Ejemplo:

L = 10,000 pies

TP @ $2\frac{7}{8}$ pg, 6.5 $\frac{lb}{pie}$,

D = 2.875 pg, d = 2.441 pg

Terminación: Aceite 30 °API (fluido)

Evento: Cementación forzada

TR @ 7pg, 32 $\frac{lb}{pie}$, D_{csg} = 7pg,

d_{csg} = 6.094pg

d_{PKR} = 3.25pg

$\rho_{cemento}$ = 15 lb/gal

P_{th} = 5,000 lb/pg^2

P_{csg} = 1,000 lb/pg^2

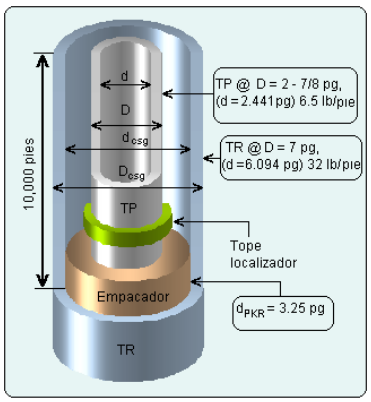
Al realizar dicha operación se tendrá un enfriamiento sobre la sarta ó aparejo de producción (**producción**).

ΔT_{avg} = -20 °F

Procedimiento de cálculo propuesto:

a) Efecto de Temperatura.
b) Efecto de Pistón.
c) Efecto de Ballooning.
d) Efecto de Buckling.
1. Buckling mecánico.
2. Buckling hidráulico.

e) Determinar la longitud de sello.
f) Determinar el diagrama de cargas axiales (**Tensión - Compresión**) será:
g) Determinar la profundidad donde se localizan dichos efectos
h) Determinar la resistencia del aparejo de producción.



Solución:

a) Efecto de Temperatura.

$$\Delta L_T = \beta L \Delta T_{avg}$$

$$\Delta T_{avg} = -20\,^{\circ}F$$

$$\Delta L_T = \left(6.9x10^{-6}\,\frac{1}{^{\circ}F}\right)\left[-20\,^{\circ}F\right]$$

$$\Delta L_T = -1.38 \text{ pies}$$

$\Delta L_T = -1.38$ pies @ **Contracción** por enfriamiento (- → **TENSIÓN**)

Solución:

b) Efecto de Pistón.

$$\Delta L_P = -\frac{L}{E\,As}\left[\Delta P_i(A_P - A_i) - \Delta P_o(A_P - A_o)\right]$$

$$\Delta F_P = \Delta P_i(A_P - A_i) - \Delta P_o(A_P - A_o)$$

$$\Delta L_P = -\frac{L}{E\,As}\left[\Delta F_P\right]$$

$$^{\circ}API = \frac{141.5}{\gamma_o} - 131.5$$

$$\gamma_o = \frac{141.5}{^{\circ}API + 131.5} \rightarrow \gamma_o = \frac{141.5}{30^{\circ}API + 131.5} \rightarrow \gamma_o = 0.876$$

$$\rho_o = \gamma_o * 8.33\,\frac{lb}{gal} \rightarrow \rho_o = 0.876 * 8.33\,\frac{lb}{gal} \rightarrow \rho_o = 7.3\,\frac{lb}{gal}$$

$$As = \frac{\pi}{4}(D^2 - d^2) \rightarrow As = \frac{\pi}{4}(2.875\,pg^2 - 2.441\,pg^2) \rightarrow As = 1.812\,pg^2$$

$$A_P = \frac{\pi}{4}(d_E^2) \rightarrow A_P = \frac{\pi}{4}(3.25\,pg^2) \rightarrow A_P = 8.295\,pg^2$$

$$A_i = \frac{\pi}{4}(d^2) \rightarrow A_i = \frac{\pi}{4}(2.441\,pg^2) \rightarrow A_i = 4.6798\,pg^2$$

$$A_o = \frac{\pi}{4}(D^2) \rightarrow A_o = \frac{\pi}{4}(2.875\,pg^2) \rightarrow A_o = 6.491\,pg^2$$

