./1,000 gal.
CW-1 5 lbs./1,000 gal.
Atomite Aqua 30 lbs./1,000 gal.
GBW and AP as gel weakens
40.	Viscosity	
41.	Temperature	
42.	Pressure	
43.	Density	
44.	Chemical Comp.	
45.	Shearing	
46.	Fluid Friction	
47.	Fluid Loss Control	
48.	Adsorption	
49.	Filtration	
50.	Mobility Control	
51.	Breaking Char.	
52.	Breaking Pressure	
-

Operational Characteristics

53.	Treating Pressure	
54.	B. H. Pressure	
55.	Surface Pressure	
56.	Volumes Injected	16,000 gal.
57.	Method of Treatment	See remarks below
58.	Alternate	
59.	Single Slug	
60.	% Pore Vol.	
61.	Rate of Injection	
62.	Temperature	
63.	Tubular goods	
64.	Corrosivity	
65.	Pumps	
66.	Equipment	
67.	Costs	
-
-

Remarks

The fracturing operation was accomplished on December 28, 1974,

Remarks (cont.)

in three stages as follows:

1. Approximately 7,650 gallons of fluid was pumped into the perforated interval slightly above shut-in pressure to break down the formation. Twenty-five 7/8-inch rubber balls were included in the fracturing fluid during this stage at the rate of one ball per every two barrels of fluid. It was estimated that approximately seven balls were effective and that a "ball-out" condition (all perforations sealed by balls) was not achieved.
2. A 2,000 gallon fracturing fluid pad containing 146,000 cubic feet of CO₂ was next pumped to prepare the fractures for accepting sand.
3. Finally, 4,250 pounds of 20-40 mesh sand in 6,000 gallons of fluid was pumped to complete the hydrofrac.

Forty-five minutes after the final stage had been pumped, the well started flowing. It produced approximately 16,000 gallons of fluid overnight, then ceased flowing.

The initial gas flow rate was 53 MSCF per day with bottom-hole pressure of 1,700 psig. At termination of testing, the gas flow rate had decreased to 7 MSCF per day and the measured bottom-hole pressure was 97 psig. The volume of fluid produced during this pumping period was 2,125 gallons.

On January 29, 1975, the well was shut in and pressure monitoring initiated. Analysis of data from the testing indicates a permeability of 0.5μ darcies in the fractured interval.

5.2 Mesaverde Gas Well, Piceance Basin, Colorado

Preliminary Information

1.	Location	NW Colorado	Piceance Creek Basin
2.	Field Name		
3.	State	Colorado	
4.	County	Rio Blanco County	
5.	Formation Name	Mesaverde	
6.	Hydrocarbon Type	Gas and sand condensate	
7.	Cumulative		

Formation Description

8.	Rock Type	Sandstone
9.	Geologic Information	Mesaverde

Formation Characteristics

10.	Permeability	Kh = 0.8 mdft
11.	Porosity	10%
12.	Matrix porosity	10%
13.	Frac. porosity	
14.	B.H. Temp.	194°
15.	Avg. Res. Press.	2252 psi
16.	Depth D.	6,980 feet
17.	Thickness (h)	gross 180 feet net 95 feet 10 zones
18.	Clay Content	
19.	Heterogeneity	Layered system with variations in rock properties
20.	Isotropic	
21.	Anisotropic	
22.	Shale content	
23.	Initial potential	58 MCFD

Methods of Analysis

24.	Design Criteria	Computer simulation of fracture geometry
25.	Post Frac. Analysis	Buildup Analysis using cross flow in layered systems. Flow and bottom-hole shut off
26.	Deliverability	
27.	Interpretations	Gas well Simulator

Productivity Modification

28.	Initial Potential	58 MCFD prefrac
29.	Post Frac: Production	200 MCFD + 130 MSCFD after 4 months
30.	Decline Ratio	
31.	Productivity Increase	1 + 2 times
32.	Kh, prefractured	0.5 md - 0.8 mdft
33.	Kh, post fractured	1.014 - 1.33

