FAILURE MODE ANALYSES FOR CASING AND LINERS IN GEOTHERMAL PRODUCTION WELLS

Jonathan D. Leaver

Ministry of Works and Development,
Wairakei, New Zealand.

ABSTRACT

A method is presented for determining casing shoe depths by probabilistic criteria. Analyses are performed and equations developed for buckling of an uncemented length of casing and stresses at wellheads. Helical buckling of liners is reviewed.

INTRODUCTION

Design of casing and tubing in the oil industry is well documented. However the design of geothermal casing strings and liners is more complex due to the greater temperature variations experienced in-service and the more corrosive nature of geothermal fluids.

Existing design methods cover various aspects of casing design but the mechanisms involved in many aspects such as blowouts are not well understood while other important factors such as the effects of random hole deviation and helical buckling of liners are not usually taken into account.

BLOWOUT PREVENTION

Blowouts occur when pressurised fluid moves through cracks and fissures in friable or fractured formations causing widening of the flow path until eventually a surface eruption and/or a large uncontrolled fluid flow at the surface occurs. Present design methods for liquid dominated reservoirs (Dench 1970, Karlsson 1978) ensure that the maximum pressure in any uncased section of well does not exceed the formation pressure above that point. The casing shoe depth is determined by equating the maximum pressure at the casing shoe which will occur during drilling with the formation pressure above the shoe. For deep wells the above mentioned methods may prove impractical as more than the usual practical limit of 4 casings may be required.

Consider a homogeneous and uniformly fractured formation in which the portion of the formation near the well susceptible to a blowout is considered to be 45 degree cone. (fig 1).

The risk of blowout is assumed to depend on the probability of finding fluid and that fluid in turn finding a path to the surface. Consider that:

1. The probability of finding fluid is proportional to the drilled depth.

2. The path to the surface is proportional to the cone base area at the surface, inversely proportional to the path length or cased depth and proportional to the ratio of the pressure differential at the casing shoe to the formation pressure.

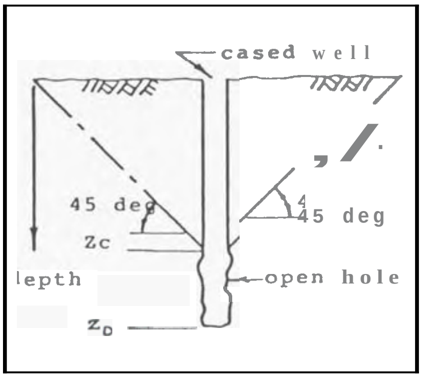


Fig. 1 Defined Volume for Blowouts

Then

risk $\propto$ surface cone area/(path length)
$\propto$ differential shoe pressure/formation pressure
$\propto$ fluid availability

hence

risk $\propto Zc^2/Zc \ast (Zd-Zc)/Zc \ast Zd$
$\propto (Zd-Zc)\,Zd$

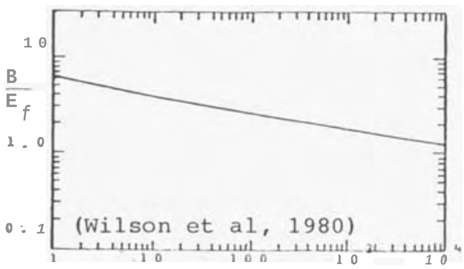
or to equalise the blowout risk

(Zd-Zc)Zd prod. = (Zd-Zc)Zd anchor

(Zd-Zc)Zd anchor = (Zd-Zc)Zd interm.

CASING BUCKLING

Except for intentionally deviated wells current design methods usually neglect buckling due to inadequate lateral support and bending due to unintentional well deviation. Design should allow for random hole deviation and elastic buckling of a nominal length of uncemented casing. The performance of casing under axial loads depends on the ability of the formation to provide the lateral restraint required to prevent buckling.



Stiffness Ratio: $64EI/(\pi D^4 Ef)$

Fig. 2 Variation in Lateral Support Coefficient with Stiffness Ratio.

The following correlation closely approximates figure 2.

$LOG(B/Ef) = 1.11-0.25*LOG(64EI/\pi D^4 Ef)$

now $Pc = 2\sqrt{(EIB)}$ ----1 (Wilson et al, 1980)

substituting for B from eq.1 gives the minimum formation modulus required to prevent buckling:

$$Ef = 0.078 \sqrt[5]{(P^2/D)^4 * 1/(EI)^3}$$

A length of uncemented casing may be modelled as a pin jointed axially restrained column (fig. 3).