Condición Inicial

$$P_{tbg1} = 0.052 * \rho_o * Prof$$

$$P_{tbg1} = 0.052 * 7.3 \frac{lb}{gal} * 10{,}000 \text{ pies}$$

$$P_{tbg1} = 3{,}796 \frac{lb}{pg^2}$$

$$P_{csg1} = 0.052 * \rho_o * Prof$$

$$P_{csg1} = 0.052 * 7.3 \frac{lb}{gal} * 10{,}000 \text{ pies}$$

$$P_{csg1} = 3{,}796 \frac{lb}{pg^2}$$

Condición Final

$$P_{tbg2} = P_{th} + 0.052 * \rho_{cmt} * Prof$$

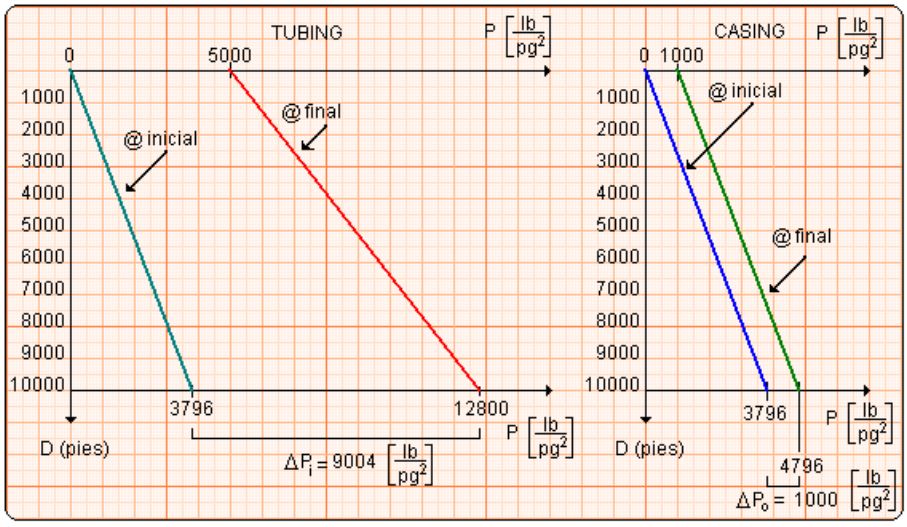
$$P_{tbg2} = 5{,}000 \frac{lb}{pg^2} + 0.052 * 15 \frac{lb}{gal} * 10{,}000 \text{ pies}$$

$$P_{tbg2} = 12{,}800 \frac{lb}{pg^2}$$

$$P_{csg2} = P_{csg} + 0.052 * \rho_o * Prof$$

$$P_{csg2} = 1{,}000 \frac{lb}{pg^2} + 0.052 * 7.3 \frac{lb}{gal} * 10{,}000 \text{ pies}$$

$$P_{csg2} = 4{,}796 \frac{lb}{pg^2}$$



$$\Delta P_i = P_{tbg2} - P_{tbg1}$$

$$\Delta P_i = 12{,}800 \frac{lb}{pg^2} - 3{,}796 \frac{lb}{pg^2}$$

$$\Delta P_o = P_{csg2} - P_{csg1}$$

$$\Delta P_o = 4{,}796 \frac{lb}{pg^2} - 3{,}796 \frac{lb}{pg^2}$$

$$\Delta P_i = 9{,}004\ \frac{lb}{pg^2} \qquad \Delta P_o = 1{,}000\ \frac{lb}{pg^2}$$

$$\Delta F_P = \Delta P_i(A_P - A_i) - \Delta P_o(A_P - A_o)$$

$$\Delta F_P = 9{,}004\ \frac{lb}{pg^2}\ (8.296\ pg^2 - 4.68\ pg^2) - 1{,}000\ \frac{lb}{pg^2}\ (8.296\ pg^2 - 6.492\ pg^2)$$

$$\Delta F_P = 30{,}754\ lb_f$$

Tal que:

$$\Delta L_P = -\frac{L}{E\ As}[\Delta F_P]$$

$$\Delta L_P = -\frac{10{,}000\ pies}{\left(30x10^6\ \frac{lb}{pg^2}\right)(1.812\ pg^2)}[30{,}754\ lbs_f\ ]$$

$$\Delta L_P = -5.65\ pies \quad @\ (-)\ Contracción \rightarrow Compresión$$

Solución:

c) Efecto de Ballooning.