Fluid Characteristics and Properties

34.	Formation Fluids	Natural gas
35.	Viscosity	
36.	F. V. F.	
37.	Hydrocarbon Sat.	
38.	API Gravity	
39.	Treating Fluids	Cross linked gel (PSD); excellent clean up qualities
40.	Viscosity	
41.	Temperature	
42.	Pressure	2252 psi
43.	Density	
44.	Chemical Comp.	40 lb. cross linked gel per 1,000 gal.
45.	Shearing	
46.	Fluid Friction	373 - 180 psi
47.	Fluid Loss Control	Low surface tension additive
48.	Adsorption	
49.	Filtration	
50.	Mobility Control	
51.	Breaking Char.	Total break in 4 hours
52.	Breaking Pressure	
	Temperature	194° F

Operational Characteristics

53.	Treating Pressure	
54.	B. H. Pressure	
55.	Surface Pressure	1200 - 1800 psi
56.	Volumes Injected	Sand 775,000 lbs. Fluid 276,000 gals.
57.	Method of Treatment	Multistage
58.	Alternate	
59.	Single Slug	
60.	% Pore Vol.	
61.	Rate of Injection	37 BPM.
62.	Temperature	
63.	Tubular goods	
64.	Corrosivity	
65.	Pumps	
66.	Equipment	
67.	Costs	\$260,000

Remarks

Sand	225,000 lbs.	100 Mesh
	434,000 lbs.	20-40 Mesh
	116,000 lbs.	10-20 Mesh

Low surface tension additives used.

Frac. length 57 ft; 47 ft

Frac. gradient .617 psi/ft.

Interpretative problems with multilayered zones: difficulty in assessing correct kh, k, values

Inability to determine radial extent of transmissibility variation

More precise selection of the zone is required; careful attention to interpretation and logging required.

In short vertical intervals, it is uneconomical to inject large volumes. Proper design of moderate volume, multiple fracs are economically more justified.

5.3 Cotton Valley A.S., Louisiana

Preliminary Information

1.	Location	North Central Louisiana
2.	Field Name	Cotton Valley
3.	State	Louisiana
4.	County	
5.	Formation Name	Cotton Valley A. S.
6.	Hydrocarbon Type	
7.	Cumulative	
-

Formation Description

8.	Rock Type ,	Med. grey - hard sandstone
9.	Geologic Information	Junassic deposits - massive fine-grain sediments
-

Formation Characteristics

10.	Permeability	Less than 1.0 md, some streaks to 100 md.
11.	Porosity	10%
12.	Matrix porosity	
13.	Frac. porosity	
14.	B.H. Temp.	230° - 280°
15.	Avg. Res. Press.	
16.	Depth D.	8200 feet - 12000 feet
17.	Thickness (h)	Gross: 500-600 feet Net: 100-200 feet
18.	Clay Content	5-15% clay kaolinite
19.	Heterogeneity	
20.	Isotropic	
21.	Anisotropic	
22.	Shale content	5% limey sand in formation
23.	Initial potential	
-

Methods of Analysis

24.	Design Criteria	Case history
25.	Post Frac. Analysis	Experimental
26.	Deliverability	
27.	Interpretations	
-

Productivity Modification

28.	Initial Potential	Variable
29.	Post Frac. Production	4-10 fold increase
30.	Decline Ratio	
31.	Productivity Increase	4-10 fold increase .5 MMCFD to 10 MMCFD
32.	Kh, prefractured	
33.	Kh, post fractured	Fracture length 1500-2500 feet
-

Fluid Characteristics and Properties

34.	Formation Fluids	Gas
35.	Viscosity	
36.	F. V. F.	
37.	Hydrocarbon Sat.	
38.	API Gravity	
39.	Treating Fluids	Water base gelled, stable, non residu
40.	Viscosity	
41.	Temperature	230°
42.	Pressure	
43.	Density	3 to 4 lb/gal. sand
44.	Chemical Comp.	CO ₂ as gas assists to help clean up
45.	Shearing	
46.	Fluid Friction	
47.	Fluid Loss Control	
48.	Adsorption	
49.	Filtration	
50.	Mobility Control	Low surface tension surfactants
51.	Breaking Char.	
52.	Breaking Pressure	
	Proppant	3 to 4 lb. sand/gal. 230° F

Operational Characteristics

53.	Treating Pressure	
54.	B. H. Pressure	
55.	Surface Pressure	
56.	Volumes Injected	80,000 gallons or more to 120,000 gallons
57.	Method of Treatment	Sand varied considerably 40,000-250,000 lb.
58.	Alternate	
59.	Single Slug	
60.	% Pore Vol.	
61.	Rate of Injection	12-24 BPM
62.	Temperature	
63.	Tubular goods	
64.	Corrosivity	
65.	Pumps	
66.	Equipment	
67.	Costs	

Remarks

Lab studies showed high proppant packing needed in the fractures to sustain production levels because of embedding and crushing

Slow clean up caused problems.

