Accurate location of feed zones: assessing obscuration by the liner in geothermal wells through analysis of fluid velocity profiles

Joel Trent[1*], Katie McLean[1]

[1]Contact Energy Ltd., Wairākei Power Station, Te Aro Road, Taupō, 3384, New Zealand

joel.trent@contactenergy.co.nz*

Keywords: *Completion testing, stage testing, well testing, geothermal wells, cold water injection, perforated liner.*

ABSTRACT

The location of feed zones in geothermal wells is commonly identified using pressure, temperature, and spinner (PTS) data from a downhole tool during completion testing after the slotted liner has been installed in the well. To inform drilling decisions in some wells, these data are also collected during a stage test before liner installation. In both tests, water is injected into the well at a set of fixed flow rates.

It is typically expected that the presence of the liner will partially obscure feed zone locations in the data collected in completion tests. Quantifying this effect is important because a stage test is not always performed due to the additional cost and the chance of open-hole collapse. Meanwhile, completion testing is always carried out as it represents the final condition of the well. Additionally, quantifying this effect is important for situations where feed zone locations need to be known with higher accuracy. For example, to correlate the location of feed zones with geology logs, to effectively use a deflagration tool for feed zone stimulation and to assess the effectiveness of chemical clean jobs.

This 'obscuration' effect has previously been considered for the identification of feed zones using temperature logs. In that research, the effect of the liner was found to: make feed zones appear shallower by 17 m on average, widen the feed zone by 114% on average and make close-together individual feed zones appear to be one zone. Here, we consider the follow-up to that research: quantifying the degree to which the liner obscures the feed zone locations by comparing fluid velocity profiles acquired from the spinner tool during open-hole testing (stage testing) with those acquired after liner installation (completion testing). Several field examples are presented, from liquid-dominated wells in the Taupō Volcanic Zone.

1. INTRODUCTION

Geothermal wells are tested after drilling, and occasionally during drilling, under cold water injection conditions to identify feed zones and get an initial understanding of their injection and production capabilities (injectivity and permeability). The stage test is performed before liner installation and typically involves the collection of PTS data, although occasionally spinner data is omitted. It may also include acoustic borehole imaging (ABI) and caliper tools for visualising fractures and understanding the varying dimensions of the wellbore downhole. The completion test is performed after liner installation and focuses on PTS data.

It is typically expected that the presence of the liner will partially obscure feed zone locations in the data collected in completion tests. This was seen to be the case when interpreting feed zones from temperature logs (Goble & McLean, 2020), with identified feed zones 17 m shallower and 114% wider after installation. This paper is a follow-up to Goble & McLean (2020), where we now consider this effect when interpreting feed zones from fluid velocity profiles. Together, these papers provide a holistic view of how the liner affects interpretations from both temperature and fluid velocity.

Given the results of Goble and McLean (2020), understanding the effect of liner obscuration is valuable in any situation where stage test data are unavailable and feed zone locations need to be known with higher accuracy. For example, when correlating the location of feed zones with geology logs or fracture data sets from ABI tools (Glynn-Morris et al., 2011; Massiot et al., 2017), as these depths are known with high accuracy. Similarly, accurate feed zone locations are needed for effective use of a deflagration tool for feed zone stimulation (McLean et al., 2016); the feed zone location needs to be known within a few metres. Additionally, understanding the effect of the liner is valuable for evaluating the effectiveness of chemical clean work which targets scaling in the formation surrounding feed zones of wells.

To extend the previous study to fluid velocity profiles, we rely on the calculation of the spinner ratio (Grant et al., 2006) to mitigate wellbore diameter effects. Otherwise, the changes in fluid velocity that could be interpreted as feed zones may instead be due to changes in wellbore diameter, as $V \propto 1 \div D$. Wellbore diameter data collected using a caliper tool could also be used to mitigate this effect; a decrease in diameter should cause a similar increase in fluid velocity if there are no feed zones present. This is the subject of another paper presented at NZGW 2024 (Purnomo & McLean, 2024).

The calculation of the spinner ratio may be seen as difficult and overly manual, particularly when it comes to aligning fluid velocity profiles and determining comparable depths for the fluid velocity between two profiles. To improve the accessibility of spinner ratio calculations and profile alignment, we present a simple algorithm with associated Python code (Trent, 2024).

2. BACKGROUND

2.1 Regional setting

The three wells investigated in this paper are located in the Wairākei-Tauhara geothermal field at the centre of the Taupō Volcanic Zone (TVZ) in the north island of New Zealand (Figure 1). The production wells, TH21 and TH26, are located to the north of the Tauhara field while the reinjection well, TH31, is located to the east. These wells are all south of the Waikato River.

2.2 Completion testing

Completion testing is performed by injecting cold water at various flow rates down a well (usually at least three rates), with a PTS tool run down and up the well, capturing PTS data as a function of depth over the open-hole section. These profiles then allow the identification of feed zones (inflows and outflows of fluid). Moreover, they allow the calculation of the injectivity and permeability of the well, which indicate its production or injection capacity. These inform future drilling and development decisions, an understanding of the geological structure underground, and the baseline 'clean' state of the well which can be used to detect future issues with scaling.

