THE REVISED LOWER BOUND METHOD - ANALYSIS OF FLOWING PRESSURE/TEMPERATURE SURVEYS FROM GEOTHERMAL WELLS

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ABSTRACT

The current study revises the *lower bound analysis method*, developed by Gunn *et al.* (1992), by incorporating into it the new fluid properties model of Andersen *et al.* (1992) for H_2O-CO_2-NaCl systems. The lower bound method was developed in order to analyse trends, errors and discontinuities, in downhole pressure and temperature measurements taken during well discharge. Any deviation of pressure from pure water saturation conditions is expressed by a minimum value of NaCl or CO_2 that must be present in the fluid to cause that deviation.

The lower bound method is further revised so that the calculation can be performed on the basis of wellhead vapor fraction, in addition to the original options of wellhead enthalpy or flash point parameters. The method is also revised to allow a "base" value of NaCl or CO_2 to be specified. The application of this revision is shown to be useful for assessing downhole measurements, especially where the geothermal fluid has *both* impurities present in significant quantities.

INTRODUCTION

Geothermal wellbore simulators can be used to build up a model for the behaviour of a discharging well, through the use of matching analysis. This is performed by calibrating the simulated downhole pressure and temperature profiles against measurements of pressure and temperature, taken from a downhole flowing survey. Gunn *et al.* (1992) have discussed matching analysis techniques in detail. Their main conclusion was that, any downhole measurements used for matching analysis, should be first carefully scrutinised for any trends, inaccuracies or inconsistencies, as there is little to be gained from calibrating the model of the well against poor measured data. Gunn *et al.* (1992) presented a simple method designed to identify such trends in downhole data, and this was termed the *lower bound method*.

The main purpose of the current study is to incorporate the fluid properties model of Andersen *et al.* (1992) into the lower bound method developed by Gunn *et al.* (1992). The method assesses the consistency of pressure and temperature measurements, taken downhole in a geothermal well during discharge. This is performed by representing the deviation of the pressure/temperature pairs, measured in the two-phase flow region of the wellbore, from pure water saturation conditions, by a "lower bound" value of either NaCl or CO_2. Andersen *et al.*'s (1992) fluid properties model has been indicated by Gunn (1993) as being particularly appropriate to representing the observed properties of geothermal fluid.

The original lower bound method is reviewed, and the changes required in the interpretation of its results, when utilising the new Andersen *et al.* (1992) fluid properties model, are indicated. The method is then extended so that a "base" quantity of either NaCl or CO_2 can be specified as being present in the fluid. Case studies are provided of applying the revised lower bound method to actual discharge test data.

THE LOWER BOUND METHOD

The Original Lower Bound Method

Gunn *et al.* (1992) demonstrated that a single pressure-temperature pair at a given enthalpy describes a functional relationship of CO_2 to NaCl at saturation. This is based on the assumption that the geothermal fluid can be represented by the three component system of H_2O-CO_2-NaCl. Depending on whether the measured two-phase pressure value lies above or below the saturation curve for pure water, a minimum possible content of CO_2 can be found that satisfies saturation conditions, or conversely, a minimum value of NaCl can be found. The earlier study mainly utilised the fluid properties model of Sutton (1976), and it was shown that the minimum possible CO_2 value required to satisfy observed saturation conditions, occurred when the NaCl content was zero, or alternatively, the minimum possible NaCl content occurred when the CO_2

content was zero (ie the lower bound value). This is because in the previous work it was assumed that the NaCl and CO_2 always act as *complements* when it comes to maintaining a constant system pressure. Generally NaCl depresses the saturation pressure, and CO_2 increases the saturation pressure. In other words, the effect of any CO_2 could be "counterbalanced" by some quantity of NaCl, or vice versa.

The original method thus determined the minimum quantity of NaCl that must exist in the fluid for a given pressure/temperature measurement, where the measured pressure is *below* the saturation pressure of pure water at the measured temperature. Similarly the method determined the minimum quantity of CO_2 that must exist in the fluid, where the measured pressure is *above* the saturation pressure of pure water at the measured temperature.