Remarks (cont.)

Also, fluids needed to be low residue or none - i.e. non residue viscous gels.

Gas assist by CO_2 is very helpful.

2 to 10 fold productivity increase

Natural fracturing hinders the fracturing process.

Optimal treatment - clean (no residue) frac fluids high sand concentrations.

Use CO_2 as gas assist in tight zones. to help clean up.

Problems caused by "Siderite" noncarbonate. And cause iron oxide to precipitate. Sequestering agents needed to combat this rising pH control.

5.4 RB-MHF #3, Rio Blanco, Colorado

Preliminary Information

1.	Location	Rio Blanco
2.	Field Name	RB-MHF 3 Well
3.	State	Colorado
4.	County	
5.	Formation Name	
6.	Hydrocarbon Type	Gas
7.	Cumulative	
-

Formation Description

8.	Rock Type	
9.	Geologic Information	
-

Formation Characteristics

10.	Permeability	
11.	Porosity	
12.	Matrix porosity	
13.	Frac. porosity	
14.	B.H. Temp.	
15.	Avg. Res. Press.	3850 psia, assumed
16.	Depth D.	Internal fractured 8058-8083 ft.
17.	Thickness (h)	
18.	Clay Content	
19.	Heterogeneity	
20.	Isotropic	
21.	Anisotropic	
22.	Shale content	
23.	Initial potential	
-

Methods of Analysis

24.	Design Criteria	The modelling study used the two-dimensional elliptical coordinate geometry plus wellbore and fracture storage.
25.	Post Frac. Analysis	33-day pressure buildup analysis
26.	Deliverability	
27.	Interpretations	Calculated build-up pressure was composed with the measured pressure.
-

Productivity Modification

28.	Initial Potential	
29.	Post Frac: Production	60 MCF/D for 100 days
30.	Decline Ratio	
31.	Productivity Increase	
32.	Kh, prefractured	
33.	Kh, post fractured	0.096 mD-ft., fracture length 155 ft.
-

Fluid Characteristics and Properties

34.	Formation Fluids	Gas
-

5.5 Bradford Oilfield, Pennsylvania

Preliminary Information

1.	Location	
2.	Field Name	Bradford Oilfield
3.	State	Pennsylvania
4.	County	
5.	Formation Name	
6.	Hydrocarbon Type	
7.	Cumulative	
-

Formation Description

8.	Rock Type	
9.	Geologic Information	
-

Formation Characteristics

10.	Permeability	
11.	Porosity	0.074
12.	Matrix porosity	Total compressibility $1.1 \times 10^{-5} \text{ psi}^{-1}$
13.	Frac. porosity	
14.	B.H. Temp.	
15.	Avg. Res. Press.	
16.	Depth D.	
17.	Thickness (h)	
18.	Clay Content	
19.	Heterogeneity	
20.	Isotropic	
21.	Anisotropic	
22.	Shale content	
23.	Initial potential	
-

Methods of Analysis

24.	Design Criteria	Use of simulator and type curve analysis
25.	Post Frac. Analysis	
26.	Deliverability	
27.	Interpretations	Use of simulator SIMPAC to generate type curves for the bounded reservoir case use of constant rate equations developed by Gringarten, Ramey and Raghavan to generate type curves for the infinite reservoir case
-

Productivity Modification

28.	Initial Potential	
29.	Post Frac: Production	
30.	Decline Ratio	
31.	Productivity Increase	
32.	Kh, prefactured	
33.	Kh, post fractured	
-

Fluid Characteristics and Properties

34.	Formation Fluids	
35.	Viscosity	
36.	F. V. F.	1.0
37.	Hydrocarbon Sat.	
38.	API Gravity	
39.	Treating Fluids	Water
40.	Viscosity	1 cp
41.	Temperature	
42.	Pressure	1,100 psi Injection
43.	Density	
44.	Chemical Comp.	

Remarks

The experiment conducted in the Bradford oilfield is for the determination of the fracture orientation trend of the reservoir, the reservoir permeability and effective fracture length of the injection well; this is done by the use of type curves.

