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Effective Containment Pressure – A Concept for Casing Shoe Strength Assessment and a Method for Forecasting It

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ABSTRACT

The method of selecting casing shoe depths has historically been based on a number of concepts, including Fracture Gradient prediction, Overburden Pressure assessment and Kick Tolerance allowance. These methods do not take into account the fractured, permeable and faulted nature of geothermal reservoirs, and thus in some instances can be a poor predictive model for casing design.

The most recent iteration of the New Zealand Code for Deep Geothermal Wells (NZS2403:2015) introduced more geothermally appropriate concept of Effective Containment Pressure (ECP) which can better account for the vagaries seen in geothermal reservoirs.

In well operations and planning, Contact Energy adopted a method for assessing ECP to use as a forecasting and predictive tool for both well construction and setting operating limits on existing wells. Applying this method has both reduced asset risk while providing a quantitative forecasting tool for well design.

1. INTRODUCTION

For well construction, the selection of casing shoe depths is an important part of any well design. Casings must be set to depths where the formations can contain the pressures exerted on them by the open-hole sections below the shoe.

A failure to set casing shoe depths correctly can lead to loss of containment at the casing shoe, which in turn can lead to contamination of shallower aquifers, uncontrolled flow of fluids into these formations, and, in the worst cases, a breach of geothermal fluids back to surface leading to a blowout. This is far from a purely academic exercise and there are numerous examples of this sort of loss of containment across the world geothermal community.

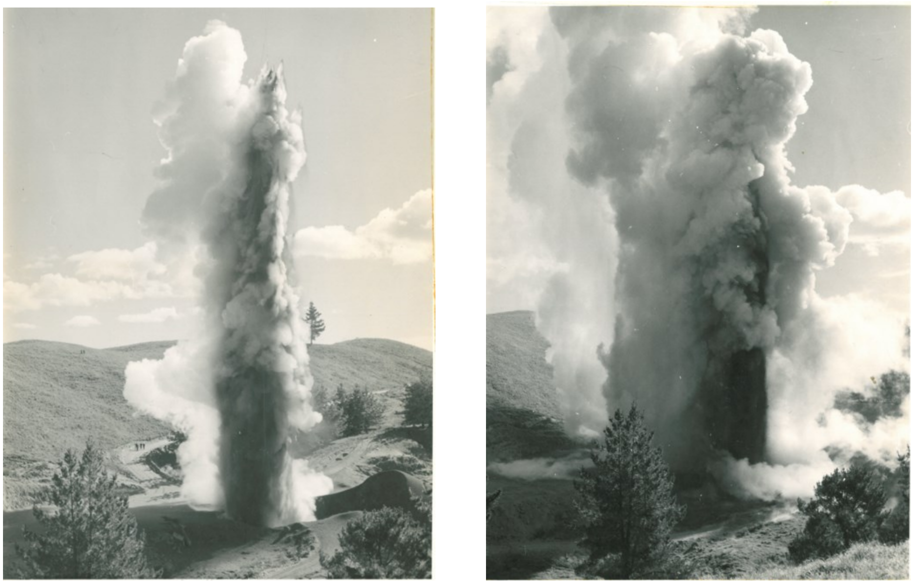

Figure 1: Blowout on WK204 at Wairakei in the 1960's. The well was drilled past the limit of the casing shoe to contain pressure. Quench water was lost to the well, the well came under pressure, and steam broke through to surface.

Too conservative an approach to casing shoe selection, whilst avoiding risk, can have a significant effect on the overall well cost in terms of materials and drilling days. For a well designer, having a good measure of the pressure containment ability of formations is of paramount importance to design the well casing points safely without excess cost.

Beyond well control considerations during drilling, for completed reinjection wells this understanding of formation containment is required in order to calculate the safe maximum wellhead pressure for reinjection. This, too, has cost implications as we'd like to use the well to dispose of as much geothermal fluid as possible, but the downside for excessive injection pressure is a potential loss of containment.

