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THE USE OF PRESSURE DROP MEASUREMENTS TO MONITOR SCALE BUILD-UP IN PIPELINES AND WELLS

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ABSTRACT

Pressure profiles in the reinjection pipelines at the Dixie Valley geothermal power plant revealed that pressure drops were substantially higher than design. Measurements indicated a fairly uniform pressure gradient throughout the lines, and the excessive pressure drop was attributed to a buildup of silica scale. Analysis of the pressure drops indicated that the pipeline roughness was far greater than had been expected. To cure this, one of the lines has been partially cleaned by pigging; pressure profiles before and after each pigging run have been analysed and show a substantial reduction in the Darcy friction factors. Reinjection well capacities increased slightly with pipeline cleaning, and it has been possible to estimate the likely benefits of further pigging operations. Similar analysis has been applied to reinjection wellbores, and evidence of scaling has been similarly found. Wellbore pressure profiles will, in the future, be used to monitor the increase in scale buildup, and to determine when a wellbore cleanout may be required.

INTRODUCTION

The Dixie Valley geothermal plant is located approximately 100 miles east of Reno, Nevada. It is a 60 MW dual flash plant with the low pressure flash at approximately 5 psig. Separated brine is reinjected into 5 injection wells by means of centrifugal pumps. Conditions at the pump discharge are typically 160 psig and 230°F.

Brine leaves the plant though a common 24" line, then is divided between a northern 16" line and a southern 18" line which connect to two separate injection areas (Fig. 1). Flows are currently more or less equal down each branch. These lines are underground except for above-ground expansion loops and therefore provide little opportunity for inspection.

In 1989, routine monitoring of the injection system revealed an unexpectedly high wellhead pressure sensitivity to flow rates. Subsequent measurements of the injection line pressure profiles showed that friction factors were much higher than had been expected, resulting in excessive pressure drop. With the drilling of a highly permeable new injection well in the north (25-5), there was concern that the additional capacity of the well could not be fully utilised because of injection line imitations, and detailed analysis of the pressure drops was undertaken.

The initial conclusion was that when the new well was connected, the wellhead pressure near 25-5 and 45-5 would drop to very close to the saturation pressure, substantially reducing injection capacities. If the pressure

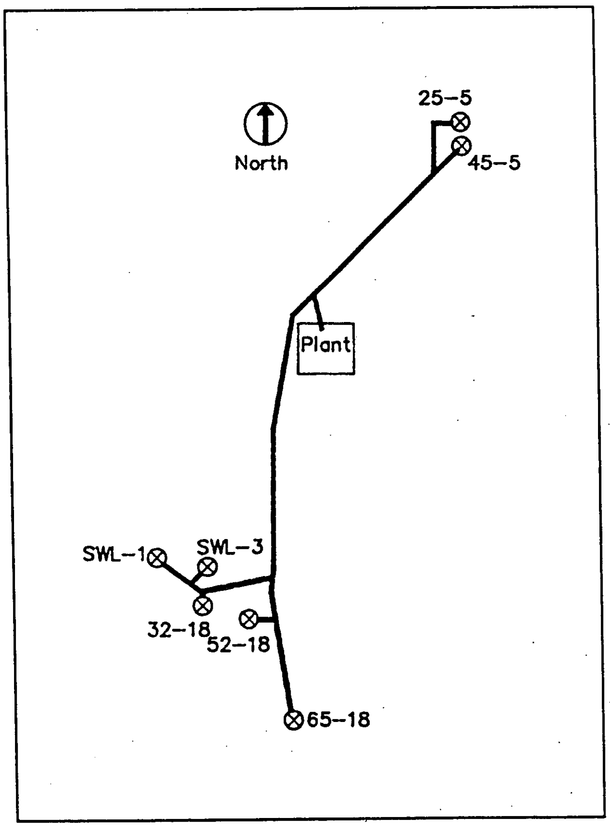

Figure 1. Injection line layout

were to drop to saturation and allow the brine to flash, the wells would be prevented from being filled to capacity, and scaling problems in and around the wellheads would be accentuated. In addition, flow measurements taken near the wellheads would be rendered inaccurate.