The method has a number of applications. One is in examining trends in the measured data through trends in the associated lower bound profile. A lower bound profile is simply the set of NaCl and/or CO_2 lower bound values plotted against depth. At each depth where a pair of pressure/temperature values exists, then so does a corresponding lower bound value, although the values are only valid if the fluid is two-phase at that depth. This is because the method works with respect to the saturation behaviour of the fluid.

It would be expected that if the downhole data is fairly accurate, and the flow in the wellbore was stable when the measurements were taken, then the lower bound values should be fairly consistent. Not only should the lower bound values either indicate all NaCl, or all CO_2, but the variation in the values should be small.

Spikes and discontinuities in lower bound profiles were interpreted by Gunn *et al.* (1992) as indicating measurement errors, or in some cases indicating the effect of secondary infeeds from the reservoir into the wellbore. This latter interpretation was considered reasonable, as it unlikely that fluid composition remains the same above and below a feed zone.

Where the lower bound values are all fairly consistent, then the magnitude of the values can be examined. If CO_2 or NaCl is the dominant impurity, then the lower bound values should closely match measured fluid composition data. Again, if this not the case it can indicate that perhaps the discharge did not reach a steady-state, that there is some measurement error, or that *both* impurities are present in significant quantities.

Lower Bound Method Options

As discussed above, the calculation of the lower bound values, from any pair of pressure/temperature measurements, requires the enthalpy to be known at each depth of interest. If the flow is considered to be adiabatic, then the enthalpy at each point can be calculated from the wellhead enthalpy, by allowing for changes in potential energy. The difficulty of this approach is that enthalpy is difficult to measure accurately, particularly where impurities actually are present.

An alternative to specifying the wellhead enthalpy is to use the temperature at the flash point. Fixing the flash point depth and temperature allows the enthalpy to be determined at each pressure/temperature pair in the wellbore. This is because the vapor fraction (ie steam quality or dryness fraction) is zero, and therefore the fluid enthalpy will equal the liquid phase enthalpy at the flash point temperature. Flash point depth and temperature can be estimated by observing the shape of the downhole temperature profile, as this is often highlighted by a sharp change in the temperature gradient.

The lower bound method was coded into Version 1 of the commercially available geothermal wellbore simulator, WELLSIM (refer Gunn and Freeston, 1991), with two options. Either the wellhead enthalpy, or the flash point depth and temperature could be specified by the user, as the basis for calculating the lower bound values.

REVISIONS OF THE LOWER BOUND METHOD

The original implementation of the lower bound method, which utilised Sutton's (1976) fluid properties model, failed to allow for the distinct non-ideality and non-linearity of the H_2O-CO_2-NaCl system, and also for the "salting-out effect" that the NaCl has on CO_2 solubility. The current investigation has found that, the phase equilibria model of Andersen *et al.* (1992) for this three component system, more accurately represents the effects that NaCl and CO_2 have on geothermal fluid properties. With such a formulation, the previously held assumption that the NaCl and CO_2 act as complements is not valid. The components can act as *substitutes* at high saturation pressures and low vapor fractions, due to the salting-out effect. However, it has been found that this generally has a negligible effect on the bound values. (For a full discussion refer to Gunn, 1993).

Apart from changing the model used for determining geothermal fluid properties, the method has been extended by adding a further option to those of basing the calculation on either wellhead enthalpy or flash point

parameters. The "maximum" vapor fraction can now also be entered as the basis of the enthalpy calculation. The maximum vapor fraction will occur at the shallowest depth that a pair of pressure/temperature measurements are available. Often this will be at the wellhead. This option works by using the specified vapor fraction value to determine the enthalpy at the shallowest depth, and subsequently at the wellhead. From then on the method works in the same manner as the wellhead enthalpy option.

The reason for adding the maximum vapor fraction option, is because generally, field measurements of enthalpy do not accurately account for the significant effects of fluid impurities. Furthermore, it has been discussed in Blakeley (1992), that there is some confusion in the literature as to the appropriate zero reference point for CO_2 vapor enthalpy. Even where the fluid is pure water, measurements of enthalpy can be in error by ± 50 kJ/kg, should the lip pressure method be used. With the value for enthalpy of the CO_2 component in dispute, because of the reference point problem, it is unlikely that measurements which explicitly consider the effect of CO_2 will necessarily be consistent with the approach used by the lower bound method.