2. METHODS FOR CASING DEPTH SELECTION

2.1 NZ Code Method

From the NZ Code of Practice, the well designer must assess the maximum expected pressure in each section, whether caused by gas, steam or injection pressures. The assessment of the maximum pressure is found from the temperature and formation pressure of the section, and the injection pressure is based on an operational requirement or decision by the well owner.

The selection of casing shoe depths for each section must ensure that each casing shoe can contain the maximum pressure expected in the hole below it. This assessment of the formation strength is subject to a number of different assessment methods described in Section 3.

2.2 Alternate Methods for Casing Shoe Depth Selection

Engineers have historically used a number of alternate methods for selecting casing shoe depths. Some are summarised below, although this is not an endorsement for their use. Such design methods cannot be tailored to each set of pressure, temperature and geology expected for each individual well, and are neither optimised, demonstrably safe, or in compliance with the NZ Code of Practice.

2.2.1 Geometric Progression

From a known conductor shoe depth and desired casing shoe depths, the intermediate casing shoe depths are selected so the shoe depths form a 'geometric progression' –the ratio of the last casing depth to the next casing depth remains constant.

2.2.2 Setting into 'Marker Formations'

Some or all casing shoes are planned to set into known or expected 'marker formations' that are assessed as being suitably competent for the casing shoe.

2.2.3 'Standard Design'

One set of casing shoe depths is used for all wells, regardless of pressure, temperature and formations expected.

2.2.4 'Kick Tolerance' Design

The concept of kick tolerance - borrowed from oil and gas - relies on the premise that the below-ground formations are over-pressured with respect to the drilling fluid column, and any permeability encountered will lead to gas entering the wellbore and displacing wellbore fluids. Kick Tolerance selects a maximum design volume of wellbore fluids displacement by gas influx on hole bottom (say a 20 bbl kick) and then calculates how much pressure this influx will produce at the casing shoe once it has migrated and expanded back to casing shoe depth.

3. METHODS FOR ASSESSING FORMATION STRENGTHS

There are a number of methods currently used by well designers to assess the strength of formations.

3.1 Overburden Pressure

The now-superseded 1991 New Zealand Code of Practice for Geothermal Drilling (NZS2403:1991) discussed using the 'Overburden' pressure of formations as the measure of formation strength and containment ability. The Overburden pressure is defined as the sum total of the weight of all overlying formations and fluids, turned into a vertical stress. Essentially the earlier Code was defining a failure pressure as that which will create a horizontal fracture and 'lift' the above formations.

The typical density of overbearing formations gives a pressure gradient of about 2.2 – 2.6 SG, which we will see later, is far too high, and leads to fewer casing strings and a risk of loss of containment.

The fundamental problem with this assessment method is that unless specific geomechanical horizontal stresses exist, the rocks do not fracture in a horizontal orientation but rather in sub-vertical planes, perpendicular to the direction of the least (confining) stress. This fracture pressure is typically significantly less than the vertical overburden pressure.

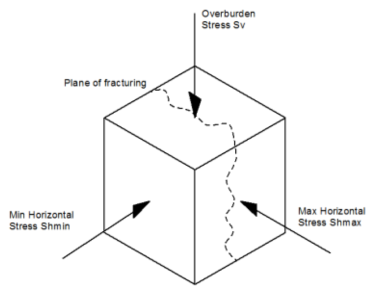

Figure 2: Formations typically fracture in sub-vertical planes, perpendicular to vector of least horizontal stress.

Fortunately, there is a method to derive the likely fracture pressure based on the vertical stress, using the rocks Poisson's Ratio to derive the horizontal stress from the known vertical stress. This is the Eaton Formula.

$$P_{frac} = P_p + \frac{\mu}{1-\mu}(S_v - P_p)$$

P_{frac} = *Pressure required to fracture the formation in the plane of least horizontal stress*
P_p = *Pore pressure in the formations being exposed to pressure*
μ = *Poisson's ratio (ratio of horizontal deformation to vertical deformation)*
S_v = *Overburden pressure*

Using representative values for this equation as gradients (S_v = 2.4 SG, P_p = 0.9 SG, μ = 0.25) gives a predicted fracture gradient of 1.40 SG, which is over 40% less than the 2.40 SG predicted by the Overburden Stress method. As seen later, the Eaton Formula provides estimates that are close to actual values measured in the field.