It was immediately suspected that silica scaling was the cause of the high pressure drops, even though physical modelling of the injection system with a silica skid prior to start-up had indicated no deposition would occur down to temperatures of about 180°F, 50°F below actual operating temperatures. During a previous workover of an injection well, and during pipeline modifications to accommodate the new injection well 25-5, a thin silica scale had been observed. In straight runs of pipe, the scale had the typical appearance of geothermal silica deposits in pipelines, with radial sawtooth ridges about 1/16" to 1/8" high facing upstream. The scale observed in one elbow was as thick as 1/4" to 1/2", and consisted of thin flakes orientated almost perpendicular to the pipe walls in an extreme form of the sawtooth ridge pattern. No hard glassy scale was seen in either case, and generally the surface of the scale could be easily scraped to a smooth base. While the observed scale was by no means heavy, it was extremely rough, and it was considered that this roughness could account for the excessive pressure drops noted.

In view of the excessive pipeline pressure drops, it was decided that pipeline cleaning would be beneficial in maximising the capacity of the existing wells, and various methods were considered. There was early concern that much of the pressure drop could have been the result of an accumulation of construction debris and detached scale at the expansion loop risers, subsequently silicified into a solid mass and severely restricting the flow area. Such aggregates have previously been observed in the injection pump strainer baskets at Dixie Valley as well as in other geothermal fields, and the bottom of the injection line risers would be a natural point of accumulation at low flow rates. A solid accumulation of this nature could preclude the use of a conventional pig as there was no desire to trap a pig at a point of severely restricted diameter, especially if that point were buried some 8 ft below ground!

To check for such restrictions, additional pressure measurements were taken immediately upstream and downstream of the expansion loops by means of limited excavation and hot tapping new pressure connections. These measurements revealed no large step changes in pressure, and it was concluded that the problem was one of fairly uniform scaling throughout the length of the line. With this knowledge, together with the observation that the surface of the scale could be scraped smooth relatively easily, a conventional wire brush pig was purchased.

In order to determine the effectiveness of pigging at a minimum cost, only the northern 16" line was pigged initially. A temporary dump line to a drilling sump was constructed near the injection wells, and a temporary pig catcher mounted. A pressure profile down the line was taken to establish a baseline, and then flow was bypassed to the dump line ready for pigging operations to begin.

A foam swab was run first. It successfully ran to the end of the line demonstrating that there were no major obstructions to contend with. The pig was then successfully run, and flow returned to the injection wells. Further pressure profiles were taken over the next week as flow rates stabilised.

Analysis of the pressure profiles taken before and after pigging indicated a substantial reduction in the Darcy friction factors after just this one run. Further runs were therefore scheduled, with continuing improvement to the line characteristics.

ANALYSIS OF PRESSURE PROFILES

The collection of accurate pressure profiles both before, during and after pigging runs enabled determination of Darcy friction factors for each interval of pipe. By monitoring these, it was possible to measure the effectiveness of each pigging run. The assumption of a realistic final friction factor then allowed prediction of the final cleaned pipe pressure profile and consequent injection well pressures. This, in turn, could be combined with the reservoir flow characteristics to determine the likely change in injection capacity.

The first pressure profile taken covered the entire injection system from the discharge of the injection pumps through to each injection wellhead. The results of this survey are shown in Table 1. The frictional component of each pressure drop was obtained by subtracting the gravitational component calculated from the brine density and elevation change for each section. The effective section lengths were determined from the measured length and the calculated equivalent length of fittings. Darcy's formula was then used to determine the friction factor for each section of pipeline.

Most friction factors were found to be in the range of 0.1 to 0.2, very high compared with the expected value of 0.01. The Moody diagram in Fig. 2 shows standard curves for various roughness values in 16" pipe; from the diagram, the measured friction factor implies an equivalent roughness height of more than 1.5". Although this is considerably more than the depth of the scale actually noted, it must be recognised that the concept of relative roughness was derived from experiments with uniform sand grains on pipe walls; the form of the silica

TABLE 1 . DIXIE VALLEY INJECTION PIPELINE PRESSURE DROPS

Profile of 26 September, before 25-5 on Line

Fluid Temperature	225 F
Dynamic Viscosity	0.0125 Cp
Specific Volume	0.0168 cub ft/lb

