USING AIR-CAP TESTING TO MONITOR AND MEASURE GEOTHERMAL WELL CASING INTEGRITY

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ABSTRACT

Monitoring and managing well casing integrity is an important part of safely managing geothermal wells over their lifetime. A failure of casing integrity can lead to contamination of shallow aquifers and ultimately could even lead to an uncontrolled blowout.

Historical methods for monitoring well casing integrity involve go-devils, casing corrosion caliper logging, camera surveys and pressure-temperature-spinner (PTS) surveys. Go-devils, casing corrosion caliper logging and camera surveys can give indications of physical damage with no information on whether integrity is compromised, whilst pressure-temperature-spinner surveys can give results on well casing leaking but only if the conditions are suitable to indicate the loss of containment.

Over the last 2 years Contact Energy (Contact) has developed a new well casing integrity assessment method. This method involves applying compressed air to the well to depress the water level, pressurise up the casing and then monitoring for leakage.

Analysis of the results of these tests can categorically indicate the existence of any leak, the depths and nature of the leak and also provide indicative leak rates that can be used to guide better engineering risk assessment and decision making.

1. THE NEED TO DETERMINE WELL INTEGRITY

The most critical function of a well (defined as a series of casings, cement sheaths and formation strengths) is to contain pressures within the wellbore and isolate these pressures from weaker formations.

During the well design process, the maximum pressures the well can produce are calculated, and then casing shoe depths are selected to set into formations that can contain these pressures. This design process is explained in detail in NZS2403 – the Code of Practice for Deep Geothermal Wells.

Over the life of a well from birth until death, this casing system can suffer deterioration. Causes of such deterioration include:

- Casing connection failures;
- External and internal corrosion;
- Casing collapse and physical deformation from thermal loads;
- Drillpipe wear on the casing; and
- Casing deformation induced by formation compaction linked to subsidence.

Such deterioration can eventually lead to a loss of casing integrity. This allows communication between the reservoir and formations at the breach and the inside of the well. If the internal wellbore pressure exceeds the formation fracture or reservoir pressure outside of the breach, fluids can flow into the formation, and can continue to flow and migrate into these shallower formations.

Under more extreme cases, this flowrate can become high enough to escalate into an underground blowout. The ultimate extreme of an uncontrolled underground blowout is a charging up of shallow formations that ultimately leads to a surface blowout.

This is by no means a theoretical hazard. A Rotokawa well suffered a severe underground blowout in the 1990's, and in Wairakei in the 1960's a casing leak in WK26 led to a catastrophic surface blowout.

Figure 1: Rig sitting over WK26 with a blowout crater in the background that was the result of an untreated casing breach

As mandated in NZS2403:2015 (The Code), part of a well owners responsibilities is that geothermal wells must be monitored for such deterioration and kept in conditions that in general meets the service requirements specified in Well Design section of The Code.

Contact undertakes a range of activities to monitor and manage well integrity across our well fleet.

2. COMMON METHODS FOR MONITORING WELL INTEGRITY

2.1 Go-Devils

Go-devils are cylindrical drifts run through the well casing. Properly designed, they serve as go/no-go gauges. By running a range of sizes over time, they can help build up a picture of casing obstructions in the wellbore.

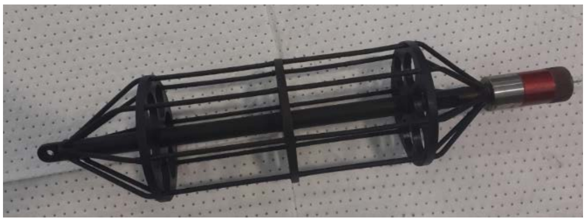

Figure 2: Typical Cage-Type Go-Devil

These obstructions can indicate casing damage. Repeated tagging or obstruction at a depth of a known casing connection would serve as a fair indication that the connection has failed. Downhole scale can also hold up a go-devil, although the depth of these tags can be more variable in depth over time as the scale builds up or is removed during well cleanouts.

