ASSESSING THE EFFECTIVENESS OF DEFLAGRATION IN MULTI-FEEDZONE WELLS

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ABSTRACT

Deflagration as a means to improve well permeability and productivity has now been trialled in several geothermal fields. For geothermal production wells the effectiveness of deflagration has been somewhat equivocal. During 2015, Contact carried out deflagration trials in three production wells. To provide an immediate indication of the effectiveness of these trials it was decided to use the overall well injectivity index as the primary indicator of improved well performance. The results seemed somewhat disappointing at the time, with only small improvements in the overall well injectivity when comparing results from pre and post-deflagration tests. However, modelling the test data with a simple spreadsheet shows that in multi-feedzone wells the overall injectivity may not be sensitive to large changes of injectivity at an individual feedzone. It appears that an improvement in production is the only definitive measure of the effect of deflagration and this may not become apparent for several weeks, or months as the well recovers from cold water injection required to cool the well sufficiently to perform the deflagration operation.

1. INTRODUCTION

Deflagration as a means of improving well permeability has been used in a number of geothermal fields: Reykjarnes Iceland (Sigurdsson, 2015), Soda Lake Nevada (Ohren 2011) and Tongonan Philippines (Energy Development Corporation personal communication 2016). The main advantages of this method of permeability stimulation are that no packers are necessary, it can be performed in a well while the perforated liner is in place, any of the permeable zones can be targeted, and the complete job can be performed using only wireline equipment.

While deflagration appears to be a proven stimulation method for coal seam and oil and gas wells, in the volcanic formations that comprise most geothermal fields the effectiveness is often not clear.

In 2015 Contact carried deflagration trials in three high temperature wells at Ohaaki. As the deflagration and associated testing program was developed, it was decided to use the change in overall injectivity index measured before and after the deflagration to define the effectiveness of the well stimulation. This information is available within hours of performing the deflagration operation and in conjunction with temperature and spinner profiles, can potentially be used to determine the effectiveness of deflagration at the target zone, and provide immediate information to select alternative target zones. For production wells the definitive measure of success is the change in production before and after deflagration. However the true change in production will not be evident for some time after the well has been quenched, reheated then discharged – Which can be several weeks or even months later.

In the Ohaaki tests the measured injectivity changes immediately before and following deflagration were quite small. Subsequent analysis indicates that for multi-feedzone wells the Injectivity Index may not be sufficiently sensitive to reflect significant changes at one feedzone.

In this paper the results from one of the tested wells are used to illustrate the insensitivity of the injectivity index. This well is deviated with a final build angle of 13° with formation temperatures at the feedzones of 285-310°C. Results here are presented in terms of vertical depth.

2. ACCURATELY LOCATING THE FEEDZONES

When designing any deflagration operation, the most important choice is accurately locating the target fracture zones - within a few metres - in order that the stimulation charge can be placed directly opposite the target zone. Ideally the feedzones are located using a combination of formation image logs, in combination with temperature and fluid velocity logs measured during injection or production. For low permeability wells the pressure pivot point observed during heatup can also provide information about shallower feedzones which may not be obvious from temperature and fluid velocity data.

Where only temperature and spinner data are available from logs run inside a perforated liner, the feedzone signature can be spread over tens of metres due to annular flow outside the liner. Even where image logs are available to identify fractures, picking the permeable fractures using the temperature and spinner data may be problematic. XY caliper logs in combination with temperature and fluid velocity logs can also be useful to precisely locate feedzones.

Fractures with high permeability can usually be located accurately from temperature and velocity logs measured during injection or production as the flows between the wellbore and formation are large. However, accurately locating feedzones in wells with low overall permeability is often more problematic. For these wells multiple, small feedzones are usually spread over much of the openhole length. Some of these zones, particularly in the upper part of the openhole section, may not be apparent at all during injection due to the small difference between the wellbore and the formation pressures – consequently there may be little or no flow from feedzones into, or out of the wellbore.