3.2 Direct Leak Off Test Measurements

A Formation Leak Off Test (FLOT) directly measures the pressure required to induce fracturing in a sample of formation. This test is undertaken after each casing has been cemented into place – the shoe and rat-hole cement is drilled out, and 3m of new formation is drilled. The hole is cleaned of cuttings and fluid is slowly injected at surface to increase the pressure in the well. This continues until a 'leak off' of fluids is seen, indicating the formation is starting to fracture. This leak-off surface pressure is added to the hydrostatic pressure of the fluid column to give a direct measurement of the pressure at the formation interface that is associated with formation fracturing.

This is a direct measure of the fracture pressure for the well being drilled, which can be used as a design value for the ongoing well construction.

Field	Well	Date	Depth (mTVDGL)	Leak-Off Pressure (psi)	Fluid Used	Fluid Density (sg)	Formation	Absolute pressure at FLOT point (bg)	FLOT Frac Gradient (sg)
Ohaaki	BR61	30-Jul-07	353	870	water	1.00	Ohaaki Rhyolite	94.6	2.73
Tauhara	TH17	20-Feb-09	38	88	water	1.00	Wairakei Breccia	9.8	2.63
Wairakei	WK245	9-Jul-05	117	220	water	1.00	Crystal Tuff	26.7	2.32
Wairakei	WK246	16-Aug-05	110	0	water	1.00	Crystal Tuff	10.8	1.00
Ohaaki	BR51	11-Nov-05	575	380	water	1.00	Broadland Dacite	82.6	1.46
Wairakei	WK247	29-May-06	249	265	water	1.00	Huka Falls Formation	42.7	1.75
Wairakei	WK268	1-Aug-12	226	221	water	1.00	Huka Falls Formation	37.4	1.69

Figure 3: Sample of FLOT Database Data.

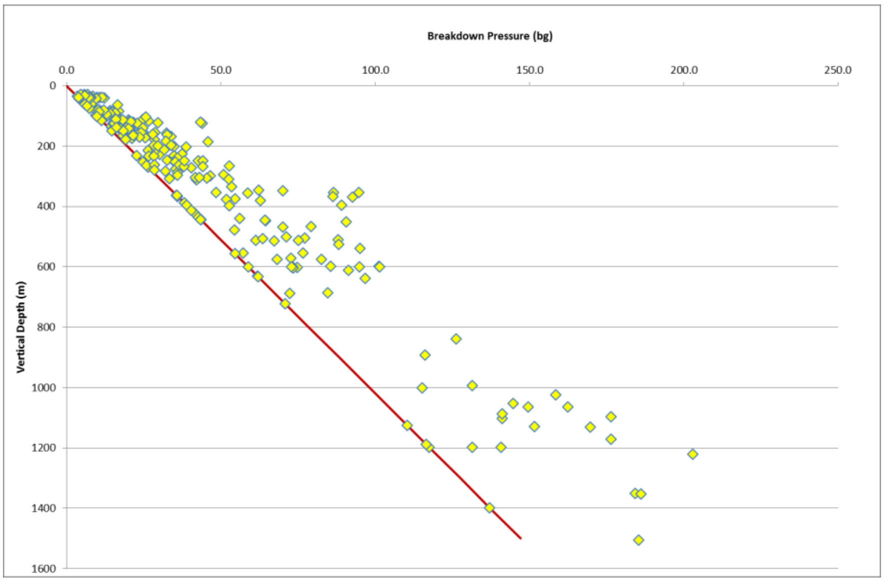

Figure 4: Collected Set of FLOT Data Points.

3.3 Determining Fracture Gradient from FLOT Data

Single point-of-fracture pressures are not particularly useable for anything other than the well and formation they were taken on. Fortunately, for a homogeneous impermeable formation, the fracture pressure typically increases linearly with depth and we can turn the single point test into a Fracture Gradient (measured in units of density) that can provide a fair forecast of the fracture pressure in the same formation at different depths.

We can also collate these Fracture Gradient measurements, by formation, depths and field, and use statistical correlations to improve predictions. Over time a large database can be assembled to improve fracture estimates.