WK092	GODEVIL	20/09/1996	10.00	
WK092	GODEVIL	20/08/1997	G2056	
WK092	GODEVIL	19/07/2010	G3400	
WK092	GODEVIL	25/08/2015	G3994	18.30
WK092	GODEVIL	22/12/2016	3246	18.30

Measurement Date	Measurement Time	Godevil Diameter [in]	Clear Depth [m]	Measurement Comment
25/08/2015	00:00:00	2.00	652.00	
25/08/2015	00:00:00	3.20	389.00	Previous tag depth 472m
25/08/2015	00:00:00	5.00	389.00	Tagged obstruction - similar to previous tag depth
25/08/2015	00:00:00	6.00	389.00	Tagged obstruction - similar to previous tag depth
25/08/2015	00:00:00	6.75	388.00	Tagged obstruction (scale?)

Figure 3. Representative Go-Devil Log Data

Thus go-devils can indicate that a problem may exist, but it can also give false-positives for well scale and even if casing damage exists, it will not provide any information on whether integrity has been lost.

2.2 Casing Caliper Logs

Casing caliper logs are mechanical and/or electronic logs run on e-line or slickline. These tools can measure the actual or relative internal diameter of the casing, and depending on the tool type, they can provide an indication of metal across a cross-section of the well casing and the internal diameter of the casing. This data is captured using mechanical arms running on the inside of the casing and/or sending out electromagnetic signals to measure the steel quantity and cross-section. This data can give indications of casing deformation, internal and external corrosion.

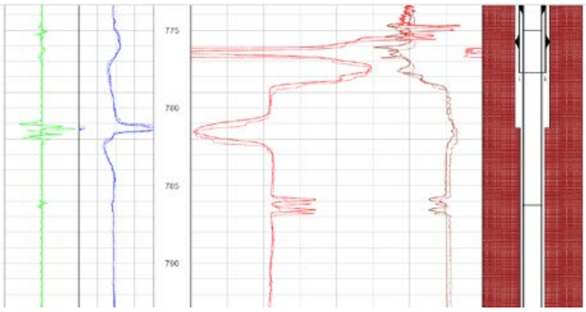

Figure 4: Example of Casing Caliper Log showing casing deformation at 781-782m. (plots from left to right, roughness, average caliper diameter, two plots indicating quantity of metal across the section, and well casing diagram)

As with Go-Devils, caliper data cannot give any categorical information on the existence of a loss of containment – it simply identifies damage and/or corrosion.

2.3 Downhole Cameras

Downhole cameras are e-line tools that can provide live and recorded video or photographic data of the internal bore of the well. Modern cameras have down and side view cameras, variable illumination, and can rotate the entire camera on command to capture 360deg of the wellbore surface.

Done properly, a camera survey can build up a much more accurate and nuanced picture of the state of the well production casing.

In some well states it may be possible to identify a loss of containment from camera images. In-flowing water might be witnessed, or 'heat shimmer' associated with a marked temperature increase in the tool can provide an indication of a breach.

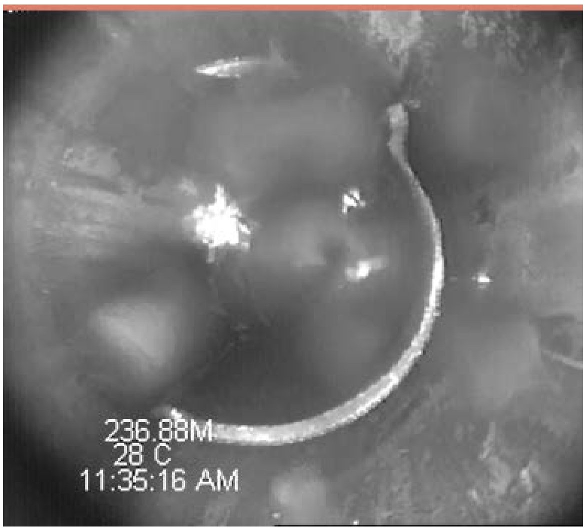

Figure 5: Example downhole camera survey image

Identification of a loss of containment via a camera survey relies on the correct well conditions (the same conditions noted below for Pressure-Temperature-Spinner logs), so a camera survey is not a reliable method to use.

Camera surveys also usually require well cooling which places stresses on the well through a heating cooling cycle.

2.4 Pressure-Temperature-Spinner Logs

A Pressure-Temperature-Spinner log is an e-line log that measures these three values (the spinner measures flowrate in the well) simultaneously inside the well.

PTS logs may be made under one of three well states – (a) shut in, (b) on bleed or (c) under production or injection. Each of these states can have significantly different well temperature, pressure and flow conditions.