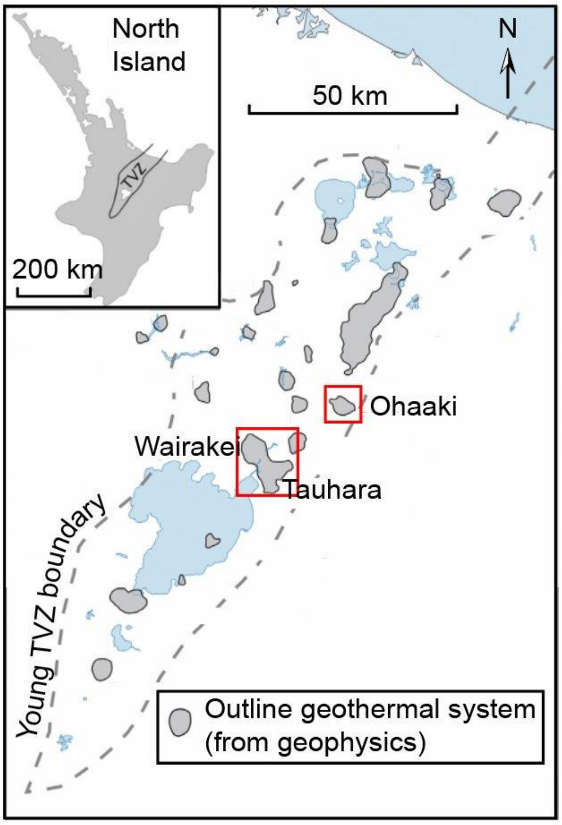

Figure 1: Map of Contact Energy Ltd.'s developed geothermal systems within the TVZ, in the Central North Island of New Zealand.

Completion testing always occurs after liner installation as this represents the final condition of the well. It may occur as a stage test before liner installation for several reasons. Stage testing is costly and risks open-hole collapse, however, it is frequently done anyway as the benefits outweigh the risks, for reasons which include (1) needing to evaluate whether downhole temperatures are cool enough for other tools, e.g. an ABI tool, or (2) evaluating whether there is sufficient injectivity to indicate that drilling deeper is not required. The data from this ABI tool, run during this stage test, allows visualisation of borehole fractures which can validate feed zone identification (Massiot et al., 2017).

2.3 Calculating fluid velocity profiles

To calculate fluid velocity profiles from spinner data we use the standard regression analysis of spinner frequency vs tool speed (Grant & Bixley, 1995, 2011). This regression is calculated from spinner data that is grouped into stations (fixed intervals) down the hole, from up and down tool runs at several speeds for a constant injection flow rate. The more data captured, either through higher data sample rates or more tool speeds, the higher the quality of velocity profiles, assuming other factors remain constant. Typically, 1 m stations are used; this depends on having an appropriate number of tool speeds and data sample rate.

The regression for calculating profiles is typically either done using a linear or bilinear analysis. The bilinear analysis consists of doing two regressions, with data separated into down and up tool runs. This can be needed due to the different pitch of the spinner impeller when travelling down and up the hole. The regression also provides an estimate of the error in the interpreted fluid velocity, which indicates the level of confidence in each interpreted value (Grant & Bixley, 1995).

If only one tool speed (up and down) is used, or only up or down tool speeds are recorded, a linear analysis must be used (Grant & Bixley, 2011). For two tool speeds, both analysis types can be used (Grant & Bixley, 2011), however, the bilinear analysis may be overly constrained.

Well stability is also important for having confidence in the interpreted velocity. If the well is stable then each spinner profile should be offset from each other by a constant amount, although this offset may be different for up and down runs (Grant & Bixley, 2011). Otherwise, performing the regression would introduce significant error; the fluid velocity at a given depth would not be constant for a given flow rate.

2.4 Interpreting fluid velocity profiles

Fluid velocity profiles capture the following information: an increase in velocity either indicates a decrease in borehole cross-sectional area or an inflow (a feed zone), while a decrease in velocity indicates the opposite, an increase in borehole cross-sectional area or an outflow (a feed zone). To understand which of these effects is occurring during analysis we can use profiles from multiple injection rates, via the spinner ratio method (Grant et al., 2006).

When the liner is present, the effective diameter that the fluid can flow in is somewhere between the liner's internal diameter and the drilled borehole diameter minus two times the liner's thickness. Therefore, profiles at the same injection rate will have a higher fluid velocity during the completion test than the stage test, other factors remaining constant. Similarly, there are often washouts just below the casing shoe, so there may be a sudden decrease and increase in fluid velocity here, particularly without the liner installed.

Inflows in geothermal wells can contain fluid in a liquid phase, steam phase, or both (two-phase). The presence of two-phase inflows will occur if the wellbore pressure is lower than the reservoir pressure at a given fluid temperature/injection rate. During injection into permeable wells the wellbore pressure tends to be lower than the reservoir pressure at shallower depths (above the pressure control point/major feed zone) and higher when deeper than this. Resultantly, inflows tend to be found at shallower depths, while deeper depths are generally liquid outflows.

Single-phase liquid inflows into single-phase liquid injection fluid can be seen as a simple increase in the fluid velocity. In contrast, a two-phase inflow looks like an initially large increase in velocity, which drops off as the steam condenses to liquid in the cold injectate. The stable velocity will have increased overall relative to before the inflow feature. The actual increase in flow is represented by the difference between the two stable velocities, and not the large spike.