Although measurements of vapor fraction are also subject to error, the CO_2 is explicitly taken into account, because the *total* liquid and vapor flow are measured, inclusive of the CO_2 component in each phase. Vapor fraction is therefore a more suitable parameter to use in the lower bound method, as field measurements will be more likely to be consistent with the corresponding calculated values.

CASE STUDIES

Los Azufres LA18, Mexico

Figure 1 shows the results from applying the revised lower bound method (as implemented in WELLSIM Version 2.1) to the Los Azufres Well LA18 downhole pressure and temperature profiles, measured at a single mass flowrate, during discharge of 96 t/hr. Two calculation options have been used, firstly, specifying wellhead enthalpy as 1607 kJ/kg, and secondly, specifying maximum vapor fraction as 33% (both values from Ambastha and Gudmundsson, 1986).

The NaCl lower bounds found from specifying a base CO_2 content of zero are very consistent, ranging between 6.9 and 8.3 wt% NaCl for most of the wellbore, with the exception of the wellhead and wellbottom values. The variations below 1250 m most likely indicate fluid entry below this point. Specifying a base value of CO_2 of 0.5 wt% simply increases the quantity of NaCl required to

"counterbalance" it to satisfy the pressure/temperature values. It should be noted that this fluid composition is not consistent with observed conditions at Los Azufres.
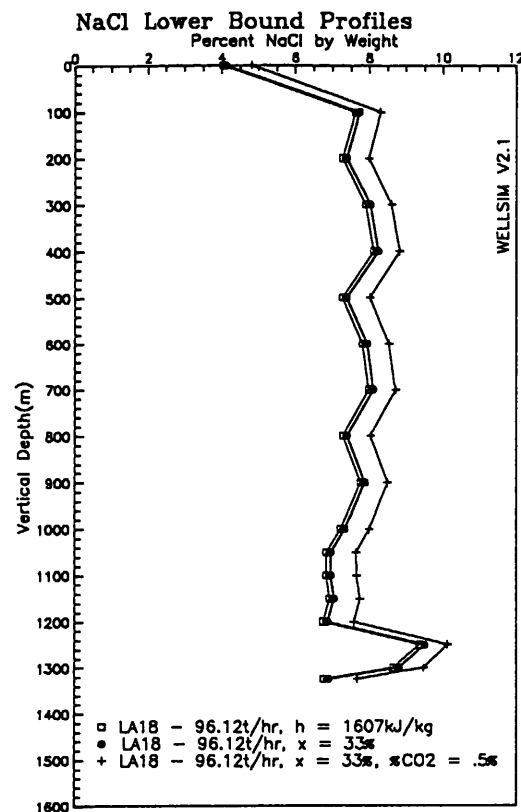

Figure 1: Lower bound profiles for Well LA18.

Ngawha NG11, New Zealand

Ambastha and Gudmundsson (1986) list one set of downhole data, from Ngawha Well NG11, measured when the well was discharging at a mass flowrate of 247 t/hr. Their published wellhead enthalpy and vapor fraction values are 965 kJ/kg and 2.5% respectively. Figure 2 shows the different results that using each of these values provides for the lower bound profiles.