Pipeline Section	Measured Pressure (psig)	Measured Flow (gpm)	Elevation (ft)	Section Length (ft)	Pipe Diameter (inches)	dP Head (psi)	dP Friction (psi)	Darcy Friction Factor	Projected Flows (gpm)	Projected Pressures (psig)	Actual Pressures (psig)	Projected dP Friction (psi)
Main Injection Line												
1. Pump delivery	161.5	4860	3476		23.00				6950	150.0	149.0	
2. Main injection line	159.0	4860	3483	400	23.00	-2.9	-0.4	-2.1E-02	6950	147.9	148.0	-0.8
3. Tee	151.5	4860	3493	300	23.00	-4.2	3.3	2.3E-01	6950	137.0	136.0	6.6
Section 5 Line												
4. Start section 5 line	151.0	1600	3493	50	15.25	0.1	0.6	3.1E-01	3900	133.4	132.5	3.7
5. 2nd loop	150.5	1600	3485	1000	15.25	3.3	3.8	9.5E-02	3900	114.1	112.5	22.6
6. 3rd loop	147.5	1600	3465	2200	15.25	8.3	11.3	1.3E-01	3900	55.5	49.5	66.8
7. 4th loop	144.0	1600	3455	1000	15.25	4.1	7.6	1.9E-01	3900	14.4	14.5	45.3
Section 5 Wells												
8. 45-5 wellhead	140.5	1600	3455	150	10.02	0.0	3.5	7.2E-02	700	13.7	13.0	0.7
9. 25-5 wellhead	144.0	0	3455	400	12.00	0.0	0.0	1.3E-02	3200	11.6	12.0	2.8
Section 18 Main Line												
10. Start section 18 line	150.5	3260	3493	50	17.25	0.1	1.1	2.5E-01	3050	136.1	134.5	1.0
11. 2nd loop	141.0	3260	3501	900	17.25	-3.3	6.2	7.7E-02	3050	127.4	126.0	5.4
12. 3rd loop	129.5	3260	3497	1500	17.25	1.7	13.2	9.8E-02	3050	117.6	115.5	11.5
13. 4th loop	116.0	3260	3474	2200	17.25	9.5	23.0	1.2E-01	3050	106.9	103.5	20.1
32-18 Branch Line												
14. 1st loop to 32-18	115.0	1270	3474	100	17.25	0.0	1.0	7.4E-01	1150	106.1	103.5	0.8
15. 2nd loop by 32-18	105.5	1270	3471	900	15.25	1.2	10.7	4.8E-01	1150	98.5	97.0	8.8
16. 32-18 wellhead	105.0	570	3471	100	15.25	0.0	0.5	9.9E-01	500	98.2	97.0	0.4
17. SWL-3 wellhead	90.0	700	3468	50	10.02	1.2	16.2	5.2E+00	650	85.4	86.0	14.0
52-18 and 65-18 Lines												
18. 1st Loop	115.5	1990	3474	700	15.25	0.0	0.5	1.2E-02	1900	106.5	103.0	0.5
19. 52-18 wellhead	105.3	1250	3466	500	15.25	3.3	13.5	1.1E+00	1200	97.3	103.0	12.4
20. 2nd Loop	115.0	740	3466	500	15.25	0.0	-9.7	-2.3E+00	700	106.0	102.5	-8.7
21. 65-18 wellhead	121.5	740	3442	2300	15.25	9.9	3.4	1.7E-01	700	112.9	109.0	3.0

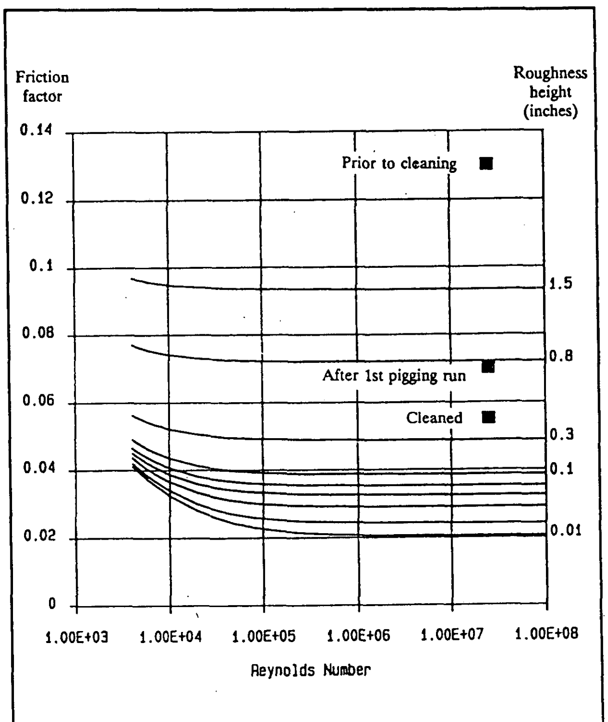

Figure 2. Moody diagram. Equivalent roughness heights are shown for 16" pipe.