This can be seen for WK260 between 640 and 690 m in Figure 2, a well in the Wairākei geothermal field. The reason this occurs is that the steam phase has a much higher velocity than the liquid phase and will travel in the centre of the well, interacting to a greater degree with the spinner impeller, while the slower liquid phase travels along the well casing. Hot inflows such as these are always accompanied by a sharp increase in temperature gradient at this depth (Figure 2), that does not drop away significantly as the tool moves deeper.

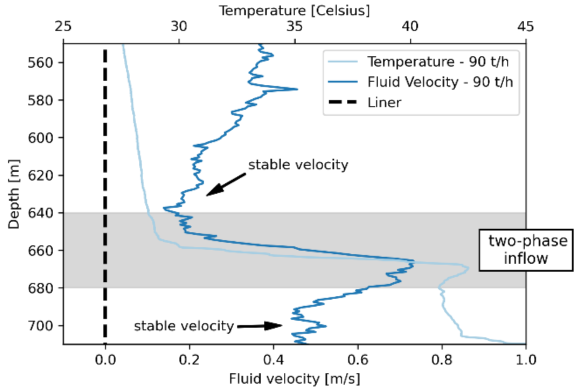

Figure 2: A two-phase inflow in WK260 (shaded) under 90 t/h injecting conditions as seen in the fluid velocity and temperature profiles.

2.4 Spinner ratio

The velocity profile down the well is given by $V(z) = W(z)/A(z)$, where $W(z)$ is the volume flow as a function of depth and $A(z)$ is the cross-sectional area (Grant et. al., 2006). If we have two velocity profiles at different flow rates, with the same cross-sectional area profile, then the ratio of flow rates should be constant between feed zones where the mass flow is constant. Similarly, the ratio should change at feed zones where the mass flow increases or decreases.

There may be some displacement of fluid profiles, such as from wireline stretch, which needs to be corrected before the ratio calculation (Grant et al., 2006). Additionally, the ratio calculation relies on having good quality spinner data at a minimum of two flow rates. Given the noisy nature of fluid velocity profiles we expect the ratio to be somewhat noisy; it's important to not read too much into small ratio changes.

3. METHOD

3.1 Well and data selection

To identify wells and datasets for this follow-up study, we used a slightly modified version of the process from Goble and McLean (2020). We began by considering the wells from their study, alongside any new wells drilled in the Wairākei-Tauhara geothermal field since 2020. Again, we do not consider wells with sidetracks or damaged casing, or stage tests that were only within the casing.

After identifying these candidate wells, we assessed them using criteria updated slightly from Goble and McLean (2020). We are interested in comparing fluid velocity profiles rather than temperature profiles, so the previous criteria of comparable injection rates, no large internal flows and only using downwards runs are either less important or no longer relevant. Updated criteria are labelled (new):

- Stage test captures data below casing shoe in the open hole;
- Completion test occurs with the liner installed;
- Data captured shows the well conditions are stable;
- Limited drilling activities between completion test and stage tests (if there is significant drilling, the well is essentially different so it is difficult to draw direct comparisons between tests);
- Good spinner data, free of issues, such as being blocked by debris, and with a reasonably high resolution (new);
- Have up and down tool runs for at least two tool speeds per injection rate (new).

WK268 and WK269 from Goble and McLean (2020) had low-resolution spinner data and typically one tool speed for each flow rate in the stage tests. Therefore, the data were of insufficient quality for our purposes.

TH26 from their study has acceptable data for our study, as do two newer wells in the Tauhara geothermal field, TH21 and TH31. The former two are production wells, while TH31 is a reinjection well.

3.2 Well and test details

To allow a direct comparison of fluid velocity profiles, we sought wells where minimal drilling activities occurred between stage and completion tests . Many stage tests occur prior to significant additional drilling which means the completion test occurs on a very different well.

The presence of large downflows masking deeper feed zones in temperature data was a concern in Goble & McLean (2020). This is an issue for TH31. However, this is not an issue when interpreting feed zones from fluid velocity profiles, reinforcing the benefit of considering both sets of data. Under injection conditions, shallower feed zones generally have a clear temperature response with a more obscured fluid velocity response, while deep feed zones tend to have subtle temperature responses and a clear fluid velocity response.

For each well and test type, the injection rates and tool speeds of the PTS tool are given in Table 1. These wells have data sampled four times per second.

Table 1: Injection rate and tool speeds for each data set used for analysis. A positive tool speed indicates a tool direction downward into the hole and vice versa.

	Injection rates (t/h)	Tool speeds (m/s)	Test Type
TH21	72, 168	±0.8, ±1.0, ±1.3	Stage
	132, 198	±0.8, ±1.0, ±1.3	Completion
TH26	80, 120, 160	±0.3, ±0.6	Stage
	56, 143	±0.6, +1.0, ±1.2	Completion
TH31	180, 210	±1.0, ±1.2	Stage
	60, 192	±0.8, ±1.0, ±1.2	Completion
	120	±0.8, +1.0, ±1.2	Completion

TH21 had no drilling activities between stage and completion testing. The stage test only had one flow rate; we will use the temperature profiles, XY caliper and ABI logs to support the identification of feed zones. The stage test velocity profile has been offset by +0.1 m/s so that both the completion and stage test hit zero velocity at about 1850 m.

TH26 had a stage test at a drilled depth of 1550 m, with data collected down to 1420 m. The well was then drilled an additional 50 m to 1600 m, with a completion test with data collected down to 1540 m. The well had some issues with unstable conditions and with quenching of the two-phase inflows in the completion test. The first and highest injection rate of 143 t/h in the completion test is the most stable and consistent with the stage test and is thus used for comparison. The 56 t/h completion test is included to mitigate wellbore diameter effects during analysis. There is some missing data for the +0.6 m/s tool speed at both 80 t/h and in the stage test.