In the example well (WELL A) shown on Figure 1, the feedzone locations have been selected using a combination of image logs, temperature and velocity profiles during injection, temperature during heatup and the pressure pivot during heatup.

The ability to accurately locate feedzones using fluid velocity and temperature logs can also be affected by the wellbore geometry:

- Variable wellbore cross section (particularly in deviated wells)
- Over-size wellbore (especially where air-drilling has been used.

2.1 Pressure Difference

During cold water injection in low permeability wells the pressures in the shallow part of the open hole are often close to the formation pressure. Thus, even where permeable zones are present, there may be little or no flow at some feedzones as there is only minimal pressure difference between the wellbore and formation. For low permeability wells the "obvious" feedzones are usually located near the bottom of the wellbore where the largest pressure difference exists. The existence of shallow feedzones may only be evident from the pressure pivot as the well heats up, or where suitable fluid velocity data is later measured during discharge.

Figure 1 shows the temperature-pressure data measured during injection and heatup in WELL A, a low permeability, multi-feedzone well.

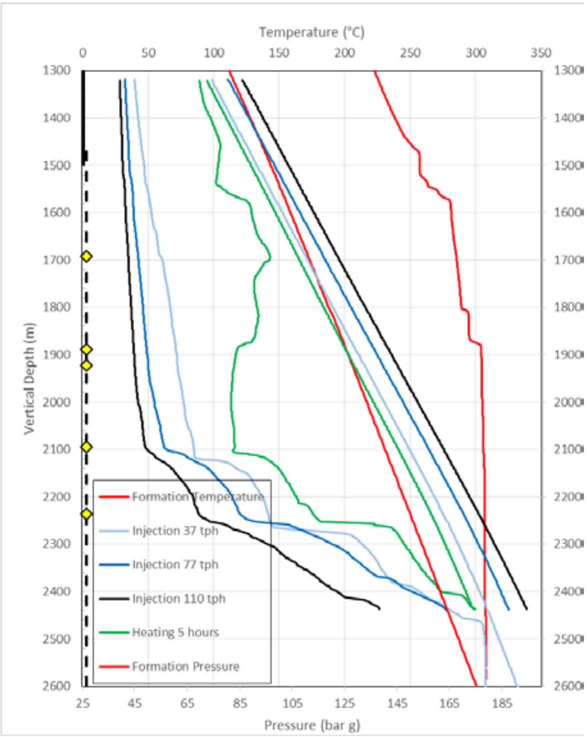

Figure 1: Typical pressure temperature profiles during cold water injection and heatup for WELL A, a low permeability, multi-feedzone well. The interpreted feedzones are indicated by the yellow diamonds.

In this case the pivot point forms at about 1900m, and for small injection rates (37 tph) the pressures at the 1700m feedzone are close to the formation pressure, while at the 2237m feedzone the difference is 12.6 bar. Temperatures during injection clearly show the deeper feedzones at 2094 and 2237m.

2.2 Wellbore cross section

The deep production wells at Ohaaki are usually deviated and drilled using an air-water system. In the formations found at Ohaaki this often results in a significantly oversized wellbore and XY caliper surveys show the hole is typically oval, and sometimes has key seat geometry. In the example for WELL B shown in Figure 2 the actual diameter is about 11 inches over much of the section, compared with the drilled diameter of 8.5 inches. Near the 1700m feedzone there is a key seat section which, in addition to the different diameter can affect spinner data where the logging tool can be held up or moves at different speed than is measured at the surface.

In some cases the XY caliper log shows the wellbore immediately adjacent to a feedzone is very much enlarged – In this case there is a 2 metre section at 2185-2186m where the diameter is more than 14 inches, which corresponds to a feedzone identified by temperature and spinner data.