Under the correct circumstances, PTS logs can indicate casing breaches. The breaches can be identified by changes in temperature, and/or fluid flowrates measured by the spinner. The 'correct circumstances' to be able to make this identification are:

- A differential pressure between the inside and outside of the well at the zone of breach;

- Sufficient flow into or out of any breach to produce enough influence on temperature or spinner results to be measureable and non-ambiguous.

2.5 Changes to Wellhead Pressure (WHP)

Although not an active measure, during well service life changes to the WHP can indicate changing downhole conditions.

An example would be a breach that allows a cold inflow into the well that cools down the deeper reservoir.

Such unexplained changes to WHP in service would normally spur the well owner to undertake further investigations.

As such, responding to changes to WHP is a reactive rather than a proactive strategy.

3. AIR CAP TESTING METHOD

Over the last 2 years, Contact Energy has trialled and adopted a simple yet effective way to assess and measure well integrity directly, being the Air Cap Test.

The Air Cap Test consists of applying compressed air to the well via the wellhead side valves while continually monitoring and logging the WHP.

The application of air to the top of the well has the effect of pushing the water level down the well. Wellbore pressure becomes a gaseous phase (air and gas if present) at the top of the well, and a liquid phase below – see Figure 6 below . Any two-phase steam will eventually condense once the air pressure exceeds the saturation pressure.

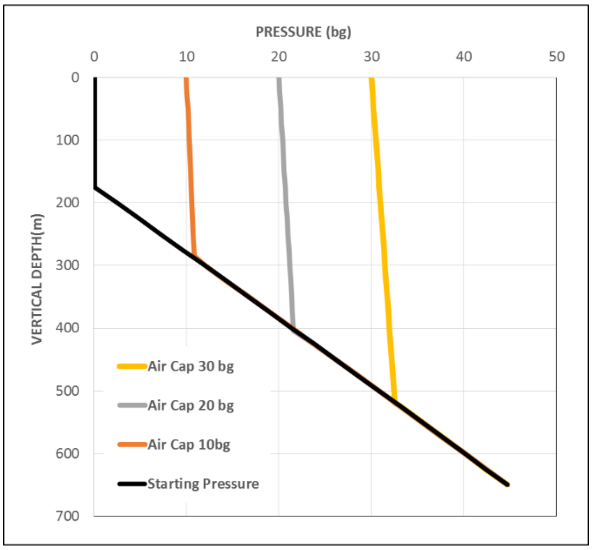

Figure 6: Well pressure profile under air cap conditions

3.1 Setting Upper and Lower Test Pressures

If we know the liquid pressure profile in the well, we can calculate the correlation between the applied WHP for the air cap and the air-water interface.

Good knowledge of the wells liquid pressure profile is important to be able to make this correlation if accurate depth data is required, although other logs can be used to understand the depths of any integrity breach.

For Contact's operations, a lower and upper bound for the applied WHP is selected.

The Lower Test Pressure is selected to be over the starting wellhead pressure. The degree of over-pressure depends on the expected state of the well casings.

The Upper Test Pressure is selected as being sufficient pressure to push the air/water interface below the deepest zone to be evaluated. There is also an engineering limit on this WHP – being either a) the Effective Containment Pressure (ECP) of the well casing or at any suspected breach (to avoid over-pressuring and risking the breakdown of formations) – or b) the surface wellhead pressure rating limitations.

The Air Cap Test developed by Contact is conducted in two stages: an initial pump-up stage followed by a long-term pressure monitoring stage.

It is important to note that the presence of a gas column in a well does not prove casing integrity. With an existing stable well gas cap, the well reservoir could be producing gas at the same rate that the well casing is leaking it, leading to a 'false-positive' of an apparent stable WHP. In this circumstance, our treatment would be to bleed off some of the gas pressure to a selected lower bound to disturb the system, followed by step increases to a determined upper bound.