TH31 had no drilling activities between stage and completion testing. The stage test had only two tool speeds per flow rate, as it was mainly undertaken to determine temperatures for the ABI logger.

To compute fluid velocity profiles, a linear analysis with 1 m stations was used across all wells on all but one flow rate. The 60 t/h flow rate in TH31's completion test instead used a bilinear analysis with 1m stations.

3.3 Two-phase inflow interpretation

We interpret the location of a two-phase inflow as from the beginning of the large velocity increase, until just after it starts decreasing in velocity. An inflow could still be coming in while the velocity is at its maximum, which is hidden by the contrasting effect of the steam condensing. This can also mean that several, close two-phase inflows may be interpreted as a single inflow.

3.4 Aligning fluid velocity profiles and spinner ratio computation

There is likely some stretch of the wireline over the course of the PTS run, such as from thermal expansion (Grant & Bixley, 2011) which can be up to 10m based on practical observation. Therefore, alignment of fluid velocity profiles from subsequent injection rates may be required (Grant et al., 2006). The profile from the first injection rate is used as the baseline as this will, in general, have the least wireline stretch. To do this, we developed a simple algorithm.

Firstly, we interpolated each of the fluid velocity profiles at common depth locations using cubic splines. We do not extrapolate, noting that profiles from different injection rates may not have identical depth ranges. When the velocity profiles have been calculated at 1 m stations (every 1 m), we interpolated at every 0.2 m, taking care to not consider a higher data resolution than is reasonable. Cubic splines were used as they enable interpolant behaviour consistent with physics: the rate of change in fluid velocity between data points should smoothly vary.

We then considered offsets in the range of -10 m to +10 m for our 0.2 m intervals that minimise one of the following two functions.

1. The variance of the spinner ratio, as calculated between the profile at the first rate and the considered rate along a depth range where there are no feed zones, per Grant et al. (2006).
2. The least squares difference between the normalised profiles at the first rate and considered rate. Normalised means that each profile has had its mean magnitude subtracted from it, so that differences in magnitude do not dominate the objective function. We only considered depth ranges that we have data for in both profiles (these are our extremities). Moreover, the extremities of both profiles related to the search range are ignored to enable a fair calculation of the objective, i.e. for our offset search range of -10m to +10m we ignored the first and last 10 metres of data.

The offset which minimises the selected function was then applied to the depths of the considered rate.

The second function is preferred, as it does not require knowledge of feed zone location. Nonetheless, each function produces offsets that are consistent within +/-0.2 m for the profiles we consider here. We have used the second function in this paper. Both functions are implemented in the provided Python file (Trent, 2024). Future work may include bundling these functions into a Python package.

The spinner ratio we compute is thus the ratio between each of the interpolated fluid velocity profiles after applying their best depth offset. When there are three profiles, we've chosen the ratio of two profiles in which the constant nature between feed zones is best shown; some ratios can show up with an approximately constant linear increasing or decreasing trend between feed zones.

3.5 Differences when comparing to the previous study

To identify feed zones, we consider velocity profiles from all flow rates in each test simultaneously, rather than interpreting feed zones for a single temperature down run per flow rate (Goble & McLean, 2020). This is so we can compute the spinner ratio to mitigate wellbore diameter effects. This means that features like two-phase inflows moving at different flow rates will not come through in our interpreted results. Similarly, the calculation of fluid velocity profiles is effectively a smoother across multiple down and up runs, where well conditions may have slightly changed, as opposed to a single temperature profile down run. Finally, we offset later fluid velocity profiles for consistency with the first flow rate profile, whereas the temperature profiles had no compensation for wireline stretch. This could be a factor if compared similar flow rates occurred at different times in the test (e.g. 1st vs 3rd).

4. RESULTS

Our discussed depths are all given in measured distance along the wellbore from the casing head flange (mCHF). We may slightly overinterpret aspects of the spinner ratio so we consider the location of fractures identified by the ABI log to provide further validation (although noting that not all fractures are permeable (Massiot et al., 2017)). Zone shifts are relative to the top of the feed zone.

4.2 TH21 fluid velocity profiles

TH21 is characterised by a strong outflow around 1200 m, zone C, with small inflows and outflows in other areas of the well. These are seen as the shaded areas in Figure 3. A summary and comparison of the apparent location of feed zones during stage and completion testing is given in Table 2. For the stage test, we also plot the temperature profile and average diameter indicated by the XY caliper tool.

In the completion test, we offset the later flow rates, 72 and 198 t/h by 2.4 and 1.2 m shallower, respectively, for consistency with the first 132 t/h flow rate.