Based on the specified vapor fraction value of 2.5%, the method calculates the flash point as occurring at around 200 m, whereas based on the enthalpy, the fluid does not flash in the wellbore at all. This is an example of the conclusion above, that field measurements of enthalpy and vapor fraction are unlikely to be consistent, when impurities are present in significant quantities. From observations of the downhole temperature measurements (not shown), it is clear that the flash point actually occurs between 500 and 600 m, at a temperature between 222 and 224°C. Using the flash point parameter option the lower bound profile is considerably more consistent.
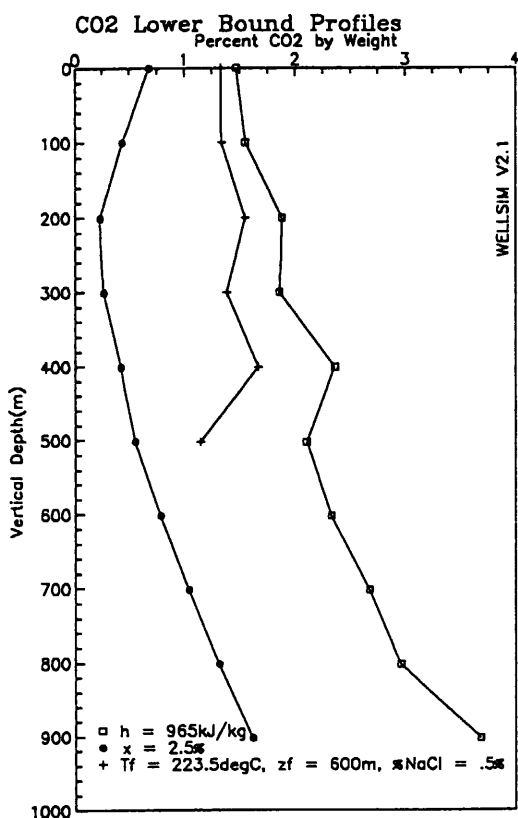
Figure 2: Lower bound profiles for Well NG11.

Figure 3: Lower bound profiles for Well East Mesa 6.

Hadgu (1989) has published typical composition data for NG11 as 1.2 wt% CO_2 and 0.5 wt% NaCl. The calculated CO_2 lower bounds, where a base value of 0.5 wt% of NaCl is specified, range from 1.15 to 1.67 wt%, which compares well with the measured composition data.

East Mesa 6, United States

The application of the revised lower bound method to data from East Mesa 6 (Ambastha and Gudmundsson, 1986) demonstrates the use of the method for diagnosing errors of data transcription and conversion. Applying the method to the data, by specifying a flash point temperature of 196°C at 1234m, indicates a distinct trend in the lower bound profile, from a CO_2 lower bound value of 17% at the wellhead, to almost zero at the flash point depth (see Figure 3). However, examining the detailed results of the method, provided in Table 1, the values calculated by the lower bound method for CO_2 partial pressure vary only slightly, and are mostly between 1.0 and 1.1 bar.
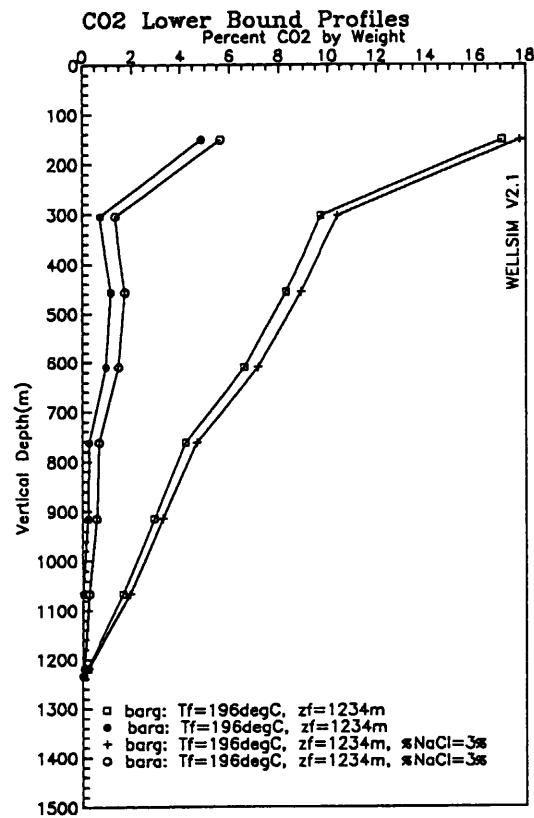
This sort of behaviour is not realistic, as CO_2 partial pressure is expected to *decrease* fairly rapidly subsequent to flashing of the fluid. Such a decrease in partial pressure has been observed in all simulations of wells discharging some CO_2. It is the lower bound values which should vary only a small amount.

