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OFFICE MEMORANDUM

TO Distribution

DATE Dec. 14, 1978

FROM D. W. Brown

SUBJECT GT-2A PUMPING TESTS: A LESSON IN HISTORY

SYMBOL G-3/78/#34

MAIL STOP 981

Batini

Project #1-3 ?! Quo Vadis?

INTRODUCTION

Following the initial redrilling of GT-2 along path GT-2A in May of 1977, a series of pumping experiments was performed to "improve" the flow connection(s) between the two wellbores, and then to evaluate the specific flow impedance of the resulting system. However, because we were so enamored with self-propping and afraid of the "paper dragon," runaway fracture extension, this evaluation was confined to the low GT-2A back-pressure data. The corresponding data on the reservoir flow performance under conditions of high back-pressure at GT-2A were essentially ignored.

In fact, it now appears that GT-2A was drilled through the primary near-vertical fracture initiated from EE-1 ~~and~~ at the 9050 foot depth. This fracture, which intersects the GT-2A wellbore at a depth of approximately 8600 feet, was initially opened up during the brief pressurization of the GT-2A wellbore to 1620 psi at the beginning of Expt. 161. This fracture connection shows up quite clearly on both the post-Expt. 161 and post-Expt. 162 temperature logs of GT-2A, but is barely discernible on the first temperature log run prior to the initial pressurization of the GT-2A wellbore. This intersection of a near-vertical fracture with the GT-2A wellbore had undoubtedly been previously held tightly shut by the wellbore stress concentration, a closure stress of about 1600 psi above S_3.

If this non-self-propped and strongly pressure dependent fracture connection in GT-2A had been recognized, we could have obtained a fracture system with about five times the effective heat transfer surface of the present EE-1/GT-2B connection, and with an initial high back-pressure specific impedance of around 4 to 5 psi/gpm -- and all without the anguish of the second (GT-2B) redrilling program.

HIGH BACK-PRESSURE FLOW OF GT-2A DURING EXPT. 161*

One of the primary objectives of Expt. 161 was to attempt to drive a near-vertical fracture downwards from GT-2A to intersect the EE-1 wellbore. To this end, a Lynes packer was set at a depth of 8275 feet in GT-2A and the wellbore below the packer pressurized to 1620 psi surface pressure at a flow rate of 4 bbl/min. At that time, Hugh Murphy noted that the slow, almost flat pressurization of GT-2A with no apparent "formation breakdown" pressure drop was typical of our previous experience while pumping into natural joints or opening (pre-existing) fractures. Hugh further inferred that this particular GT-2A flow connection had been sealed or closed to flow prior to this test. I would further conclude from a re-examination of the Expt. 161 data, that the high-pressure flow connection opened at this time in GT-2A was not the one previously identified at a depth of 8640 feet (by Lee Aamodt on the basis of a slight depressurization at EE-1 while drilling, and subsequently by Hugh Murphy on the basis of a temperature anomaly on the GT-2A temperature log run just prior to Expt. 161). This latter flow connection is probably a slightly open high-angle (60° to 70°) joint of the type seen so frequently in the USGS televiewer scan of GT-2, encountered in the GT-2B core cut at a depth

*For reference, see Hugh Murphy's May 12, 1977 memo: "Very Preliminary Analysis of Exp. 161 - Fracture Extensions in GT-2 and EE-1."

of 8770 feet, and shown by the oriented caliper log in GT-2B at a depth of 8850 feet.*

After eight minutes of flow into GT-2A, the pumping test was terminated after an apparent flow bypass of the packer. As planned, the packer was left in GT-2A while EE-1 was pressurized and flow initiated from EE-1 to GT-2A. However, with the drill pipe valved off, the still-inflated packer in GT-2A provided a considerable annular flow impedance, forcing an inadvertent (and essentially uncontrolled) high GT-2A back-pressure flow condition on this phase of Expt. 161. After several false starts, a total of 155,000 was pumped into EE-1 at 10 bbl/min, over a period of about six hours. The injection pressure at EE-1 slowly increased from 1850 psi to 1885 psi during this time, while the GT-2A back-pressure was dropping from 1140 psi to 860 psi. The latter pressure decrease was probably due to a slowly deteriorating (or flow erroding) Lynes packer.