"Type curves were generated by numerical and semi-analytical techniques to facilitate reservoir characterization from the constant - pressure, declining - rate injection data."

"Water was injected as constant pressure into a single well in a fractured-reservoir for a period of 32 days followed by a 9 day shut-in period."

"Type - curve analysis of the constant pressure case for fractured wells is a useful device for history matching and can provide reservoir and well characteristics including permeability, effective fracture length, and, in some cases, the distance to a boundary or permeability discontinuity."

5.6 Los Alamos Geothermal Test GT-1, New Mexico

Preliminary Information

1.	Location	Las Alamos
2.	Field Name	Geothermal Test Hole GT-1
3.	State	New Mexico
4.	County	
5.	Formation Name	
6.	Hydrocarbon Type	
7.	Cumulative	

Formation Description

8.	Rock Type	Precambrian basement rock
9.	Geologic Information	

Formation Characteristics

10.	Permeability	
11.	Porosity	
12.	Matrix porosity	
13.	Frac. porosity	
14.	B.H. Temp.	100° C
15.	Avg. Res. Press.	
16.	Depth D.	785 m., about 175 m. into the Precambrian basement rock
17.	Thickness (h)	
18.	Clay Content	
19.	Heterogeneity	
20.	Isotropic	
21.	Anisotropic	
22.	Shale content	
23.	Initial potential	

Methods of Analysis

24.	Design Criteria	Theory of a penny-shaped crack
25.	Post Frac. Analysis	Plot of surface pressure vs. time
26.	Deliverability	
27.	Interpretations	

Productivity Modification

28.	Initial Potential	
29.	Post Frac. Production	
30.	Decline Ratio	
31.	Productivity Increase	Recovery as high as 32% was recorded
32.	Kh, prefractured	
33.	Kh, post fractured	Permeability of the fracture, 10^{-7} to 10^{-8} darcys

Fluid Characteristics and Properties

34.	Formation Fluids	
35.	Viscosity	
36.	F. V. F.	
37.	Hydrocarbon Sat.	
38.	API Gravity	
39.	Treating Fluids	Water
40.	Viscosity	
41.	Temperature	
42.	Pressure	
43.	Density	
44.	Chemical Comp.	
45.	Shearing	
46.	Fluid Friction	
47.	Fluid Loss Control	
48.	Adsorption	
49.	Filtration	
50.	Mobility Control	
51.	Breaking Char.	177 bars
52.	Breaking Pressure	
-

Operational Characteristics

53.	Treating Pressure	
54.	B. H. Pressure	240 bars, about 60 bars above the estimated overburden weight
55.	Surface Pressure	
56.	Volumes Injected	4,500 l.
-
-

5.7 Los Alamos Geothermal Test GT-2, New Mexico

Preliminary Information

1.	Location	Los Alamos
2.	Field Name	Geothermal Test Hole GT-2
3.	State	New Mexico
4.	County	
5.	Formation Name	
6.	Hydrocarbon Type	
7.	Cumulative	Hot dry rock geothermal program; hydraulic fracture experiments

Formation Description

8.	Rock Type	Precambrian basement rock
9.	Geologic Information	

Formation Characteristics

10.	Permeability	
11.	Porosity	
12.	Matrix porosity	
13.	Frac. porosity	
14.	B.H. Temp.	150° C
15.	Avg. Res. Press.	
16.	Depth D.	773 m.
17.	Thickness (h)	
18.	Clay Content	
19.	Heterogeneity	
20.	Isotropic	
21.	Anisotropic	
22.	Shale content	
23.	Initial potential	

Methods of Analysis

24.	Design Criteria	
25.	Post Frac. Analysis	Use of one-dimensional diffusion model to calculate fluid losses

$$\frac{\partial P}{\partial t} = K \frac{\partial P}{\partial x^2}$$

26.	Deliverability	
27.	Interpretations	

Productivity Modification

28.	Initial Potential	
29.	Post Frac: Production	
30.	Decline Ratio	
31.	Productivity Increase	
32.	Kh, prefractured	
33.	Kh, post fractured	Permeability of the fracture, 10 ⁻⁷ to 10 ⁻⁸ darcys