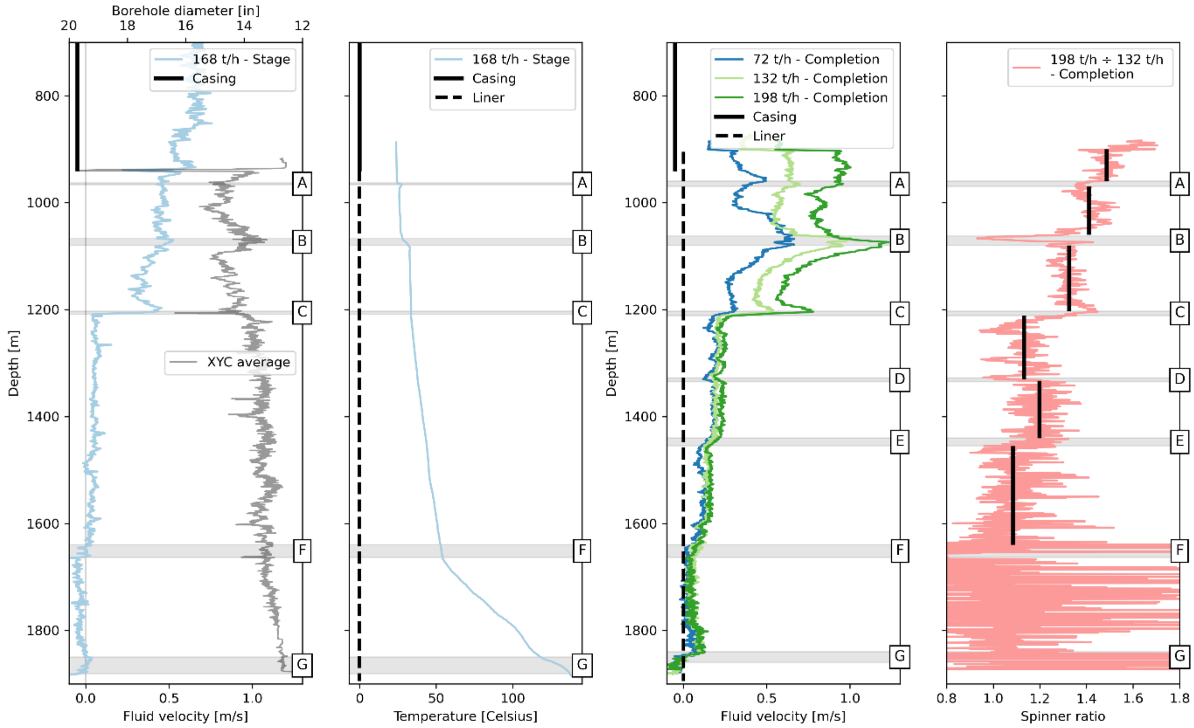

Figure 3: TH21 open-hole stage test and completion test fluid velocity profiles and spinner ratio. Shaded areas are interpreted feed zones indicated by the temperature profiles, fluid velocity profiles and spinner ratio.

Table 2: TH21 interpreted feed zone depths (mCHF) for the open-hole stage test and completion test across all flow rates, alongside comparison of feed zone width and apparent shift.

	Stage Test			Completion Test				
Zone	**Range**		**Zone Width**	**Range**		**Zone Width**	**Percent Increase**	**Zone Shift**
A	963	966.5	3.5	960	970	10	186%[1]	3[1]
B	1067	1080	13	1062	1080	18	38%[1]	5[1]
C	1203	1209	6	1203	1211	8	33%	0
D				1328	1335	7		
E				1440	1455	15		
F	1640	1663	23	1640	1663	23	0%	0
G	1850	1881	31	1840	1860	20	-35%	10

[1] Stage test feed zones were not interpreted from fluid velocity profiles so are not directly comparable.

The first six feed zones (A-F) show up as clear step changes in the completion test, while zone G is seen as a velocity decrease. Feed zones A and B can be seen as temperature increases in the stage test, with F and G seen as small velocity decreases and temperature gradient increases. Zones D and E do not show up in the stage test, given the XY caliper data. If we had a second flow rate, we might have been able to see them in a spinner ratio. Zone A comparisons will not be discussed here because it was not interpreted from the fluid velocity profile.

In the completion test feed zone B appears as a two-phase inflow in the two higher flow rates, which quench the zone by the time the 72 t/h flow rate is reached. This is seen as significant spikes in fluid velocity at the higher rates, while no major spike is observed at the lowest rate. Similarly, in the stage test, this zone is quenched, which may be due to a longer high flow rate before data collection. It could also be because the zone is easier to quench without the liner present.

Feed zone C appears 33% broader with no change in the top of the loss zone between the stage and completion test; its bottom is 2 m deeper. Zone F has no apparent change.

However, zone F is likely only 3 m in width rather than 23 m based on the ABI log which had several large apparent open fractures between 1664-1666 m. Zone G appears to shrink by 35% while shifting 10 m higher between the stage and completion tests. However, this may also be an unfair comparison due to the very low fluid velocities at this depth.

4.3 TH26 fluid velocity profiles

TH26 is characterised by the presence of two-phase inflows, seen as the shaded areas in Figure 4. A summary and comparison of the apparent location of feed zones during stage and completion testing is given in Table 3.

In the stage test, we offset the later flow rates, 120 and 160 t/h by 0.2 and 0 m deeper, respectively, for consistency with the first 80 t/h flow rate. In the completion test, we offset the later flow rate of 56 t/h by 1.2 m shallower for consistency with the first 143 t/h flow rate.

The first three two-phase inflows in the stage test, A, B and C can be seen clearly as the large velocity peaks that drop quickly as the steam condenses. These have widths of 3, 2.5 and 2.5 m, respectively. In the more stable 143 t/h completion test flow rate, these all appear to merge into one zone ABC, which is 9 m higher in the well and spans 20.5 m, which is an apparent increase of 46%. ABC has peaks in this inflow feature that could be correlated with each feed zone.