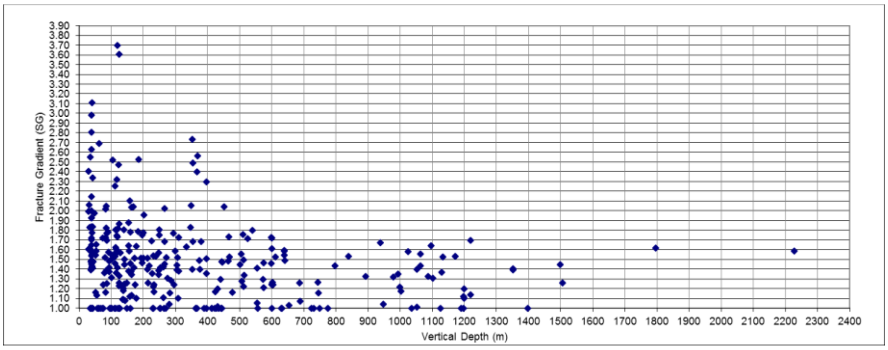

Figure 5: FLOT Data Tests converted to Fracture Gradient.

Collection of such data represents a non-trivial financial investment, however the quantitative data it provides for well design and operations makes this a valuable resource and worth the investment by optimising casing design and providing prediction tools for the maximum safe operating pressures for a well.

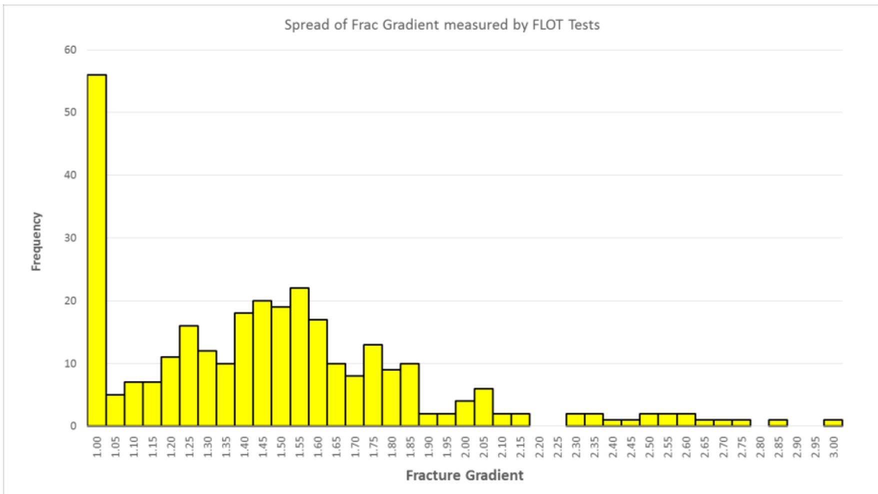

Figure 6: Histogram spread of obtained Fracture Gradients.

FLOT tests having losses at the start of the test have been assigned a Frac Gradient of 1.00

3.4 'Field Values' for Formation Strength

A simplistic first-pass method for using the database of Fracture Gradient data into a useable forecasting and design tool is to allocate 'field values' for the average Fracture Gradient for a field. This is simply taking the average or median value of all tests for a field, then allocating that as the field Fracture Gradient for all formations and casing shoes.

There are clear differences in the Fracture Gradient between even adjacent fields. For instance, one of Contact Energy's geothermal fields has an average of 1.20 SG, while another field has an average of 1.40 SG.

However, taking a single point estimate for the fracture gradient is not wholly satisfactory. It does not address any detail on the relative Fracture Gradient compared to depth, and cannot be tailored for any one well design, to the detail of known formation sections.

Ultimately, assessing wells in terms of casing shoe fracturing is a flawed concept, as discussed below.

4. THE CONCEPT OF EFFECTIVE CONTAINMENT PRESSURE

4.1 The Flaw with the Concept of Leak off Pressure and Fracture Gradients

Leak off Test Pressures and Fracture Gradient values do not account for the properties of fractured and permeable geothermal formations. Figures 7 and 8, below, shows the percentages of FLOT tests that resulted in a positive 'good' test, and those that had losses immediately outside of the casing shoe. In these tests, the 3m section of formation tested was already permeable and the results do not reflect formation fracture strengths.