Fluid Characteristics and Properties

34.	Formation Fluids	Water
35.	Viscosity	0.002 P for water at 150° C and 200 bars
36.	F. V. F.	
37.	Hydrocarbon Sat.	
38.	API Gravity	
39.	Treating Fluids	
40.	Viscosity	
41.	Temperature	
42.	Pressure	
43.	Density	
44.	Chemical Comp.	
45.	Shearing	
46.	Fluid Friction	
47.	Fluid Loss Control	
48.	Adsorption	
49.	Filtration	
50.	Mobility Control	
51.	Breaking Char.	
52.	Breaking Pressure	

Operational Characteristics

53.	Treating Pressure	
54.	B. H. Pressure	
55.	Surface Pressure	150 bar (2200 psi)

5.8 Well B, Open Hole Completion

Preliminary Information

1.	Location	
2.	Field Name	Well B, Open hole completion
3.	State	
4.	County	
5.	Formation Name	
6.	Hydrocarbon Type	
7.	Cumulative	This is an example showing the fracturing results of an oil well.

Formation Description

8.	Rock Type	Lime
9.	Geologic Information	

Formation Characteristics

10.	Permeability	.333 md.
11.	Porosity	
12.	Matrix porosity	
13.	Frac. porosity	
14.	B.H. Temp.	
15.	Avg. Res. Press.	
16.	Depth D.	125 ft.
17.	Thickness (h)	
18.	Clay Content	
19.	Heterogeneity	
20.	Isotropic	
21.	Anisotropic	
22.	Shale content	
23.	Initial potential	

Methods of Analysis

24.	Design Criteria	The different factors affecting the recovery of fractured wells are analyzed separately.
25.	Post Frac. Analysis	
26.	Deliverability	
27.	Interpretations	

Productivity Modification

28.	Initial Potential	2 BOPD
29.	Post Frac. Production	89 BOPD (right after fracture treatment)
30.	Decline Ratio	
31.	Productivity Increase	
32.	Kh, prefractured	
33.	Kh, post fractured	

Fluid Characteristics and Properties

34.	Formation Fluids	
35.	Viscosity	
36.	F. V. F.	
37.	Hydrocarbon Sat.	
38.	API Gravity	
39.	Treating Fluids	No. 5 fuel oil
40.	Viscosity	
41.	Temperature	
42.	Pressure	
43.	Density	
44.	Chemical Comp.	
45.	Shearing	
46.	Fluid Friction	
47.	Fluid Loss Control	
48.	Adsorption	
49.	Filtration	
50.	Mobility Control	
51.	Breaking Char.	
52.	Breaking Pressure	
	Proppant	1 lb. of sand per gal. of fuel oil
-

Operational Characteristics

53.	Treating Pressure	
54.	B. H. Pressure	
55.	Surface Pressure	
56.	Volumes Injected	8400 gals.

5.9 Woodlawn, Cotton Valley, East Texas

Preliminary Information

1.	Location	Jones Gas Unit No. 3
2.	Field Name	Woodlawn
3.	State	East Texas
4.	County	Harrison
5.	Formation Name	Cotton Valley Formation
6.	Hydrocarbon Type	Gas
7.	Cumulative	Massive hydraulic fracturing of well

Formation Description

8.	Rock Type
9.	Geologic Information

Formation Characteristics

10.	Permeability	0.012 md.
11.	Porosity	
12.	Matrix porosity	
13.	Frac. porosity	
14.	B.H. Temp.	
15.	Avg. Res. Press.	
16.	Depth D.	10,000 ft.
17.	Thickness (h)	42 ft.
18.	Clay Content	
19.	Heterogeneity	
20.	Isotropic	
21.	Anisotropic	
22.	Shale content	
23.	Initial potential	

Methods of Analysis

24.	Design Criteria	
25.	Post Frac. Analysis	Flow test
26.	Deliverability	
27.	Interpretations	

Productivity Modification

28.	Initial Potential	210 Mcfd
29.	Post Frac: Production	2,000 Mcfd right after frac.; 1,600 Mcfd after 3 months
30.	Decline Ratio	
31.	Productivity Increase	1600/210 = 7.62
32.	Kh, prefractured	
33.	Kh, post fractured	
	Fracture Length	in the range of 2,500 ft.