3.2 Pump Up Stage

For the pump-up operation, the current procedure is to pump up the wellhead from the Lower Test Pressure to the Upper Test Pressure in a series of steps (Figure 7). For each step, WHP pressure is increased by pumping in air, with the air being turned off once the intended step WHP is reached. In this shut-in state, the WHP is logged for a period of 10-15 min per stage to monitor for changes, and the process is repeated for the next step WHP

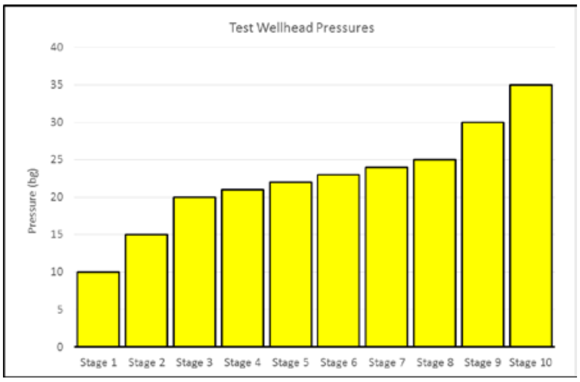

Figure 7: Example WHP steps for testing

Because WHP correlates with the air/water interface depth, selection of these step pressures can be used to test the integrity of the well casing in sections, so that the depth of a leak can be identified more clearly.

STAGE	WHP	Air / Water Interface Depth
Stage 1	10	284
Stage 2	15	340
Stage 3	20	395
Stage 4	21	407
Stage 5	22	418
Stage 6	23	429
Stage 7	24	440
Stage 8	25	451
Stage 9	30	507
Stage 10	35	564

Table 1: Correlation between applied WHP and Air/Water Interface

From the above example we can correlate the air/water interface depths using the known well liquid pressure. Finer resolution on test pressures (seen above in Stages 3-8) can give finer resolution on the air/water interface, and therefore the zone being tested.

3.3 Long Term Pressure Monitoring Stage

Once the final step pressure has been achieved, the Air Cap Test moves to a long term pressure test (for at least 4 hours, often overnight or even extending over multiple days). This provides a good indication of changes to any leak rates compared to the air/water interface which serves as a second set of data to compare to the data collected during the pump-up stage. Other well pressure transients and activity can be seen in this dataset as well. It can also indicate the final pressure that the well stabilises to.

3.4 Review and Interpretation of the Collected Data

The method of identifying leaks is a loss of pressure that cannot be explained away by surface equipment leakage. The lower test pressures can be used to verify surface air losses and this can be used to better calibrate the data set for deeper tests. The leak rates we are interested in identifying downhole are higher than those expected at surface so minor surface losses are not considered a problem.

To get air leakage, the wellbore pressure must exceed the formation fluid pressure behind the casing, and a relative increase in this internal wellbore pressure should result in an increased air loss rate.

The pressure data conveys the following information: ;

- the existence of any downhole leaks;
- the depth range of downhole leaks, and identification of depth range where well casing maintains integrity;
- a comparison of leak rate compared to applied pressure;
- extrapolating air loss rates to an expected fluid loss rate can be used for risk assessment and decision-making; and
- holding a base-line dataset that can be compared over time to identify deteriorating well conditions.

4. EXAMPLE OF AIRCAP TEST DATA

4.1Well data and aircap results

Contact has a well, here referred to as CW-99, that has three zones that may have compromised integrity.

These zones were identified via a Casing Caliper Log. The log data is shown in Figure 8. As this caliper log can make no assessment on integrity, an Air Cap Test was undertaken to determine if any of these zones had a loss of integrity.

The expected WHP to get the air/water interface to these depths (approximately) is;

Defect	Location	Hydrostatic Pressure at Defect	Equivalent WHP
1	Stage Collar at 285m	23.2 bg	22.7 bg
2	Mid Joint Corrosion at 326m	26.6 bg	25.9 bg
3	Mid Joint Corrosion at 341m	27.8 bg	27.0 bg

Table 2: Equivalent WHP to test Casing Anomalies in well CW-99

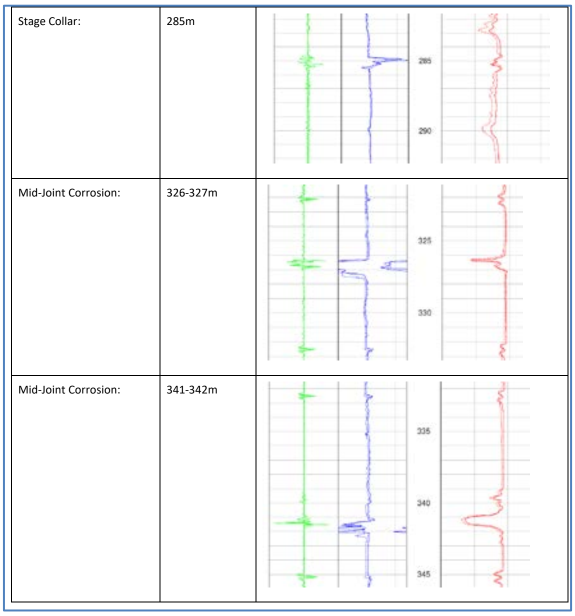

Figure 8: Casing Anomalies in well CW-99

The WHP plot for the entire Air Cap Test on well CW-99 is shown below.