deposition in this situation is radically different from that of the experiments used to derive Moody's curves, and it should not be expected that the roughness values derived from the curves will have direct correspondence with actual scale thicknesses. The important point is simply that even a relatively thin layer of silica scale can have an effect on pressure drops far greater than its thickness would suggest.

Based on the friction factors determined from this first profile, predictions were made for the pressure profile which might be expected once 25-5 came on line. These predictions are also shown in Table 1. It can be seen that a dramatic drop in wellhead pressure at 45-5 of almost 130 psi was predicted with the increased flow rate, and this led to early investigations into pigging. When 25-5 was actually put on line, the measured profile was very close to that which had been predicted, and it appeared that injection capacity was indeed being severely constrained by the pipeline. Because this had been correctly anticipated, preparations for pigging were already well advanced, and the first pigging run followed soon after.

Following the first pigging run, a pressure profile of the northern line was taken again. This was analysed in the same manner as before to derive the Darcy friction factors. Table 2 shows the results. It can be clearly seen that the friction factors, although still high, have been substantially reduced by an average of 50%. The success of this operation encouraged further pigging runs, and in each case pressure profiles were taken before and after the runs and analysed to monitor the impact on friction factors. These results are also summarised in Table 2, and show a continuing reduction in friction factors, although the incremental effect of each run diminishes.

This program has not yet been completed in that there still appears to be room for further reduction of friction factors. The equivalent roughness for new steel pipe is generally accepted as being about 0.0018", but even with regular cleaning with the wire brush pig, it is not expected that this limit could be closely approached. As the last two pigging runs have indicated little improvement, the pipeline may already be close to the practical limit for cleaning, but in any case it should not be expected that the equivalent roughness could be reduced below about 0.1", corresponding to a friction factor of about 0.04.

Predicting the final pressure profiles and flow rates for fully cleaned pipe is complicated by interaction with the reservoir. As line pressure drops are decreased, injection wellhead pressures and therefore injection rates will rise, affecting the line pressure drops. In addition, the injection pump discharge pressure is a function of flow rate, but at the current operating point the characteristic curves are relatively flat and can be ignored for small flow changes. Determining a new operating point is best visualised by plotting pipeline characteristic curves of flow rate against wellhead pressure at the end of the line for various stages of cleaning, together with the equivalent curve for the injection wells (Fig. 3); the point of intersection of the pipeline and well curves is the operating point. Fig. 3 shows that with successive cleanings, the operating point has moved in the direction of increasing wellhead pressure and increasing injection rate. If an assumption is made for the clean pipe friction factor, then the final cleaned line operating point can be predicted. The figure also clearly shows the diminishing impact of each pigging run, perhaps indicating that the effort required to reach a fully clean condition may not be worthwhile.

EVALUATING THE SUCCESS OF PIGGING

The value of cleaning the injection lines lies both in increasing the injection capacity, and in limiting scale buildup to avoid possible future problems with heavy scale. Pigging has clearly demonstrated that it can control buildup of scale at Dixie Valley, but unfortunately the increase in injection capacity has been much less than hoped for. The reason for this is the nature of the injection reservoir. A large part of the injection capacity at Dixie Valley, and all of the capacity in the northern sector discussed in this paper, is in relatively shallow aquifers somewhat isolated from the remainder of the field. Within these aquifers, very high permeabilities have been found, but it appears that they are of limited volume. They are both connected to the rest of the field as evidenced by interference and tracer tests, but the permeabilities of the connections are much lower than the permeabilities within the aquifers themselves. As a result, although very high wellbore injectivities have been measured and wells often have very high initial injection rates, the aquifers rapidly increase in pressure resulting in declining injection rates and severe interference between wells. The net result is that even the substantial