$$\Delta L_B = -\frac{2\,L\,\mu}{E}\left[\frac{\Delta P_{ia} - \Delta P_{oa} R^2}{R^2 - 1}\right]$$

$$^{o}API = \frac{141.5}{\gamma_o} - 131.5$$

$$\gamma_o = \frac{141.5}{^{o}API + 131.5} \rightarrow \gamma_o = \frac{141.5}{30^{o}API + 131.5} \rightarrow \gamma_o = 0.876$$

$$\rho_o = \gamma_o * 8.33\ \frac{lb}{gal} \rightarrow \rho_o = 0.876 * 8.33\ \frac{lb}{gal} \rightarrow \rho_o = 7.3\ \frac{lb}{gal}$$

$$As = \frac{\pi}{4}(D^2 - d^2) \rightarrow As = \frac{\pi}{4}(2.875\ pg^2 - 2.441\ pg^2) \rightarrow As = 1.812\ pg^2$$

$$A_P = \frac{\pi}{4}(d_E^2) \rightarrow A_P = \frac{\pi}{4}(3.25\ pg^2) \rightarrow A_P = 8.295\ pg^2$$

$$A_i = \frac{\pi}{4}(d^2) \rightarrow A_i = \frac{\pi}{4}(2.441\ pg^2) \rightarrow A_i = 4.6798\ pg^2$$

$$A_o = \frac{\pi}{4}(D^2) \rightarrow A_o = \frac{\pi}{4}(2.875\ pg^2)$$

$$A_o = 6.491\ pg^2$$

Condición Inicial

$$P_{tbg1} = 0.052 * \rho_o * \text{Prof}$$

$$P_{tbg1} = 0.052 * 7.3 \frac{lb}{gal} * 10{,}000 \text{ pies}$$

$$P_{tbg1} = 3{,}796 \frac{lb}{pg^2}$$

$$P_{csg1} = 0.052 * \rho_o * \text{Prof}$$

$$P_{csg1} = 0.052 * 7.3 \frac{lb}{gal} * 10{,}000 \text{ pies}$$

$$P_{csg1} = 3{,}796 \frac{lb}{pg^2}$$

Condición Final

$$P_{tbg2} = P_{th} + 0.052 * \rho_{cmt} * \text{Prof}$$

$$P_{tbg2} = 5{,}000 \frac{lb}{pg^2} + 0.052 * 15 \frac{lb}{gal} * 10{,}000 \text{ pies}$$

$$P_{tbg2} = 12{,}800 \frac{lb}{pg^2}$$

$$P_{csg2} = P_{csg} + 0.052 * \rho_o * \text{Prof}$$

$$P_{csg2} = 1{,}000 \frac{lb}{pg^2} + 0.052 * 7.3 \frac{lb}{gal} * 10{,}000 \text{ pies}$$