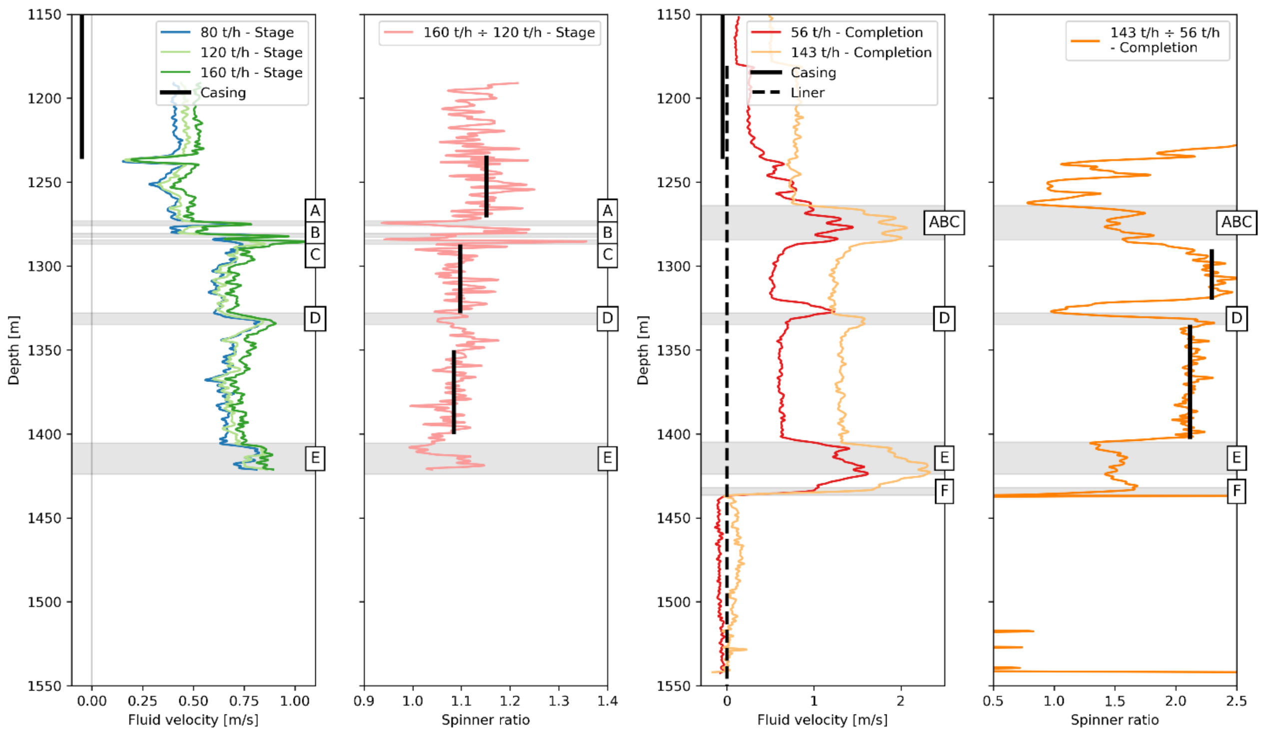

Figure 4: TH26 open-hole stage test and completion test fluid velocity profiles and spinner ratio. Shaded areas are interpreted feed zones indicated by the fluid velocity profiles and spinner ratio.

Table 3: TH26 interpreted feed zone depths (mCHF) for the open-hole stage test and completion test across all flow rates, alongside comparison of feed zone width and apparent shift.

	Stage Test			Completion Test				
Zone	**Range**		**Zone Width**	**Range**		**Zone Width**	**Percent Increase**	**Zone Shift**
A	1273	1276	3	1264	1284.5	20.5	46%[1]	9
B	1280.5	1283	2.5					
C	1284.5	1287	2.5					
D	1328	1335	7	1328	1335	7	0%	0
E	1405.5	1424	18.5	1405	1424	19	3%[2]	0.5
F				1432	1436.5	4.5		

[1] Calculated as a combined zone of A, B and C, using the top of A and bottom of C from the stage test.
[2] Zone width for the stage test is indicative as the tool may not have reached below the feed zone, thus the percent increase may not be accurate.

Feed zone D is present with the same location in both the stage and completion tests. However, the two-phase inflow feature shifts between the 143 t/h and 56 t/h flow rates in the completion test. This indicates that the well state changed; the second feed zone became less quenched at this lower flow rate. This did not occur in the stage test, which could indicate that the liner was obstructing this quench. However, there was no comparably low flow rate in the stage test, so this is uncertain.

Feed zone E appears to move higher by 0.5 m, between the stage and completion tests, again looking at the more stable 143 t/h flow rate. We cannot compare the width as the stage test concluded midway through this depth. There is a dip in the ratio just before zone E in both tests, but we do not interpret it as a feed zone as there is no temperature change.

Feed zone F is only present in the completion test as the stage test did not reach this depth.

4.4 TH31 fluid velocity profiles

TH31 is characterised by a strong liquid inflow under the casing shoe and significant outflows below 2600 m, seen as the shaded areas in Figure 5. A summary and comparison of the apparent location of feed zones during stage and completion testing is given in Table 4. The temperature profiles are isothermal below the large inflow so cannot be used to interpret other feed zones.