TABLE 2. CHRONOLOGY OF INJECTION LINE FRICTION FACTORS

Date / Purpose	26-Sep-89 Before 25-5 on line		26-Sep-89 After 25-5 on line		2-Nov-89 After 1st pigging run		22-Nov-89 After 2nd & 3rd		20-Feb-90 After 4th pigging run	
Location of monitoring point	Pressure (psig)	Friction Factor	Pressure (psig)	Friction Factor	Pressure (psig)	Friction Factor	Pressure (psig)	Friction Factor	Pressure (psig)	Friction Factor
First expansion loop	151.0		132.5		137.0		135.0		140.0	
Second expansion loop	150.5	9.5E-02	112.5	1.0E-01	124.0	6.7E-02	127.0	5.5E-02	135.0	5.2E-02
Third expansion loop	147.5	1.3E-01	49.5	1.4E-01	93.0	7.3E-02	111.0	5.4E-02	123.0	5.5E-02
Fourth expansion loop	144.0	1.9E-01	14.5	1.7E-01	79.0	7.5E-02	99.0	7.9E-02	116.0	7.0E-02
45-5 wellhead	140.5	7.2E-02	13.0	1.8E-01	79.0	-	98.0	2.0E-01	113.0	7.3E-01
25-5 wellhead	144.0	-	12.0	1.2E-02	78.0	4.4E-03	97.0	1.0E-02	115.0	6.1E-03

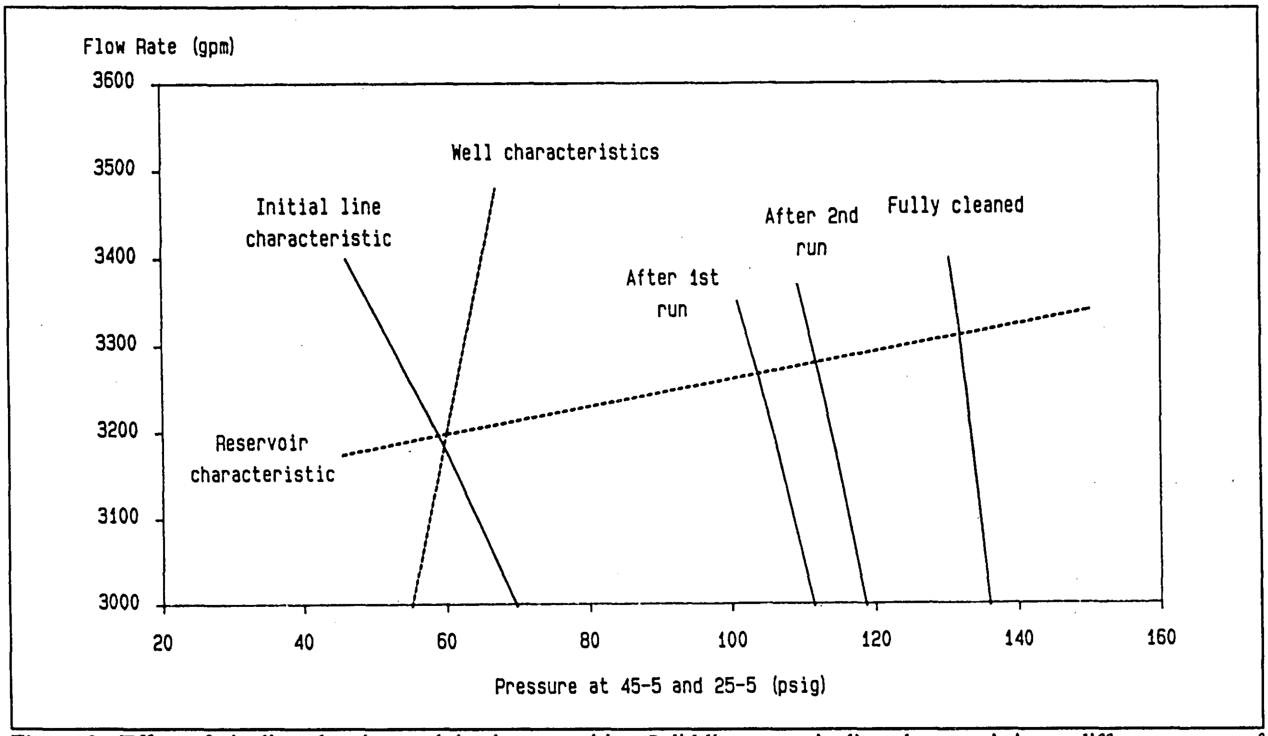

Figure 3. Effect of pipeline cleaning on injection capacities. Solid lines are pipeline characteristics at different stages of cleaning; dashed lines are well and reservoir characteristics.

improvements achieved in the pipeline flow characteristics have not produced a similarly substantial rise in injection capacity.