Depth	Meas Pres	Meas Temp	Calc Vapor Fraction	Calc CO_2 Part P	CO_2 Lower Bound
(m)	(barg)	(°C)	(%)	(bar)	(wt %)
152	2.7	125.5	29.4	1.3	17.0
305	3.1	134.0	21.3	1.0	9.7
457	3.7	139.5	19.0	1.1	8.3
610	4.3	145.0	16.5	1.1	6.6
762	5.2	153.0	12.8	1.0	4.2
915	6.4	161.0	10.1	1.0	2.9
1067	7.9	170.0	7.2	1.0	1.7
1219	13.2	192.0	1.1	1.0	0.2
1234	14.3	196.0	0.0	1.0	0.1

Table 1: Lower bound values for Well East Mesa 6 (flash point temperature = 196°C, flash point depth = 1234m).

Ambastha and Gudmundsson (1986) cite Gould (1974) and Nathenson (1974) as the sources for the data on East Mesa Well 6. Neither of these sources indicate whether the measured pressure data is in gauge or absolute pressure. It is suggested that it is possible that the gauge values, given in Ambastha and Gudmundsson (1986), are in fact *absolute* pressure values. This is because, the consistent value for CO_2 partial pressure required to satisfy saturation conditions, is roughly the difference between gauge and absolute pressure. Figure 3 shows the large change that occurs in the calculated lower bound profile when absolute pressure values are used instead. With the exception of the shallowest measurement, the CO_2 lower bound values become reasonably consistent, ranging from 0 to 1.2 wt%.

Nathenson (1974) notes that this well has about 3 wt% of dissolved salts. Figure 3 also shows the lower bound profiles found when a base value of 3 wt% NaCl is specified for both the gauge and absolute pressure cases. The range of the CO_2 lower bounds becomes somewhat wider for the absolute pressure case, but the general consistency remains.

Broadlands Wells, New Zealand

Figure 4 shows the results of applying the revised lower bound method to data from a number of discharge tests performed in the Broadlands field (Bixley and Clotworthy, personal communication, 1992). In general, all the lower bound profiles are fairly consistent, and with the exception of one test of Broadlands Well B, the CO_2 lower bounds range from 0 to 1.3 wt% CO_2. The actual CO_2 at Broadlands ranges from around 0.5 to 3.5 wt%. The sudden discontinuity in the profile for BRB, found from applying the method to the downhole pressure and temperature data taken at a discharge of 139 t/hr, coincides with the presence of a gassy two-phase feed at 730 m.

High Salinity Well

Figure 5 shows the lower bound profiles for a high salinity well, with a flash point at around 850 m. The measured composition is 0.13 wt% CO_2, and about 23 wt% NaCl. The results of the revised lower bound method are shown with and without a base CO_2 content of 0.13 wt%.
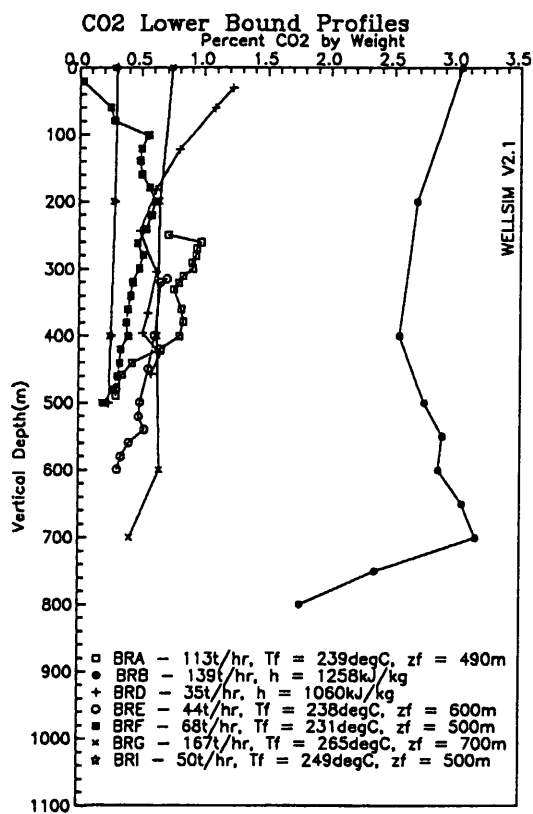