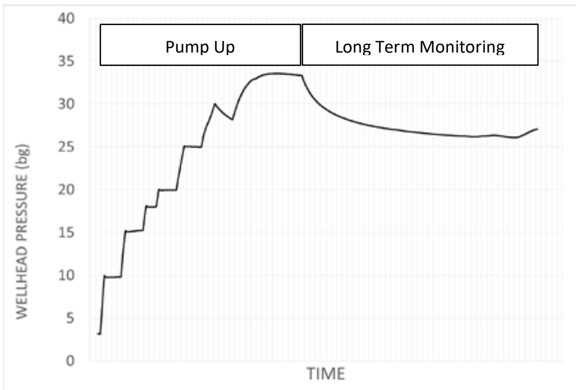

Figure 9: WHP data from aircap test on well CW-99

4.2 Analysis of Leaking Zones

The Air Cap Test data shows that the well maintained integrity (no leak-off at pressure hole points) until the pressure exceeds 25bg, above which the pressure reclines, indicating leakage. The final test pressure of 35bg was not achieved; the observed plateau in pressure is only sustained with continuous air input to the well. In this state, the leakage rate equals the inlet air flowrate – measured to be 315 standard cubic feet per minute (scfm). The peak WHP in this state is 33.6 bg.

Upon shutting-in the air flow, the pressure drops over time as the air leaks off downhole until the WHP stabilises between 25-27 bg.

Note that at the end of the long pressure hold period, the WHP starts to increase. This is a feature of this wells behaviour rather than the aircap test and can be ignored.

Looking closely at the data (Figure 10), we see leak-off starting at a WHP of 26.3bg – indicated by the change in slope at this point. This is near to the expected WHP required to leak into the mid-joint corrosion at 326m. Thus this zone at 326m has lost integrity.

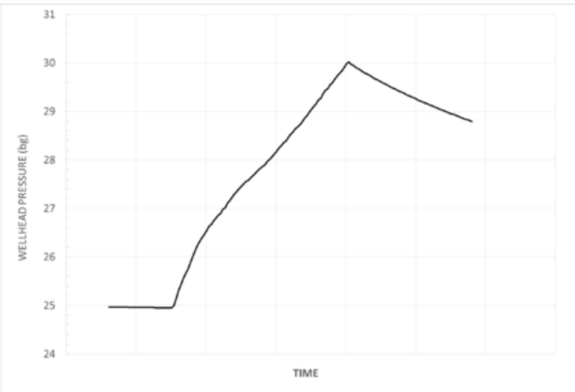

Figure 10: Pressure Plot at Start of Leak-Off

From the Long Term Pressure Monitoring phase, we plotted WHP leak rate (bg/min) against actual WHP and obtained the following chart.

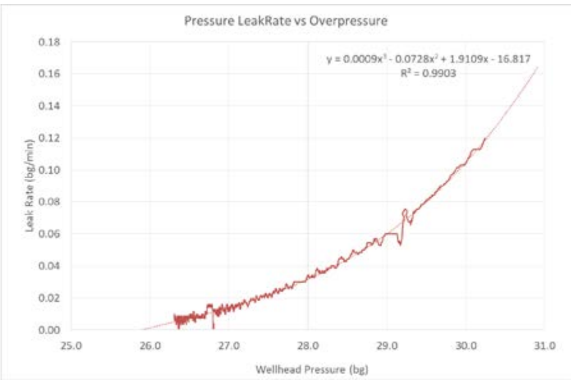

Figure 11: Leak Rate vs WHP for Long Term Leak off Test

Apart from some minor anomalous data at 26.8 bg and at 29.2 bg, the overall trend strongly indicates a steady bleed off to a final stable pressure of 25.9bg, and does not show any change in leak rate that would indicate additional leakage around 27.0 bg, which indicates that there is no additional leakage at the bottom zone at 341m.

These test results indicate that:

- there is no leak-off seen at 285m (c.23bg);
- there is confirmed leak-off at 326m (c.26 bg); and
- there is no identified additional leak off at 341m (c.27 bg).