In the northern sector, the injection capacity was initially greatly enhanced by pigging, but within four days almost 90% of the original increase was lost as the aquifer was pressured. On Fig. 3 this effect can be represented by distinguishing between a well characteristic curve and a reservoir curve, the slope of the latter being only about 10% of the former. The locus of operating points as the pipeline was cleaned proved to be the reservoir characteristic rather than the well characteristic, and early expectations of a substantial increase in injection capacity were not realised.

PRESSURE PROFILES IN INJECTION WELLS

The same form of analysis can be applied to pressure profiles within the injection wells themselves. If silica is depositing in the surface pipework it can be reasonably expected that scale will also form downhole, at least to the depth where downhole temperatures have increased above surface temperatures. Using standard KPG type gauges to measure wellbore pressure profiles should therefore yield information on friction factors and indirectly on scale buildup. In practice, however, the pressure profile is so dominated by the gravitational head that the instrument precision is usually inadequate to allow useful frictional pressure gradients to be extracted.

In one case at Dixie Valley, however, a combination of high flow rates, large friction factors and a relatively small diameter well allowed a detailed frictional pressure drop profile to be determined. Fig. 4 shows a plot of frictional pressure drop per 100 ft against vertical depth. While there is some scatter in the data, the large increase in pressure drop from the 9-5/8" casing to the 7" liner at 5400 ft is clearly apparent. Likewise the frictional drop clearly disappears between 6300 ft and 6400 ft, implying that this is the major point of fluid exit from the well.

While these results suggest the method to be of some use as a flowmeter, their main value is in confirming that the extracted frictional pressure drops reflect real features in the well, adding confidence to use of the data for determining friction factors. The friction factors derived directly from this data using Darcy's equation are shown in Fig. 5. This plot shows a surprising linear decline of friction factor with depth, with a factor of 0.07 at 1,000 ft declining to about 0.02 at 6,000 ft. The shallowest value at 1,000 ft is fairly similar to the values from the surface pipeline before cleaning, and from Moody's diagram indicates an effective scale thickness of almost 1/2". Again, this number is probably not very meaningful, but it does strongly suggest that there is similar scale buildup downhole as has been observed on the surface.

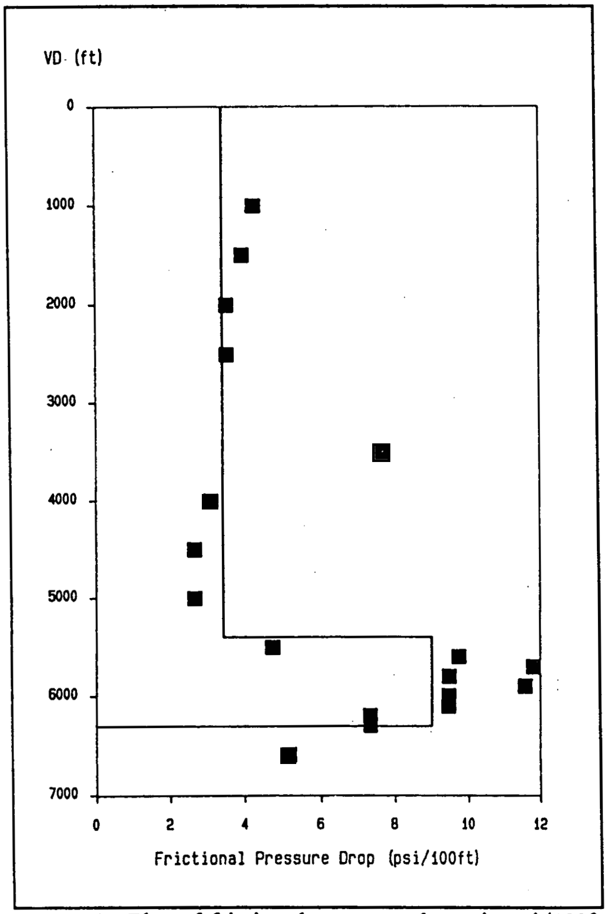

Figure 4. Plot of frictional pressure drops in psi/100ft against depth for well 45-5.