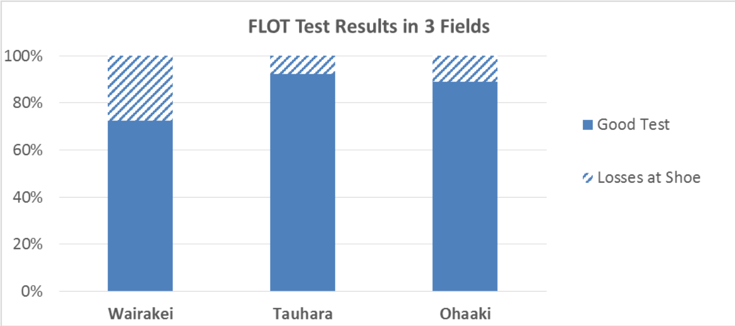

Figure 7: FLOT test results from three well fields.

If we get a positive result from a FLOT from any casing shoe, we have a direct value for the pressure required to initiate breakdown at the shoe – we can use this data for the rest of the well section. However, if we get losses directly out of the shoe, following the logic that we use for the above assessment, then the shoe cannot hold any pressure, and we cannot safely drill any further in the well. This is patently absurd. We need to reconsider our well design philosophy to address the effect of permeable formations. An example of the change to our thinking can best be demonstrated as below.

FLOT results can be tightly tied to formations.

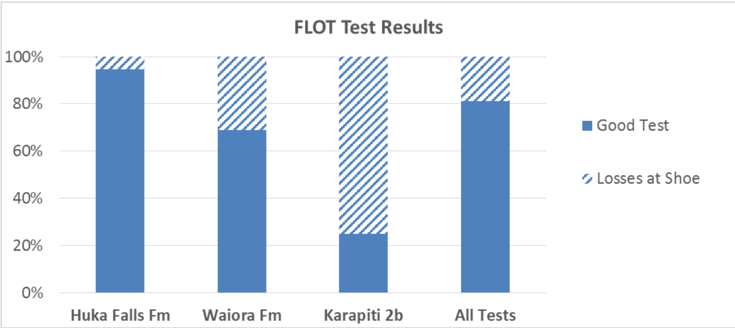

Figure 8: Effect of formations on FLOT results.

4.2 The Philosophy Behind Effective Containment Pressure

The best way to demonstrate the difference between Leak Off Pressure and Effective Containment Pressure can be shown by the situation below, describing two casing shoe depth options for a well.

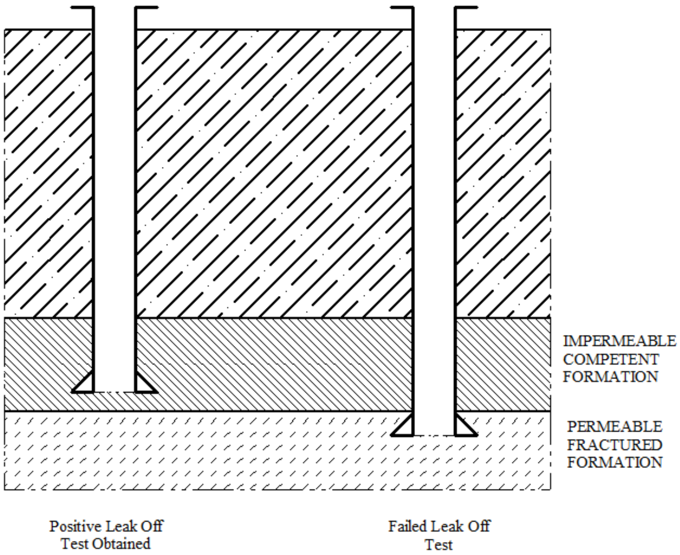

Figure 9: Drilling past a competent formation does not remove its influence on pressure containment.

In the example above, the shallower casing would give a positive pressure test, while the deeper casing would not – yet both are cased through the competent formation, and this formation remains as a barrier to well pressure reaching shallower formations.