4.3 Analysis of Leak Rate

The leak rate data obtained above represents air exiting the casing breach. In service, these zones are submerged and we are more interested in the volumetric leak rate this zone may see with liquid water.

We can use the test data obtained to approximate a liquid leak rate for the well. The data we have used for this is the air loss rate found at the WHP peak where the airflow in is equal to the air loss rate out.

The airflow at this balance point is 315 scfm as measured at the air compressor, and the differential 'drive' pressure to achieve this air loss rate is (33.6 – 25.9 =) 7.7 bg.

At elevated pressures the 315 scfm leak rate equals an actual loss rate of about 10 actual (compressed) cu ft/min or about 300 actual litres per minute of air, at a drive pressure of 7.7 bg.

We can apply the following equation to forecast water loss rate from the calculated air loss rate.

$$\frac{Q_a}{Q_w} = \frac{\eta_w}{2\eta_a} \times \frac{P_1 + P_2}{P_2}$$

Qw = volumetric flowrate with water	(litres per min)
Qa = volumetric flowrate with air	(litres per min)
ηw = viscosity of water	(Pa-s)
ηa = viscosity of air	(Pa-s)
P1 = Higher Pressure (leaking from)	(bg)
P2 = Lower Pressure (leaking into)	(bg)

Equation 1: Correlation Between Gas Leakage and Liquid Leakage

Using Equation 1, the equivalent water leak rate can be calculated to be approximately 50 litres per minute at 7.7 bg or about 0.4 tonnes per hour per bar.

It should be noted that this equation (Equation 1) is imperfect and has been used to get approximate values. Future work is required to obtain an improved correlation between gas leak rates and water leak rates.

4.4 Conclusions from Air Cap Test data

This Air Cap Test identified (i) zones having a loss of containment, and (ii) indications of the equivalent water loss rate of this zone.

Engineering decision making and risk assessments can now be made using significantly better data.

5. COMPARISON TO EXISTING METHODS

The Air Cap Test Method offers a number of other benefits besides better quality integrity data:

- It doesn't require downhole tools, with subsequent removal of risks of these tools becoming stuck or lost in hole;
- It doesn't require a clear through-bore as is required for logging tools;
- Casing testing can be undertaken below any well obstruction, rather than just down to the depth that logging tools will not pass any further; and
- It provides a direct measurement for the true metric of well integrity management - leaking casing - rather than just a proxy of casing damage.

Imperfections in the Method include:

- Testing requires the well to be shut in for the duration of the test. This is typical for most logs; and
- conducting the test imparts a (generally mild) thermal cycle to the well, where steam may be displaced by warm air.

Relative to the previous methods discussed, the Air Cap Test Method is less costly and time consuming, based on experience to date (Figure 12);

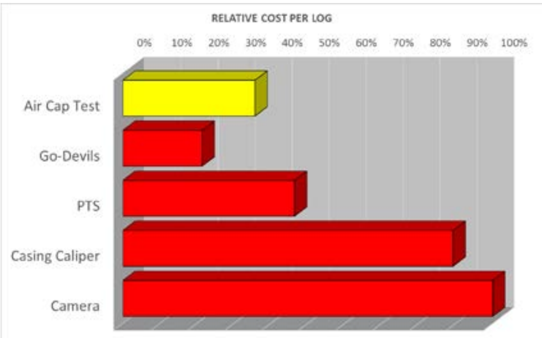

Figure 12: Relative cost of Air Cap Compared to Alternate Methods

6. CONCLUSION

The Air Cap Test provides a significantly improved method for monitoring and measuring actual well integrity.

Whilst existing methods are in place to monitor the well casings for damage and deformation, and these methods are good for monitoring the well casing over time and being able to predict future containment issues, none of them can categorically and directly measure actual leakage.

The air-cap method currently used by Contact provides information on the depth of any loss of containment. This assessment can be extended over multiple zones and, beyond the first zone encountered. This assessment can also be done below any of casing deformation or damage where logging tools may not pass.

In addition to identification and depth assessment for any breach, the method also provides good information on the leak rate. With this data, the Engineer can make the best decisions based on reliable data rather than rough numbers and conjecture.

Repeatability of testing can provide base-case tracking to monitor for any deterioration over time.

The test itself is cost-effective and does not have a risk of lost or stuck tools that would be seen with an equivalent wireline log.