Fluid Characteristics and Properties

34.	Formation Fluids	Gas
35.	Viscosity	
36.	F. V. F.	
37.	Hydrocarbon Sat.	
38.	API Gravity	
39.	Treating Fluids	Polyemulsion (1/3 water, 2/3 condensate)
40.	Viscosity	20-25 cp
41.	Temperature	Emulsion can be stable at 250° F
42.	Pressure	
43.	Density	7 lb/gal.
44.	Chemical Comp.	Water was 1.5% KCl with 50 lb. of synthetic polymer/1,000 gal. water
45.	Shearing	
46.	Fluid Friction	
47.	Fluid Loss Control	Fluid loss coefficient about 1×10^{-4} ft./sq. root min.
48.	Adsorption	
49.	Filtration	
50.	Mobility Control	
51.	Breaking Char.	
52.	Breaking Pressure	

Operational Characteristics

53.	Treating Pressure	
54.	B. H. Pressure	
55.	Surface Pressure	9,000 psi
56.	Volumes Injected	537,000 gal.
57.	Method of Treatment	
58.	Alternate	
59.	Single Slug	
60.	% Pore Vol.	
61.	Rate of Injection	17 bbl/min.
62.	Temperature	
63.	Tubular goods	
64.	Corrosivity	
65.	Pumps	Eight high-pressure dump trucks
66.	Equipment	Eight blenders
67.	Costs	\$250,000

Remarks

The fracturing results of this well can be ranked good.

In order to determine the most economical and efficient proppant mixture, fracture-flow-capacity tests of cores were done in the laboratory. This led to selection of the 20-40 mesh sand as proppant, which yields a good flow capacity and is not too expensive.

5.10 Rock Springs, #3 Green River Oil Shale, Wyoming

Preliminary Information

1.	Location	Rock Springs
2.	Field Name	Rock Springs Site 4 Well 3
3.	State	Wyoming
4.	County	Sweet Water
5.	Formation Name	Green River oil shale
6.	Hydrocarbon Type	Oil shale
7.	Cumulative	Field testing of fracturing techniques for creating <u>fluid-flow paths</u> in impermeable oil shale; <u>only</u> hydraulic fracturing experiment is described here
-

Formation Description

8.	Rock Type	Oil shale
9.	Geologic Information	
-

Formation Characteristics

10.	Permeability	
11.	Porosity	
12.	Matrix porosity	
13.	Frac. porosity	
14.	B.H. Temp.	
15.	Avg. Res. Press.	
16.	Depth D.	71.0 - 78.5 ft.
17.	Thickness (h)	
18.	Clay Content	
19.	Heterogeneity	
20.	Isotropic	
21.	Anisotropic	
22.	Shale content	
23.	Initial potential	
	Oil Yield	19.0 to 26.5 gal./ton
-

Methods of Analysis

24.	Design Criteria	
25.	Post Frac. Analysis	Air injection and production test of wells
26.	Deliverability	
27.	Interpretations	
-

Productivity Modification

28.	Initial Potential	25 scfm
29.	Post Frac: Production	105 scfm
30.	Decline Ratio	
31.	Productivity Increase	
32.	Kh, prefractured	
33.	Kh, post fractured	
-

Fluid Characteristics and Properties

34.	Formation Fluids	Oil shale
35.	Viscosity	
36.	F. V. F.	
37.	Hydrocarbon Sat.	
38.	API Gravity	
39.	Treating Fluids	Untreated water, gelled water
40.	Viscosity	
41.	Temperature	
42.	Pressure	
43.	Density	
44.	Chemical Comp.	
45.	Shearing	
46.	Fluid Friction	
47.	Fluid Loss Control	
48.	Adsorption	
49.	Filtration	
50.	Mobility Control	
51.	Breaking Char.	
52.	Breaking Pressure	400 psig
	Sand	20/40 mesh; 8/12 mesh

Operational Characteristics

53.	Treating Pressure	600 psig
54.	B. H. Pressure	
55.	Surface Pressure	
56.	Volumes Injected	3,450 gal. of water
57.	Method of Treatment	
58.	Alternate	
59.	Single Slug	
60.	% Pore Vol.	
61.	Rate of Injection	504 gpm
62.	Temperature	
63.	Tubular goods	
64.	Corrosivity	
65.	Pumps	
66.	Equipment	
67.	Costs	
	Sand weight	2,100 lb. 20/40 mesh 400 lb. 8/12 mesh

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