The data, calculated buoyancy corrections and specific impedances for seven times during this flow interval are summarized in Table I.

Figure 1 shows the corresponding downhole pressure at 8600 feet in GT-2A -- the fracture outlet pressure -- plotted vs the specific impedance values from Table I. A remarkably linear correlation results, which has many significant features.

Obviously, the most striking feature is the strong dependence of reservoir specific impedance on the GT-2A downhole pressure, a fact that has been unequivocally demonstrated by the recently-completed 28-day high back-pressure experiment (Expt. 186) on our present EE-1/GT-2B flow connection. If we

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*There may have been some self-propping on such a high-angle joint by shear displacements during previous high-pressure EE-1 flow operations, which extended the pressure field a considerable distance from the EE-1 wellbore.

TABLE I

GT-2A High Back-Pressure Flow During Expt. 161

Time	Q_{out} gpm	Surface Pressure, psi GT-2A	Surface Pressure, psi EE-1	Buoyancy Difference* psi	Specific Impedance psi/gpm
0720	46	1140	1850	216	18.7
0830	43	1035	1855	223	22.7
0930	44	1010	1860	230	23.1
1030	42.9	1000	1870	238	24.3
1130	40.5	955	1875	247	27.2
1230	42.8	900	1880	256	27.4
1330	39.5	860	1885	266	31.0

*EE-1 to GT-2A at 8800 feet.

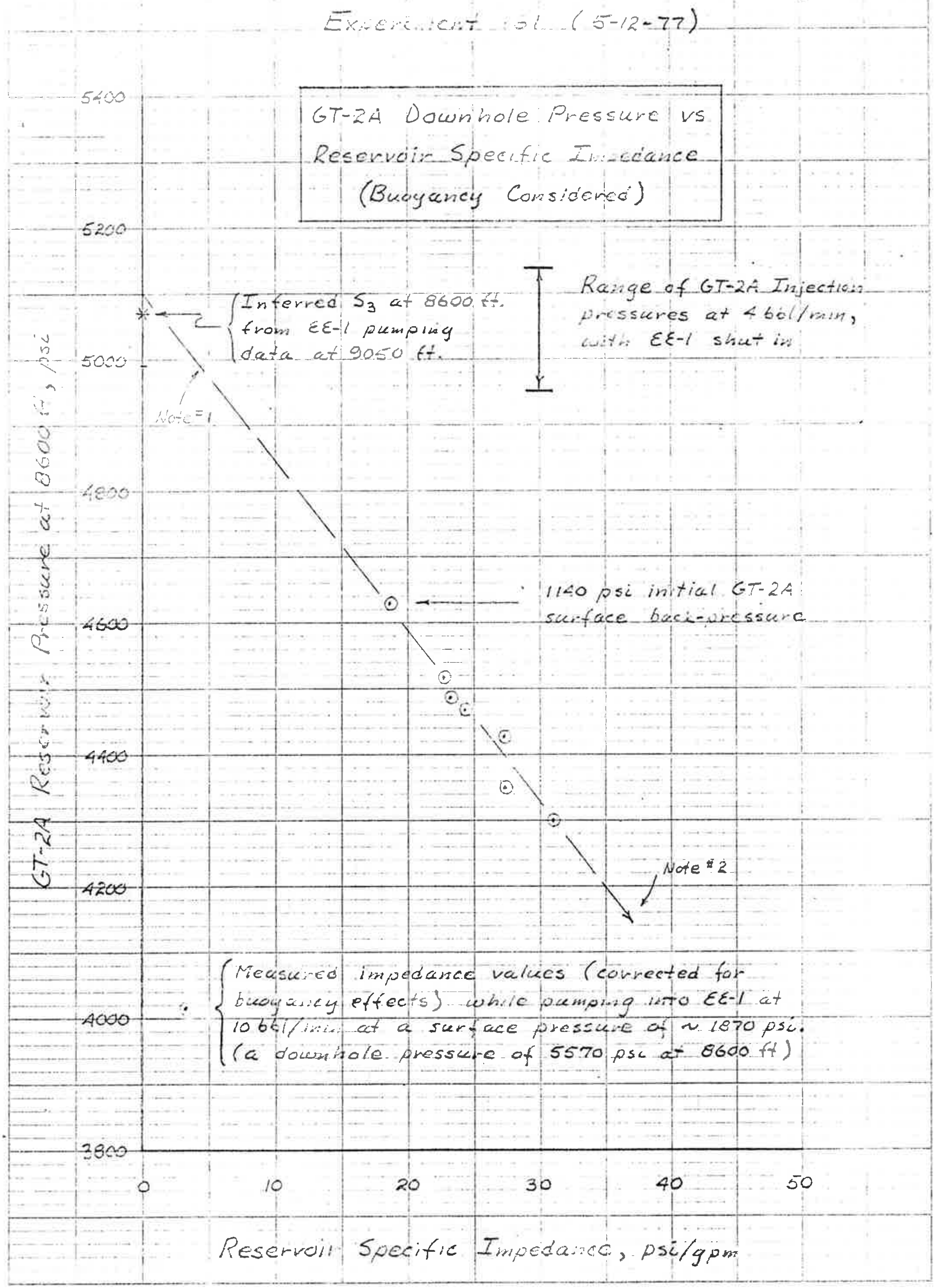
Experiment ... (5-12-77)
GT-2A Downhole Pressure vs
Reservoir Specific Impedance
(Buoyancy Considered)
5400
5200
5000
4800
4600
4400
4200
4000
3800
GT-2A Reservoir Pressure at 8600 ft, psi
Inferred S_3 at 8600 ft. from EE-1 pumping data at 9050 ft.
Note #1
Range of GT-2A Injection pressures at 4 bbl/min, with EE-1 shut in
1140 psi initial GT-2A surface back-pressure
Note #2
Measured impedance values (corrected for buoyancy effects) while pumping into EE-1 at 10 bbl/min at a surface pressure of ~ 1870 psi. (a downhole pressure of 5570 psi at 8600 ft)
0
10
20
30
40
50
Reservoir Specific Impedance, psi/gpm