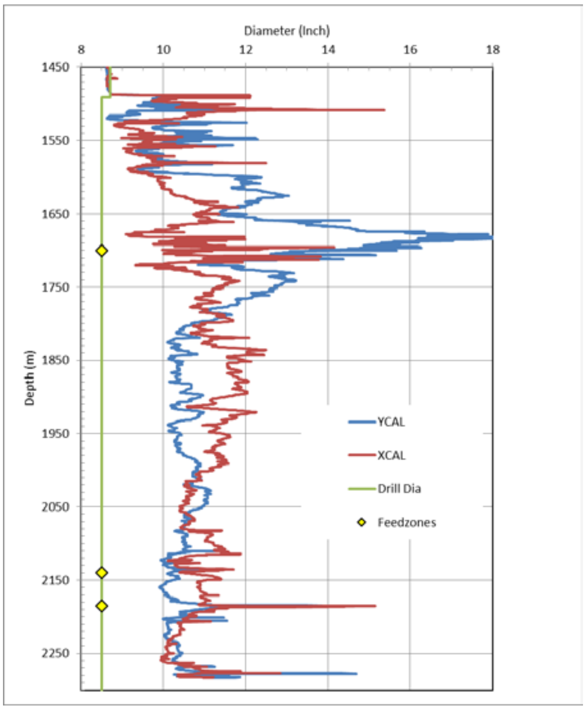

Figure 2: XY caliper for WELL B. The drillbit diameter is shown in green.

In a deviated wellbore, already significantly oversize (10-12 inches), the perforated 7 inch liner will be lying against the bottom side and it seems unlikely that the PTS tool (2 inch diameter) will be sampling a fluid velocity that properly reflects the total flow over the complete wellbore cross section.

2.3 Formation Image Log

For WELL A, an acoustic formation image log was run from 1998-2436m. Over this interval several fractured zones were identified. However, only one of these zones, at 2094m was confirmed to have open permeable fractures by temperature and fluid velocity data (The signature of open fracture can be the same as that for a closed fracture on acoustic image logs for certain types of mineral fill).

2.4 Summary

Combining the information from the formation image logs, temperatures and spinner for WELL A, five feedzones are identified at: 1692, 1885, 1923, 2094 and 2237m. The precision of these interpreted feed depths is considered to be ±5 metres.

3. CHANGE OF INJECTIVITY INDEX AT ONE FEEDZONE

The main purpose of this review is to evaluate the sensitivity of the change in overall well injectivity using the downhole pressure data measured before and after an actual deflagration test, where there has been a change at only one of several feedzones.

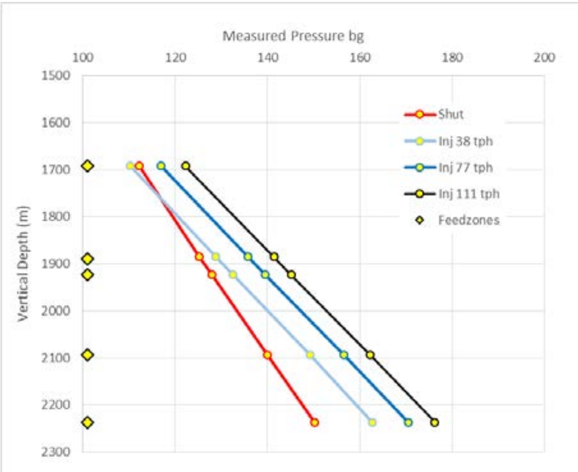

Figure 3: Measured pressures in WELL A before deflagration

The downhole pressures measured before deflagration in WELL A are plotted on Figure 3, and tabulated on Table 1. The equivalent post-deflagration pressure values are tabulated in Table 2. The analysis assumes a simple model with an overall injectivity of 5.6 t/h.b and three main feedzones, each with injectivity values 30% of total and two minor zones, each of 5% of total (1.8 t/h.b at 1885, 1923 and 2094m and 0.3 t/h.b for the two minor zones at 1692 and 2237m). The flow lost to each zone can then be calculated using the measured pressures. In this case the calculated total flows for the pre-deflagration data are close to the actual values.