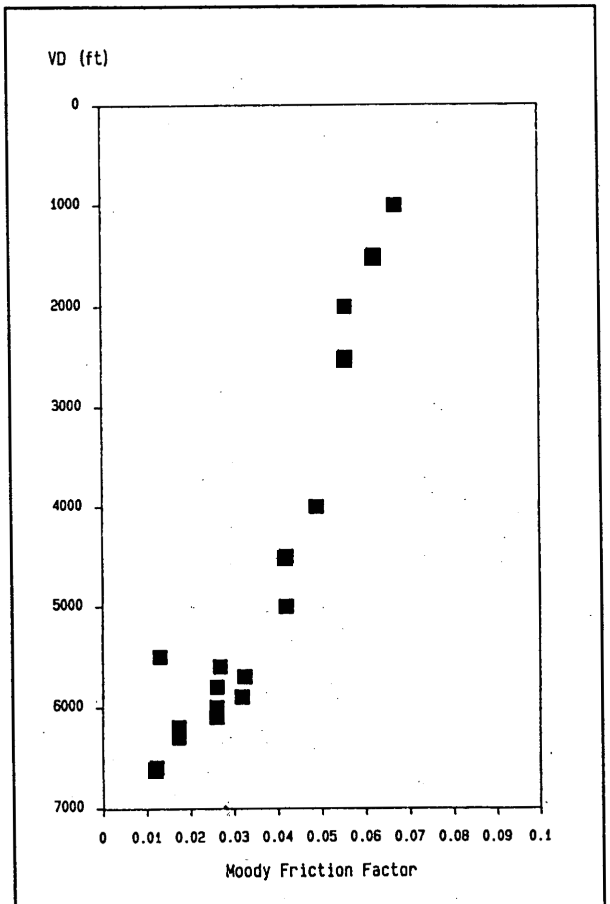

Figure 5. Plot of friction factors against depth in well 45-5

Perhaps the most interesting feature illustrated by Fig. 5 is the linearly declining trend of friction factor with depth, implying decreasing deposition rates with depth. This is unexpected since deposition rates generally increase with brine residence time. It is possible that the decrease could be a function of temperature increase down the well on silica solubility, but the measured increase of only 5°F seems insufficient to account for this. Another possibility is that the aluminum thought to promote the deposition mechanism is gradually depleted by ongoing deposition, providing a natural limit to the amount of deposition possible. It is also possible that the deposition rate does not actually change, but rather that the roughness of the scale decreases with depth.

Although analysis suggests that scale has formed in the wellbore and is causing unwanted pressure drops, the relatively high cost of remedial work has for the moment stopped any further effort. The well will continue to be surveyed periodically, and it is hoped that the analysis method outlined in this paper will be able to detect any increase in frictional pressure drops in the wellbore. If such an increase appears to be affecting the well's injection capacity, then a workover could be scheduled. It is unlikely, however, that a workover could be economically justified in the foreseeable future because the limiting factor in injection capacity is not actually the well capacities in this area, but rather the permeability between the local aquifer and the main reservoir.

CONCLUSIONS

Analysis of detailed pressure profile measurements throughout the injection system at Dixie Valley has been successfully used to indicate the presence of silica scale. The effect of the scale on pipeline pressure drops was much larger than had been expected from simple consideration of scale thickness, largely because of the scale's extreme roughness. To reduce these pressure drops, one injection line has been cleaned with a wire-brush pig. The degree of cleaning attained with each pigging run was monitored by analysing further pressure profile measurements, a method which appears to have given good results. Analysis techniques have been developed to allow prediction of the impact of further cleaning on injection capacity.

Similar analysis of the pressure profile of an injection well was able to show that scale was also forming inside the well. The degree of scaling shallow in the well was similar to that of the surface piping, but appeared to decline with depth. The well will be periodically surveyed, and future analysis may be able to indicate whether frictional pressure drops have further increased and whether a workover is required.

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