In the stage test, we offset the later flow rate of 210 t/h by 2 m shallower, for consistency with the first 180 t/h flow rate. In the completion test, we offset the later flow rates, 60 and 192 t/h, by 4.6 and 2 m shallower for consistency with the first 120 t/h flow rate.

TH31 can be seen to have a distinct inflow, A, and two distinct outflows, D and E, in the fluid velocity profiles of both tests. Zone D also shows up as a distinct step change in the spinner ratio for both tests. Feed zone A appears 83% wider and 3 m higher in the completion test than the stage test. Feed zone D has no apparent change, while zone E appears to shrink by 14% (1 m) and becomes 1 m deeper. However, in the completion test the fluid velocity does not reach zero by 2082 m so this zone may extend further.

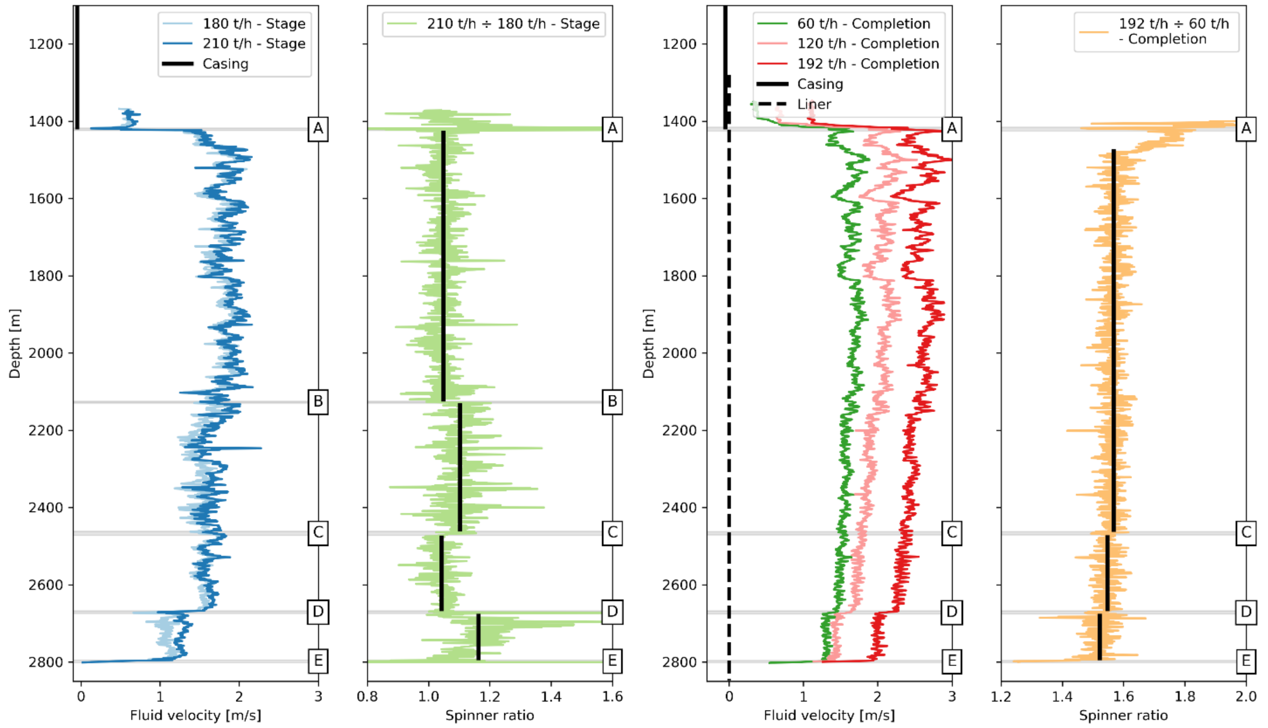

Figure 5: TH31 open-hole stage test and completion test fluid velocity profiles and spinner ratio. Shaded areas are interpreted feed zones indicated by the fluid velocity profiles and spinner ratio.

Table 4: TH31 interpreted feed zone depths (mCHF) for the open-hole stage test and completion test across all flow rates, alongside comparison of feed zone width and apparent shift.

	Stage Test			Completion Test				
Zone	**Range**		**Zone Width**	**Range**		**Zone Width**	**Percent Increase**	**Zone Shift**
A	1418	1424	6	1415	1426	11	83%	3
B	2125	2130	5					
C	2462	2472	10	2463	2471	8	-20%	-1
D	2668	2675	7	2668	2675	7	0%	0
E	2795	2082	7	2796	2082	6[1]	-14%	-1

[1] Zone width for the completion test is indicative as the tool may not have reached below the feed zone, thus the percent increase may not be accurate.

Feed zone B is present in the stage test, while feed zone C is present in both tests. They cannot be seen as a significant fluid velocity change. Instead, they can be seen as a distinct step change in the spinner ratio. Both appear to be very small and are likely suppressed by the large inflow at zone A. Feed zone C appears to shrink by 20% and becomes 1 m deeper. These zones are correlated with zones of high fracture density in the ABI logs; zone B correlates to a suggested fault with high fracture density between 2037-2137 m, while zone C correlates to a zone with moderate fracture density between 2412-2489 m. This suggests that we are not interpreting noise, demonstrating the importance of using multiple data sources when making interpretations.

We could potentially interpret a feed zone between D and E in the stage test, based on the spinner ratio. However, the ABI log has a very low fracture density in this region. While this could still be formational permeability, we chose not to interpret this as a feed zone.