Figure 1

were to have tested the GT-2A flow connection under conditions of suitably high back-pressure, we would have found a very acceptable level of <u>initial</u> reservoir specific impedance: about 4 to 5 psi/gpm at a GT-2A surface back-pressure of 1500 psi (with a <u>warm</u> column of fluid, corresponding to a down-hole pressure of only about 5000 psi: Note #1 on Fig. 1).*

This linear reservoir pressure vs specific impedance curve (a negative slope of about 26 psi per psi/gpm) extrapolates** to a zero GT-2A back-pressure specific impedance of 66 psi/gpm, almost identical to the value of 65 psi/gpm measured near the end of Expt. 161 (refer to pg. 2 of Murphy's memo on Expt. 161). This downward extrapolation to a measured value lends considerable credence to the inferred linear relationship between near-wellbore fracture flow impedance and confining stress, at least for stress levels near the least principal earth stress (S_3).

The upward extrapolation of this same curve provides us with additional important information concerning the nature of our reservoir flow impedance. Besides being primarily dependent on the fracture outlet pressure level, it appears that the overall reservoir specific impedance would have become vanishingly small at pressure levels above the local value for S_3: A good method for selectively controlling the individual flows through a multiply-fractured HDR reservoir, by installing specifically-sized flow restrictions along the outflow wellbore between the several fracture connections.

That the reservoir specific impedance approaches zero near the local value of S_3 is no coincidence: this is the downhole pressure level for which the wellbore stress concentration vanishes, and for which the fracture

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*The routine measurement of reservoir <u>pressure</u> as well as temperature would be a very helpful addition to future flow experiments.

**Note #2 on Fig. 1.

is in a state of incipient inflation in the vicinity of the outlet. The method used to infer the value of S_3 at 8600 feet from the EE-1 pumping data is covered in Appendix A. However, it is significant that the range of injection pressure levels for flow into this same fracture connection in GT-2A brackets the inferred value for S_3, as shown in Fig. 1.