This process is then repeated using the measured post-deflagration pressures and adjusting the injectivity value for *only* the 1885m feedzone (Table 2), so that the overall injectivity increases from 5.6 to 9.5 t/h.b. In this case the injectivity value for the 1885m zone needs to be increased by three times from 1.8 to 5.3 t/h.b. For the post-deflagration results the total calculated flow does not agree so well with the actual injected flows.

4. CHANGE OF FLUID VELOCITY PROFILE

If there is a significant change of injectivity index at one zone, there should be an accompanying change in the fluid velocity profile during injection. An increase in the overall well injectivity will result in decreased pressures for the same

Table 1: Injectivity analysis for multi-feedzone well – Pre-deflagration. In this case the overall injectivity index was 5.6 t/h.b.

Measured Pressures					
Feedzone	**0**	**38**	**77**	**111**	**t/h**
1692 m	112.2	110.2	116.9	122.3	bg
1885 m	125.3	128.8	135.8	141.4	bg
1923 m	128.0	132.6	139.6	145.2	bg
2094 m	140.0	149.3	156.6	162.3	bg
2237 m	150.2	162.8	170.5	176.3	bg

Pressure difference between wellbore and formation					
1692 m	0.0	-2.0	4.7	10.1	bar
1885 m	0.0	3.5	10.5	16.1	bar
1923 m	0.0	4.6	11.6	17.2	bar
2094 m	0.0	9.3	16.6	22.3	bar
2237 m	0.0	12.6	20.3	26.1	bar

Calculated flows at each feedzone					
	II				
1692 m	**0.3**	-1	1	3	t/h
1885 m	**1.8**	6	19	29	t/h
1923 m	**1.8**	8	21	31	t/h
2094 m	**1.8**	17	30	40	t/h
2237 m	**0.3**	4	6	8	t/h
	6	35	77	111	t/h

Table 2: Injectivity analysis for multi-feedzone wells – Post-Deflagration. The overall injectivity index has increased by 60%, from 5.6 to 9.5 t/h.b. Assuming ALL the increase comes from a single feedzone at 1885m, the II at that zone has increased by 3X from 1.8 to 5.3 t/h.b

Measured Pressures					
Feedzone	**0**	**37**	**77**	**111**	**t/h**
1692 m	112.2	110.0	113.8	117.8	bg
1885 m	125.3	129.1	132.7	136.9	bg
1923 m	128.0	132.8	136.5	140.7	bg
2094 m	140.0	150.1	153.5	157.8	bg
2237 m	150.2	163.7	167.5	171.8	bg

Pressure difference between wellbore and					
1692 m	0.0	-2.2	1.6	5.6	bar
1885 m	0.0	3.8	7.4	11.6	bar
1923 m	0.0	4.8	8.5	12.7	bar
2094 m	0.0	10.1	13.5	17.8	bar
2237 m	0.0	13.5	17.3	21.6	bar

Calculated flow at each feedzone					
	II				
1692 m	**0.3**	-1	0	2	t/h
1885 m	**5.3**	20	39	62	t/h
1923 m	**1.8**	9	15	23	t/h
2094 m	**1.8**	18	24	32	t/h
2237 m	**0.3**	4	5	6	t/h
	9.5	50	84	125	total

injection rate, so the stimulated feedzone will be accepting more fluid and all the other feedzones will be accepting less. These flow changes should change the velocity profile. Is the velocity profile derived from spinner data sufficiently sensitive to detect such a change?

The calculated flows at each feedzone are shown in bottom panels of Tables 1 and 2. Using these values, Figure 4 shows the flow profile expected before and after deflagration while injecting 111 t/h, assuming all of the fluid is confined within the 7 inch perforated liner. This indicates that there should be a significant change in the velocity profile between the 1885 and 2094m feedzones, as permeability improvement has caused the fluid loss at 1885m to double from about 30 to 60 t/h. The accompanying change in the velocity profile should be evident from the spinner data.