Let the applied compressive load be P. The net compressive load is P-P'. Using the Rayleigh-Ritz method of analysis (Timoshenko and Gere, 1972) gives the potential energy of the system:

$$P.E. = U-(P-P')h \text{ ----------2}$$

Now from geometrical considerations

$$h = 0.5\int_0^L (dV/dX)^2 dX$$

assuning $v = e*\sin(\pi X/L)$ for $0 \leq x \leq L$

then $h = e^2 \pi^2/(4L)$

Now $U = EI/2 \int_0^L (d^2v/dX^2)^2 dX$

and $d^2v/dX^2 = e\,\pi^2/L^2 \sin \pi X/L$

integrating gives:

$$U = EIe^2 \pi^4/(4L^3)$$

after substituting for h,U in eq.2 the minimum buckling load is found by finding the minimum value of P.E. with respect to 'e'. Substitute $P' = EAh/L$ from Hooke's Law and finding $d(P.E.)/de$ gives:

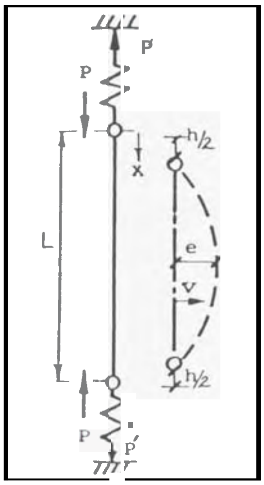


Fig. 3 Analogy for Pin Jointed Axially Restrained Column

$$d(P.E.)/de = \pi^2 e/(2L) * (\pi^2 EI/L^2 + EAe^2\pi^2/(2L^2) - P)$$

$$= 0 \quad \text{for minimum}$$

hence for non-trivial solution

$$P = \pi^2 EI/L^2 + EAe^2 \pi^2/(2L^2)$$

Euler buckling — additional term due end axial restraint

Consider the bending stress in the above column with an initial reentrant deviation of θ deg. in length L (fig. 4)

Now $w_{max} = M_oL/(8EI)$

$\theta = M_oL/2EI$

$w_{max} = L\theta/4$

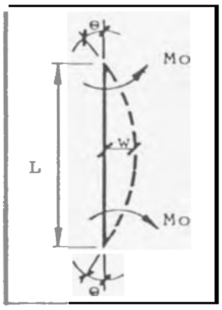


Fig. 4 Column Deviation Analogy

Applying the secant formula for initial eccentricity 'w' gives:

$$S_{max} = P/A + PLD\theta/(460I)\ \sec(L/2\sqrt{(P/EI)})$$

where

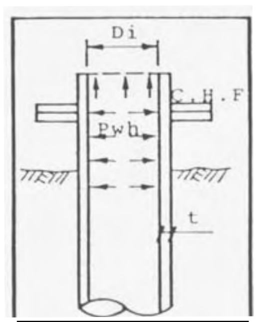
$$P = \text{applied load} - EAe^2\ \pi^2/(2L^2)$$

WELLHEAD STRESSES

The wellhead may be considered as a pressure vessel. The tensile stress induced in the casing by the vertical pressure component is related to that induced by the hoop loading. The two may be combined into a single yield criterion. For **biaxial** stresses Mises gives:

$$S_{max} = \sqrt{0.5((S1-S2)^2 + (S2-S3)^2 + (S3-S1)^2)}$$

Since there is no lateral restraint at the wellhead (fig. 5).



Big. **5** Schematic Shut-in Wellhead

$S1 = 0$

$S2$ = vertical tensile stress

$= \pi * Di^2 * Pwh/(4A)$

for $A \sim \pi * Di * t$

then $S2 = Di * Pwh/(4t)$

also $S3 = Pwh * Di/(2t)$

hence $S3 = 2S2$

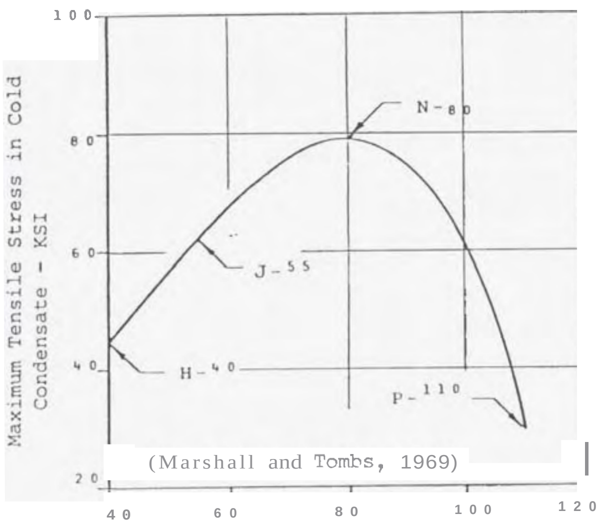
substituting above gives:

$$S_{max} = 0.43Pwh * Di/t$$

Design should account for hot and cold conditions at the wellhead. For hot wellhead conditions the yield stress at the corresponding well temperature is the limiting stress, but for cold conditions this is modified for the effects of stress corrosion cracking in cold geothermal condensate (fig. *6)*.

A correlation for fig. 6 is:

$$St = 58.7 - 2.43Sy + Sy^2/14.2 - Sy^3/2163$$



Minimum Yield Strength Sy (K.S.I.)

Fig. 6 Tensile strengths in cold geothermal condensate

HELICAL BUCKLING OF LINERS

Design equations (Lubinsky et al, 1962) assume:

1. No pressure differential between the inside and outside of the liner.
2. The effect of coupling is small.
3. No friction between the liner and formation.
4. Holes are inclined at no more than 10 degrees to vertical.
5. Flowing fluid friction may be ignored.

Buckling f a liner in an empty hole is a function of the axial compressive load. However in a fluid filled hole because the surface areas on either side of the helix are different, there is a net stabilising force which reduces the buckling tendency.

Relevant design factors are: (fig. 7)

i. Neutral buckling point.
This occurs where the compressive stress equals the hydrostatic pressure. (Goins, 1980)

If $P_s = P_f * A$

then $L_n = (P-P_s)/(W_{buoy})$

ii. Induced helical bending stress.

$$S_h = De/(4I) * (P-P_s)$$

iii. Change of length in helical buckling.

$$\Delta L_h = -e^2 (P-P_s)^2/(8EIW_{buoy})$$

Design is aimed at preventing yielding of the liner.

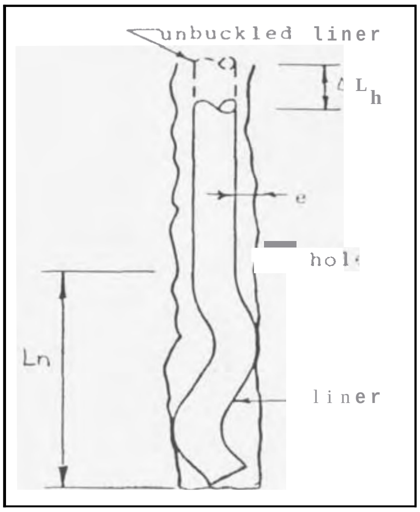


Fig. 7 Helical Buckling of Liner

As the buckling stress is directly proportional to the liner formation clearance the appropriate value of 'e' for design requires careful judgement.

CONCLUSIONS

The analyses and equations developed above should enable casings and liners to be better designed against particular failure modes. Site conditions will continue to necessitate that judgement be used to determine some design factors such as the design uncemented length, with past performance of casing the best guide to the choice of factors.

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NOTATION

A = steel area, in.^{2}
B = minimum confining modulus for buckling p.s.i.
D = outside diam., in,
D_i = inside diam., in.
e = Liner/casing formation clearance, in.
E = elastic modulus, p.s.i.
E_f = elastic formation modulus, p.s.i.
h = column length change, in.
I = moment of inertia, in.^{4}
L = column length, in.
ΔL_h = Length change due to helix, ft.
L_n = helically buckled length, ft.
M_o = applied moment, lb-in.
P = axial compressive load, lb.
P' = axial tensile load, lb.
P_c = critical buckling load, lb.
P_f = fluid pressure, p.s.i.
P_s = stability force, lb.
P_{wh} = wellhead pressure, p.s.i.
S_1, S_2, S_3 = orthogonal principal pipe stresses, p.s.i.
S_h = helical bending stress, p.s.i.
S_{max} = maximum induced casing stress, p.s.i.
S_t = tensile strength in cold geothermal condensate, k.s.i.
S_y = yield strength, k.s.i.
t = pipe wall thickness, in.
U = strain energy of buckling, 1b.-in.
v = lateral column deflection, in,
w = mid-point column deflection, in.
W_{buoy} = buoyant weight, lb./ft.
x = vertical height, in.
Z_c = cased depth, ft.
Z_d = drilled depth, ft.

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