5. DISCUSSION

5.1 Quantifying general effect of liner

We find that the effect of the liner on the apparent location of feed zones interpreted from fluid velocity profiles is:

- To make shallower feed zones (< 1500 m) generally appear wider and slightly shallower,
- To make deeper feed zones (> 1500 m) appear the same or slightly narrower and deeper, and
- For shallow two-phase zones that are close together, the liner appears to merge adjacent feed zones.

For shallower feed zones, which are often two-phase inflows, the apparent top of the feed zones are shifted 2.5 m shallower when the liner is present. The feed zone that merges appears 46% broader; this is dependent on the number of adjacent feed zones and their relative displacement. The remaining four feed zones appear between 0% and 83% broader, or 30% on average. This effect is stronger closer to the casing shoe.

For deeper feed zones, which are liquid inflows and outflows, the apparent top of feed zones is either unchanged or 1 m deeper, with only feed zone G in TH21 appearing 10 m shallower. The feed zones appear between 0% and 35% narrower or 14% on average. The width of most of these zones only changes by 0-2 m, so this may not be a significant difference. This indicates that the liner does not have a strong impact on the fluid velocity profiles of deep liquid feed zones (inflows and outflows). The 1 m changes could be attributed to blank sections of the liner at connection locations; on the liner used this is around 2 m for every 11.5 m of length.

The difference between shallower and deeper feed zones may be because the flow pathways (Goble & McLean, 2020) are much more consistent before and after the liner when only a liquid phase is present. In contrast, when there is a steam phase present, they become more complicated, particularly as it condenses.

A couple of feed zones were apparent in one test but not the other. However, this cannot be attributed to the liner as this occurred in TH21's stage test and TH31's completion test. In both cases they were minor.

These results serve as an indication for other wells. However, they may not be representative for wells with different characteristics (e.g. lower permeability).

5.2 Comparison to previous study

The results for deeper feed zones could not be observed in the temperature profiles and is, therefore, a useful contribution of this paper. The results for shallower feed zones are consistent, although the strength of the two effects is weaker in our study (30% vs 114% broader and 2.5 m vs 17 m shallower). This is partly due to differences in well selection as the effects were stronger for feed zones close to the casing shoe; WK268 and WK269 both have three to five feed zones within 100 m of the casing shoe (Goble & McLean, 2020), whereas TH21 and TH31 have one each. The rest of these results can be explained by the differences in methodology (Section 3.5), and between spinner and temperature measurements. It may be worth considering the temperature profiles for TH21 and TH31 in the future for a more direct comparison. However, only the shallowest feed zone can be seen in TH31's temperature profile.

6. CONCLUSION

In conclusion, if the aim is to understand the location of feed zones with high accuracy, and only completion testing data is available (with the obscuring liner), the following considerations are relevant, when interpreting feed zones from fluid velocity profiles:

- For shallow feed zones, particularly two-phase inflows, the presence of the liner during completion testing makes a feed zone appear 2.5 m shallower and 30% broader on average.
- For close, adjacent two-phase inflows, the presence of the liner may reduce resolution by making them appear to be one zone.
- For deeper feed zones, which are in a liquid phase, we generally expect the liner to have a negligible effect.

ACKNOWLEDGEMENTS

We acknowledge the work of Ielish Goble, who led the study this work follows up on (Goble & McLean, 2020). We began by considering the wells selected in their study, and only consider additional wells drilled on the Wairākei-Tauhara field since that publication.

REFERENCES

Glynn-Morris, T., Mclean, K. & Brockbank, K. (2011). *Characterizing feed zones in geothermal fields: integrated learnings from completion testing, image logs and continuous core.* Proc. 33rd New Zealand Geothermal Workshop, Auckland, New Zealand.

Goble, I. & McLean, K. (2020). *Accurate location of feed zones: assessing obscuration by the liner in geothermal wells.* Proc. 42nd New Zealand Geothermal Workshop, Waitangi, New Zealand.

Grant, M.A. & Bixley, P.F. (1995). *An improved algorithm for spinner profile analysis.* Proc. 17th New Zealand Geothermal Workshop, Auckland, New Zealand.

Grant, M.A. & Bixley, P.F. (2011). *Geothermal Reservoir Engineering* (2nd ed). s.l.:Elsevier.

Grant, M.A., Wilson, D. & Bixley, P.F. (2006). *Spinner data analysis to estimate wellbore size and fluid velocity*. Proc. 28th New Zealand Geothermal Workshop, New Zealand.

Massiot, C., McLean, K., McNamara, D.D., Sepulveda, F. & Milicich, S.D. (2017). *Discussion between a reservoir engineer and a geologist: permeability identification from completion test data and borehole image logs integration.* Proc. 39th New Zealand Geothermal Workshop, Rotorua, New Zealand, 22-24 November, 2017.

McLean, K., Zarrouk, S.J. & Wilson, D. (2016). *Application of numerical methods for geothermal pressure transient analysis: a deflagration case study from New Zealand*, Proc. 41st Workshop on Geothermal Reservoir Engineering, Stanford University, Standford, California.

Purnomo, F. & McLean, K. (2024). *Correcting for variations in borehole diameter in fluid velocity profiles*. Proc. 46th New Zealand Geothermal Workshop, Auckland, New Zealand.

Trent, J. (2024). *SpinnerRatioAnalysis.* Github. https:// https://github.com/JoelTrent/SpinnerRatioAnalysis

ISSN 2703-4275