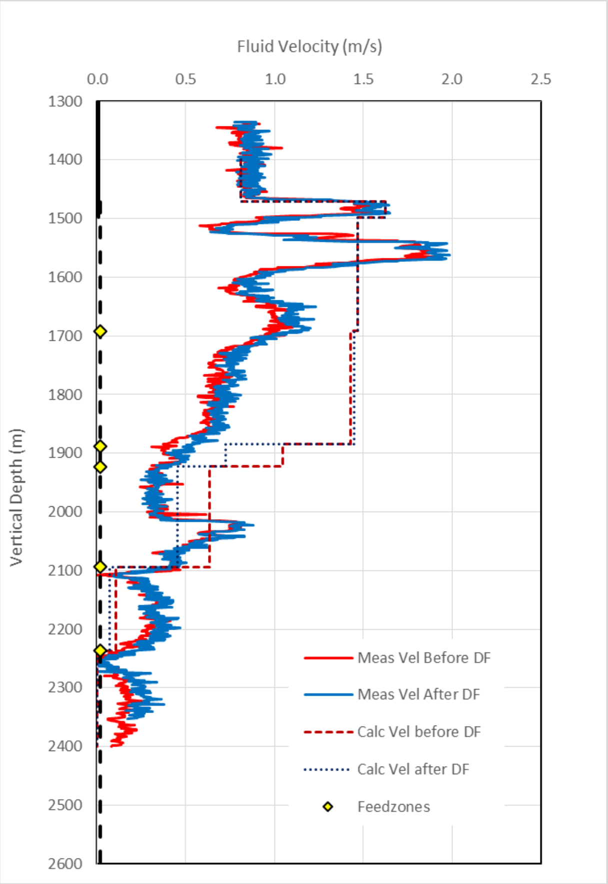

Figure 4: Velocity profiles before and after deflagration. The calculated velocities assume *all* the flow is confined within the 7 inch perforated liner. Drilled diameter was 8.5 inches.

However in this case, the spinner velocities measured before and after deflagration were almost identical. Inside the production casing and top part of the 7 inch liner there is excellent agreement between the expected and measured velocities. From 1500-1900m the spinner velocity shows considerable variation, considered to be due the variation in hole size (The high velocity section between 1540-1570m is ignored, as the velocity is significantly in excess of the expected maximum). Below 1570m velocities are much less than expected, indicating that the hole is significantly oversize (or that there is a loss zone at 1570m which is not supported by any other information).

In addition to variable hole size effects, apparent low fluid velocities indicated by the spinner is probably due to unrepresentative sampling in the deviated wellbore.

5. DISCUSSION & CONCLUSION

For the well considered here (WELL A), two deflagration charges were run. The first charge was fired at the 2120m feedzone. This seemed to make little impact on the overall well injectivity, so the second charge was fired at 1885m, with the result that the final injectivity value increased approximately 70% from 5.6 to 9.5 t/h.b, implying that most of the change was due to stimulation of the 1885m feedzone.

It is possible that part of the increase in permeability may be due to thermal stimulation. However as there was only 30 hours between the two sets of data any thermal effect should be minimal.

The analysis in Tables 1 and 2 is not intended to be a precise analysis, but to explore the order of change of injectivity that can be expected in an individual feedzone to account for the overall well injectivity change. In this case the change of injectivity required at the 1885m feedzone was a threefold increase from 1.8 to 5.3 t/h.b. Thus the increase in overall injectivity of 70% is the result of an increase of 300% at the stimulated feedzone.

In multiple feedzone wells with overall moderate permeability, significant changes in the injectivity index at a single feedzone may result in minimal change in the overall well injectivity value. Also the spinner data may not be sufficiently sensitive to detect changes in the fluid flow profile. Thus the velocity profile and overall injectivity changes may not be useful tools to evaluate the effects of well stimulation or to choose alternative target zones during a well stimulation programme.

For production wells, the definitive proof of improved permeability is an improvement in production flowrate. Such improvement may not become evident until several weeks, or months after a deflagration program, when the well temperatures have fully recovered and flowrates stabilised.

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