The aim of well pressure integrity cannot be prevention of pressure leak-off at the casing shoe (because as above, this may be impractical or impossible) but must be the prevention of pressure migrating back to a place where it can create problems.

For well design with a high possibility of permeable zones, we need to consider the sum total of pressure containment contributions of all formations between the casing shoe and surface. The Code refers to this as the Effective Containment Pressure (ECP). The definition in the Code is;

"*Pressure that a formation at any depth can contain so that fluid will not migrate to the surface or other shallow aquifers either directly or through faults or nearby wells*"

ECP is not the same as Fracture Gradient pressure, as it relates to overall containment, and not avoiding fracturing at the shoe.

5. A METHOD FOR FORECASTING ECP

The Code describes the concept of ECP, it does not provide a method for assessing it.

Contact Energy's method treats the geological stratigraphy like a layer cake and assess the physical properties and strength of each formation in turn. We then subdivide each formation into competent and permeable (fractured) sections.

The pressure gradient within the fractured sections is governed by the hydrostatic pressure in the fractures.

We consider that the gradient of pressure containment within the competent section is the formation's Fracture Gradient, but assessed from the top of that formation rather than from back to surface. Thus, to assess a well, we need to find and use four values for each formation section;

- The vertical thickness of the formation unit (m)
- The average competent Fracture Gradient (SG)
- The degree of competency (%)
- The fluid density in the fractures (SG)

Our database of FLOT results became instrumental in carrying out this assessment. As an example, for one formation unit;

Formation	Absolute pressure at FLOT point (bg)	FLOT Frac Gradient (sg)
Karapiti 2a Rhyolite	74.7	1.26
Karapiti 2a Rhyolite	54.6	1.49
Karapiti 2a Rhyolite	42.0	1.38
Karapiti 2a Rhyolite	35.4	1.31
Karapiti 2a Rhyolite	73.3	1.25
Karapiti 2a Rhyolite	43.5	1.00
Karapiti 2a Rhyolite	40.5	1.00
Karapiti 2a Rhyolite	22.5	1.00
Karapiti 2a Rhyolite	43.6	1.00
Karapiti 2a Rhyolite	41.9	1.00

Note that failed leak off tests (losses at the shoe) are represented by a Frac Gradient of 1.00.

The above dataset provides 10 test samples. Of these we can make the following assessment of the formation:

- The competent fracture gradient is 1.34 SG based on the average of the five good tests;
- The formation competency is 50% based on the proportion of failed tests; and
- The fluid density at 200 DegC (average temperature in this formation) is 0.86 SG (from steam tables)

Along with the known or forecast formation vertical thickness we have the four formation factors required to undertake the assessment.

Mathematically, for a column of n geological formations, the ECP can be determined to be;

$$ECP = 0.0981 \times \sum_{i=1}^{n} L_i.(c_i.FG_i + (1 - c_i).\rho_{f_i})$$

ECP	=	*Effective Containment Pressure at bottom of Section n*	*(barg)*
L_i	=	*Vertical Length of Formation Section i*	*(m)*
c_i	=	*Degree of competency of formation i*	*(%)*
FG_i	=	*Competent Fracture Gradient of Formation i*	*(SG)*
ρ_{fi}	=	*Fluid Density in Fractures in formation i*	*(SG)*

For a representative well section, the calculated ECP would be as shown in Figure 10.