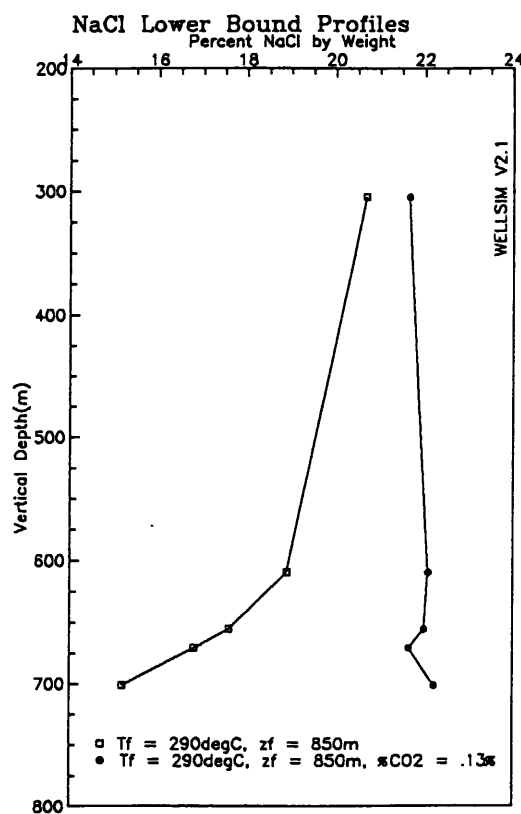Figure 4: Lower bound profiles for Broadlands wells.

Figure 5: Lower bound profiles for a high salinity well.

These results demonstrate the sensitivity of the analysis when high levels of impurities are present. With the base CO_2 content specified, the method provides NaCl lower bounds that are in good agreement with the measured composition.

INTERPRETATION OF LOWER BOUND PROFILES

Comparison with the Original Method

The lower bound profiles predicted by the revised method, which utilises the fluid properties model of Andersen *et al.* (1992), give somewhat different results from the original method (cf Gunn, 1992). In general, the lower bound values for CO_2 found with the revised method, are higher than those found with the original method. The reason for the change is that the phase equilibria model requires a higher concentration of CO_2 to maintain a particular partial pressure, than does Sutton's (1976) approach. However, the original method, although somewhat less accurate with respect to the magnitudes of the bounds, was still valid in terms of the general trends observed, and any subsequent interpretations.

Apart from the magnitudes of the calculated lower bounds being different, the revised lower bound method allows a base quantity of either NaCl or CO_2 to be specified. This has been shown to be particularly useful when large amounts of impurities are present. At high concentrations of NaCl, specifying a base quantity of CO_2 has been shown to change the shape of the lower bound profile, in fact making the NaCl lower bound values more consistent (eg Figure 5). Furthermore, assessing such high salinity wells was not possible with the original method, because the method was only considered valid up to salinities of 10.5 wt%, whereas Andersen *et al.*'s (1992) model is considered valid up to 30 wt% of NaCl in the presence of up to 5 wt% of CO_2.

General Interpretation

As was summarised by Gunn *et al.* (1992), there are a number of outcomes that can occur from the application of the lower bound method. Taking into account the revisions to the method, these are now as follows.

1) *The lower bound values vary only slightly, and are generally consistent.*
This generally means that the pressure/temperature measurements are at the very least consistent *separately*. To determine whether the pressure and temperature measurements are consistent with each other, requires a comparison of the lower bound values to the measured fluid composition. If both NaCl and CO_2 are present in

significant amounts, then measured concentrations of one or the other should be specified as the base value in the method. Well NG11 in Figure 2, and the well in Figure 5, are both excellent examples where base impurity values have been specified, resulting in consistent lower bound values. The examples for wells at Broadlands, in Figure 4, are all good examples of generally consistent measurements. Such results indicate that the pressure, temperature and fluid composition data are all reasonably consistent with each other, and can be used to calibrate wellbore simulator input parameters, or to validate two-phase pressure drop models.