ATTEMPTED FRACTURE EXTENSION FROM EE-1

Based on the previous analysis of Expt. 161, it was concluded that we were unable to drive the main EE-1 fracture (at 9050 feet) upwards to intersect the GT-2A wellbore, only 450 feet above. This was after pumping almost 200,000 gallons into EE-1 at the highest pumping rates and pressures yet attempted: 10 bbl/min at surface pressures reaching 1885 psi. The alternative -- and to the author much more plausible -- conclusion is that the main EE-1 fracture already intersected the GT-2A wellbore; we were just unable to convince ourselves that it did (too big of a hurry, with that expensive drilling rig just sitting there eating up money!).

Another interesting aspect of this portion of Expt. 161 becomes evident from numerous subsequent EE-1 pumping tests: There was no discernible growth in the area of the EE-1 fracture system during Expt. 161, based on high-flow $A\sqrt{K\beta}$ measurements both before and after Expt. 161.* This fact strongly implies that at reservoir inlet pressure levels up to at least 450 psi above the local value of S_3, even after extended periods of pumping, the pre-existing EE-1 fracture system was stable -- no apparent fracture extension! This is obviously contrary to the "established" theory, which however neglects pore fluid pressure effects. The pore fluid associated with the pressurized

*These conclusions are based on the numerous reservoir flow analyses performed by Hank Fisher, and he concurs in this conclusion.

fracture apparently extends beyond the region of the fracture tip and stabilizes the fracture against subsequent growth at pressure levels considerably above that at which the fracture was initially formed. One can speculate as to the mechanics of this phenomon, but the evidence is clear.