SECTION	Frac Grad	Percent Competent	Formation Fluid Density	Effective Section Frac Grad	Vertical Top	Vertical Bottom	Vertical Height	Section Pressure	Press. at Bottom
	sg	%		sg	m	m	m	bg	bg
Surface	-				-	-	-	-	-
Aranas Formation	1.45	65%	0.50	1.12	-	95	95	10.4	10.4
Wilson Massif	1.35	90%	0.98	1.31	95	280	185	23.8	34.2
Norrie Intrusion	1.25	20%	0.96	1.02	280	460	180	18.0	52.2
Lock Rhyolite	1.70	90%	0.95	1.63	460	750	290	46.2	98.4
				-	750		-	-	98.4
				-	-		-	-	98.4
				-	-		-	-	98.4
				-	-		-	-	98.4
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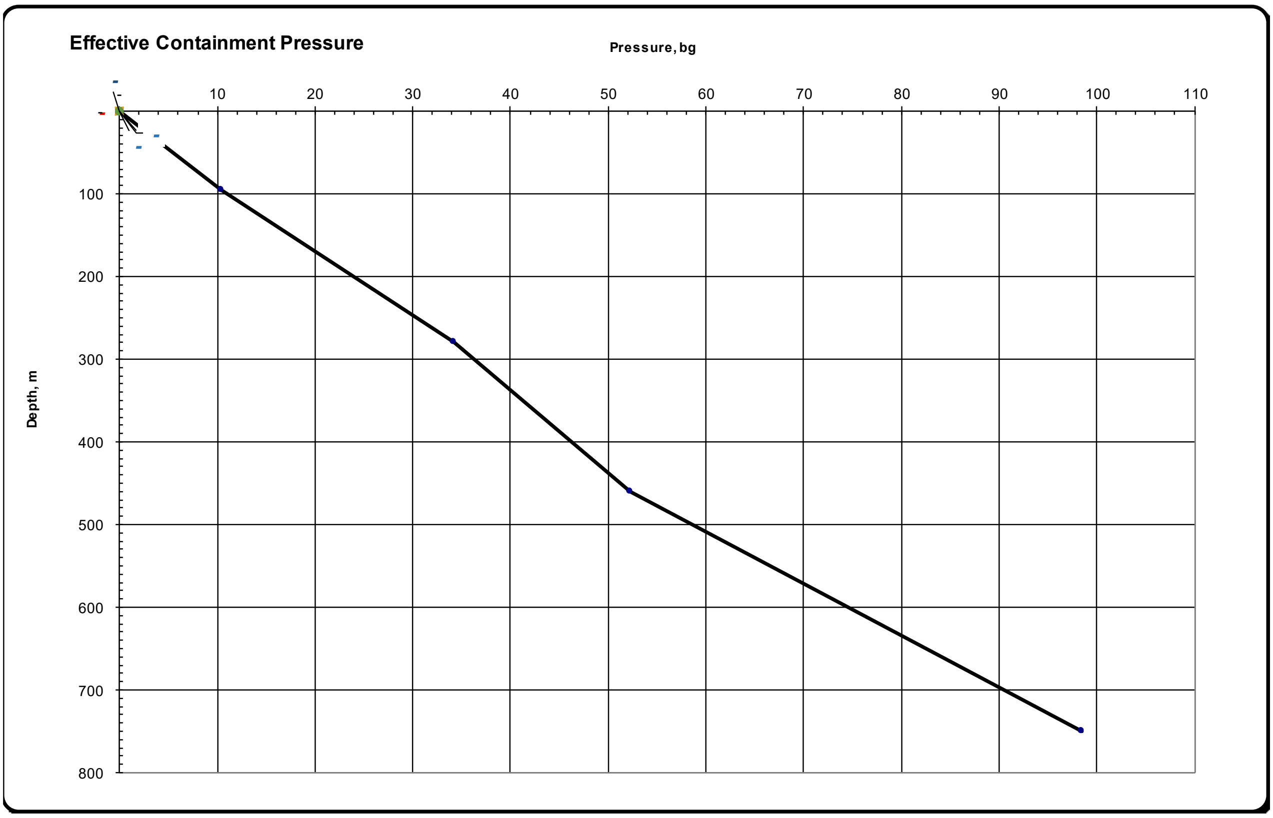

Figure 10: Example ECP Forecast.

6. CONCLUSION

The concept of Effective Containment Pressure (ECP) represents a new way of considering pressure containment in geothermal wells, and is intended to take into consideration the permeable and fractured nature of many geothermal formations. It is not the same as a Fracture Gradient analysis.

We have constructed a method for assessing the ECP for individual wells, based on knowledge or assessment of each formations strength, degree of permeability and formation fluid density.

This method can be tailored to each wells geological column and is well suited as a casing design tool, or for assessing the maximum operational pressures for existing wells.