In some cases, the lower bound method can provide values which might not vary a great deal, but do not correspond to the measured fluid composition, for example Well LA18, in Figure 1. Because CO_2 has a much more significant effect on saturation conditions than NaCl (on a weight percent basis), this is particularly of concern when lower bound values are significantly different from measured CO_2 levels. This may be caused by the pressure measurements having been taken at a different time from the temperature measurements, and in the intervening period wellbore conditions may have changed. Matching *both* the measured pressure and temperature profiles by wellbore simulation will clearly be unlikely. Calibration of input parameters can thus only be performed by allowing for an offset in the match of one or the other measured profile.

2) *The lower bound values follow a distinct sloping trend.*
This may indicate that a base quantity of either NaCl or CO_2 needs to be specified, for example, as in Figure 5. The example of Well East Mesa 6 indicated that where such a trend extends over a very large range, that this could be due to the data being specified in the incorrect units. Looking at the detailed results of the analysis can highlight absolute pressures entered in gauge, for example as seen in Table 1, or perhaps vice versa.

3) *Spikes occur in otherwise consistent lower bound profiles.*
"Spikes" can be considered to be a single pressure/temperature measurement that is inconsistent, and these values should be removed during matching. It is interesting that spikes often tend to occur closer to the wellhead: for example, Well LA18 in Figure 1, Well East Mesa 6 in Figure 3 (using absolute pressure values), and Well BRF in Figure 4. This is particularly unfortunate when the inconsistent value is at the wellhead itself, as it may mean that the basis for a wellhead/down simulation is inaccurate to start with. For example, the lower bound value for Well LA18 at the wellhead, shown in Figure 1, indicates that the wellhead pressure is higher than would

be expected from an observation of all the other lower bound values. Because NaCl depresses saturation pressure, the small value of the NaCl lower bound at the wellhead indicates a comparatively higher pressure. Where wellhead pressure is used as the input condition to a simulation of Well LA18, it can be expected that the pressure will be overpredicted down the entire length of the wellbore.

4) *Discontinuities exist in otherwise consistent lower bound profiles.*
"Discontinuities" can be considered as an indication of an actual change in fluid composition within the wellbore, due to the presence of a secondary feed zone. Such a discontinuity is shown for Well BRB in Figure 4. Discontinuities may also indicate that the flash point has been reached, and that flow in the wellbore is now liquid. *Liquid* flow will be indicated by a generally increasing trend in CO_2 lower bounds with depth, as the pressure of compressed liquid is of course greater than the saturation pressure of pure water. (This is because CO_2 lower bounds occur when the measured pressure is greater than the saturation pressure of pure water at a particular temperature).

5) *Significant random variations exist in lower bound profiles.*
Where highly random variations occur in lower bound profiles, it indicates that the measurements are of very poor quality, and are probably of little use for matching analysis. The best example of such variations is for Well HGP-A in Gunn *et al.* (1992), where measurements taken at four different flowrates all display highly random behaviour.

CONCLUSIONS

The original lower bound method of Gunn *et al.* (1992) was developed to analyse trends and discontinuities in downhole pressure and temperature measurements taken during well discharge. The current study has incorporated into the method a new fluid properties model. In the original method, the "lower bound" value of either NaCl or CO_2 was considered to occur when the other component was not present. Application of the revised method to a range of actual geothermal data has indicated that this assumption is generally acceptable.

The lower bound method has been revised to allow the calculation to be performed with respect to vapor fraction, as well as the original options, based on either wellhead enthalpy or flash point conditions. The flash point option is clearly the recommended approach to use, where a distinct flash point is delineated by gradient changes in the

downhole temperature profile. However, not all wells experience flashing within the wellbore, and in such cases the flash point option is therefore not applicable. Basing the calculation on wellhead enthalpy is often not satisfactory, because of the difficulty in obtaining a realistic enthalpy measurement, particularly in the presence of significant amounts of NaCl or CO_2. In such cases vapor fraction should be used instead, when a measured value is available.

Finally, the method has also been revised to allow a known, or base quantity, of NaCl or CO_2 to be specified. The usefulness of this revision has been demonstrated, as it has been shown to allow the consistency of downhole measurements to be assessed when *both* components are present in significant quantities. Previously this was not possible.

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