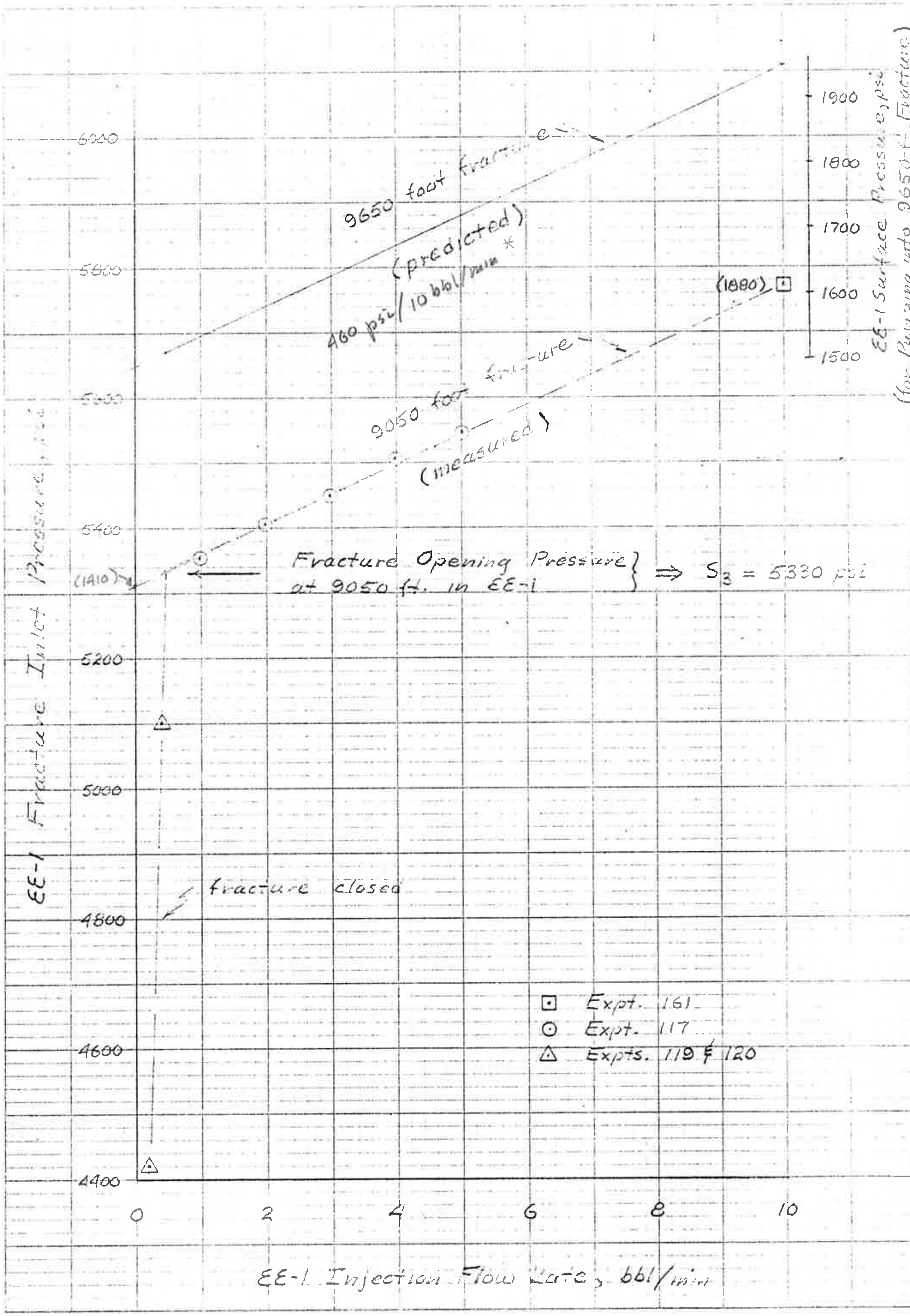
IMPLICATIONS REGARDING SUBSEQUENT FRACTURING OPERATIONS IN EE-1

Following the successful re-cementing of the bottom 600 or so feet of the EE-1 casing, a series of fracture inflation and/or fracture extension experiments is planned, to increase the effective heat transfer area of the EE-1/GT-2B reservoir. As the first experiment, the existing EE-1 fracture intersecting the wellbore at a depth of 9650 feet will be inflated and flow tested.* However, for a meaningful test of this alternate fracture connection to GT-2A, both the EE-1 pumping pressure and the GT-2B back-pressure must be suitably high.

Assuming an initial EE-1 pumping rate of 100 gpm (the minimum pumping rate for our present centrifugal pumps), the predicted EE-1 surface pressure would be approximately 1600 psi, more than our present pump capability by about 250 psi. However, if the EE-1 surface pressure is limited to the unreasonably low value of 1300 psi presently specified*, the inlet flow rate into the EE-1 fracture at 9650 feet would only be about 20 gpm -- not much of a flow test.

These foregoing conclusions are based on the EE-1 downhole pressure vs flow rate data shown in Fig. 2. The measured data represent a composite of numerous EE-1 pumping tests preceding the extensive cooling of the EE-1 reservoir inlet region during the 75-day heat extraction experiment. The

*See G-3 memo by Aamodt et al, "Workover Program Prior to and Coincident With the Drilling of EE-2," Nov. 15, 1978.



* 3000 psi at EE-1 ⇒ ≤ 33 bbl/min

Figure 2

upper curve is the predicted pressure-flow performance for the 9650 foot fracture in EE-1 which is presently in a stage of cooldown similar to that for the 9050 foot fracture prior to the 75-day test. Also shown on Fig. 2 is the inferred value of S_3 at a depth of 9050 feet, based on pumping data including that for Expt. 161.

If we were to be so fearless as to pump into EE-1 at a surface pressure of 1800 psi* (corresponding to a flow rate of about 280 gpm into the 9650 foot fracture), and were to hold a GT-2 surface back-pressure of 1600 psi (corresponding to an initial fracture outlet pressure of about 5100 psi), an excellent flow test of the 9650 foot fracture should be obtained. I would hazzard a guess that for these conditions, an overall reservoir specific flow impedance below 5 psi/gpm would be obtained.

IMPLICATIONS REGARDING SUBSEQUENT REDRILLING/FRACTURING OPERATIONS

In Rod Spence's timely memorandum on Phase II plans,** he discusses a methodology for determining wellbore fracture intersections. This would be accomplished, during the drilling of the second hole, by continuously pressurizing the first -- and deeper -- hole subsequent to having formed several near-vertical hydraulic fractures along its wellbore (see pg. 10 of Rod's memo). I wish to take exception to this approach for the following reason: It has been singularly unsuccessful in our only two redrilling operations to date in identifying primary near-vertical fracture intersections in the hole being drilled.

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*Which I may point out we have already done without any apparent extension of any of the EE-1 fractures, as discussed above.

**G-3/78/#32, "Plans for Phase 2 Drilling and Reservoir Formation," R. W. Spence, Nov. 1, 1978.

The most notable example of this was while drilling along path GT-2B in late May of 1977. Following a sharp pressure decrease at EE-1 while drilling at a depth of 8769 feet, GT-2B drilling operations were immediately suspended and a diamond core cut through the remainder of the fracture intersection. What did we discover in the core? Not the anticipated near-vertical fracture! Instead, we found a conjugate set of high-angle (∿70°) weakly calcite-cemented joints striking roughly north-south. What's more, we never did discover a vertical fracture intersection along the GT-2B wellbore by pressurizing EE-1, although I am totally convinced, based on the results of the recent high back-pressure experiment (Expt. 186), that such a connection does indeed exist near the bottom of GT-2B. I feel that the presently-proposed method of detecting fracture interception in G-3/78/#32 must be replaced. I would propose the following method instead:

1. Keep the previously-drilled hole pressurized as an aid in indicating when the region of the vertical fracture is being approached (be seepage flow indications.) However, this information may tend to confuse us more than it helps!
2. Drill a suitable distance beyond the anticipated depth of interception; say 20 to 30 feet horizontally.
3. Terminate drilling operations temporarily; run and set a single open-hole packer an appropriate distance off bottom.
4. While holding a suitable back-pressure (near the local value of S_3) on the region below the packer,* pump into the previously-drilled hole at approximately the same rate and pressure at which that particular near-vertical fracture was originally formed.

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*The annulus above the borehole should be maintained at no greater than hydrostatic pressure, to hold all other fracture connections up the hole tightly closed.

5. Flow test and otherwise evaluate the given fracture connection; then commence drilling again until the vicinity of the next vertical fracture is approached.

6. Repeat steps 1-5 above.

> "Those who cannot remember the past are condemned to repeat it."
>
> George Santayana

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APPENDIX A

Inferred Value of Least Principal Earth Stress (S_3) at 8600 feet, Based on EE-1 Pumping Data for the 9050 foot Fracture

S_3 Value at 9050 feet in EE-1: 5330 psi

The inflation of a pre-existing fracture by a series of increasing steps in flow rate, with sufficient time allowed for equilibration at each step in flow, appears to be our best method of measuring S_3. The "knee" in the lower curve of Fig. 2, which represents the point at which the fracture opens, is here taken as the value of S_3.

Matrix Stress at 9050 $\sigma_3 = 1630$ psi

From the "effective stress" concept

$\sigma = S - \gamma P_o$

P_o = pore fluid pressure

γ = pore fluid effectiveness

~ 1 from many laboratory tests on granite with microcracks

σ = Matrix stress

S = Total stress

For a full hydrostatic pressure pore fluid saturation, and at the geothermal gradient in temperature to 9050 ft,

$\bar{\rho}_{H_2O} \sim 0.409$ psi/ft

$P_o = 3700$ psi

$\sigma_3 = 5330 - 3700 = 1630$ psi

Total Vertical Stress at 9050 feet $S_1 = 10{,}000$ psi

for an average rock density of 2.55 g/cc

Vertical Matrix Stress at 9050 feet $\sigma_1 = 6300$ psi

$$\sigma_1 = S_1 = \gamma P_o$$

$$\gamma \sim 1.0$$

$$\sigma_1 = 10{,}000 - 3700 = 6300 \text{ psi}$$

Poisson's Ratio, σ_1 to σ_3 $\nu = 0.205$

$$\sigma_3 = \frac{\nu}{1-\nu}\sigma_1 = C_1\sigma_1$$

$$C_1 = 1630/6300 = 0.2587$$

$$\nu = 0.205$$

Total Vertical Stress at 8600 feet $S_1 = 9500$ psi

Pore Fluid Pressure at 8600 feet $P_o = 3520$ psi

Vertical Matrix Stress at 8600 feet $\sigma_1 = S_1 - P_o = 5980$ psi

Least Principal Matrix Stress at 8600 feet $\sigma_3 = 1550$ psi

$$\sigma_3 = C_1\sigma_1 = 0.2587\ (5980) = 1550 \text{ psi}$$

Least Principal Total Stress at 8600 feet $S_3 = 5070$ psi

$$S_3 = \sigma_3 + P_o = 1550 + 3520 = 5070 \text{ psi}$$