$$P_{csg2} = 4{,}796 \frac{lb}{pg^2}$$

Condición inicial

$$P_{tbg1avg} = \frac{P_{tbg1} + 0}{2}$$

$$P_{tbg1avg} = \frac{3{,}796 \frac{lb}{pg^2} + 0 \frac{lb}{pg^2}}{2}$$

$$P_{tbg1avg} = 1{,}898 \frac{lb}{pg^2}$$

$$P_{csg1avg} = \frac{P_{csg1} + 0}{2}$$

$$P_{csg1avg} = \frac{3{,}796 \frac{lb}{pg^2} + 0 \frac{lb}{pg^2}}{2}$$

$$P_{csg1avg} = 1{,}898 \frac{lb}{pg^2}$$

Condición final

$$P_{tbg2avg} = \frac{P_{tbg2} + P_{th}}{2}$$

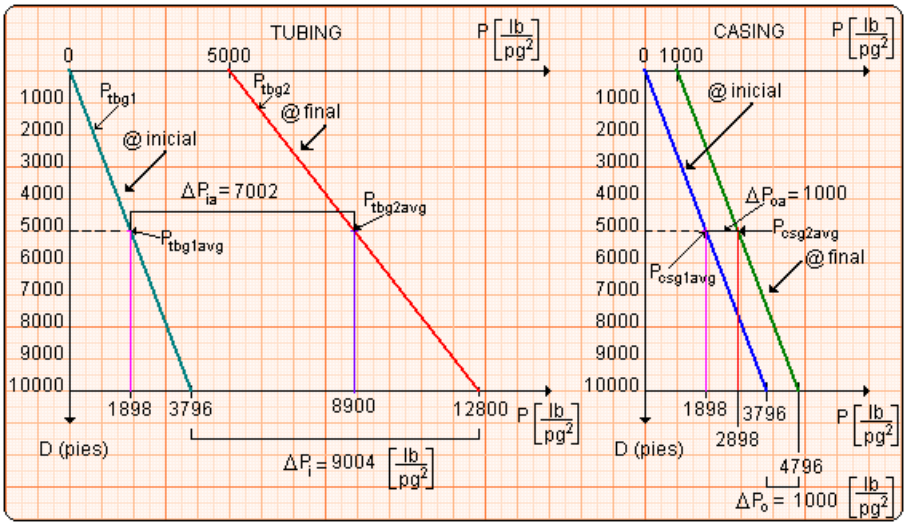
$$P_{tbg2avg} = \frac{12{,}800 \frac{lb}{pg^2} + 5{,}000 \frac{lb}{pg^2}}{2}$$

$$P_{tbg2avg} = 8{,}900 \frac{lb}{pg^2}$$

$$P_{csg2avg} = \frac{P_{csg2} + P_{csg}}{2}$$

$$P_{csg2avg} = \frac{4{,}796 \frac{lb}{pg^2} + 1{,}000 \frac{lb}{pg^2}}{2}$$

$$P_{csg2avg} = 2{,}898 \frac{lb}{pg^2}$$



$$\Delta P_{ia} = P_{tbg2avg} - P_{tbg1avg}$$

$$\Delta P_{ia} = 8{,}900\ \frac{lb}{pg^2} - 1{,}898\ \frac{lb}{pg^2}$$

$$\Delta P_{ia} = 7{,}002\ \frac{lb}{pg^2}$$

$$\Delta P_{oa} = P_{csg2avg} - P_{csg1avg}$$

$$\Delta P_{oa} = 2{,}898\ \frac{lb}{pg^2} - 1{,}898\ \frac{lb}{pg^2}$$

$$\Delta P_{oa} = 1{,}000\ \frac{lb}{pg^2}$$

$$R = \frac{D}{d}$$

$$R = \frac{2.875\ pg}{2.441\ pg}$$

$$R = 1.178$$

$$\Delta L_B = -\frac{2\,L\,\mu}{E}\left[\frac{\Delta P_{ia} - \Delta P_{oa}\,R^2}{R^2 - 1}\right]$$

$$\Delta L_B = -\frac{2\,(10{,}000\ pies)\,0.3\ cp}{30\ x\ 10^6\ psi}\left[\frac{7{,}002\ \frac{lb}{pg^2} - \left(1{,}000\ \frac{lb}{pg^2}\,(1.178)^2\right)}{(1.178)^2 - 1}\right]$$

$$\Delta L_B \cong -2.89\ pies \quad @ \quad \text{Contracción} \rightarrow \text{Tensión}$$

Solución:

d) Efecto de Buckling.

1. Buckling mecánico.

$$\Delta L_{bm} = \Delta L_{LH} + \Delta L_b$$

$$\Delta L_{LH} = -\frac{F_{PKR}\, L}{E\, As}$$

Como no existe la $\downarrow F_{PKR} = 0\,lbs_f$ por lo tanto no hay efecto mecánico.

Solución:

2. Buckling hidráulico.

$$\Delta L_{bHYD} = -\frac{r^2\, F_f^2}{96\ E\ I\ w}$$

$$w = w_s + w_i - w_o$$

$$w_s = \frac{Wn}{12}, \qquad w_i = \frac{\rho_i}{231} A_i, \qquad w_o = \frac{\rho_o}{231} A_o$$

$$w_s = \frac{6.5\ \frac{lb}{pie}}{12} \rightarrow w_s = 0.542\ \frac{lb}{pg}$$

$$w_i = \frac{15\ \frac{lb}{gal}}{231}\ (4.679\,pg^2) \rightarrow w_i = 0.303\ \frac{lb}{pg}$$

$$w_o = \frac{7.3\ \frac{lb}{gal}}{231}\ (6.491\,pg^2) \rightarrow w_o = 0.205\ \frac{lb}{pg}$$

$$w = 0.542\ \frac{lb}{pg} + 0.304\ \frac{lb}{pg} - 0.205\ \frac{lb}{pg} \rightarrow w = 0.640\ \frac{lb}{pg}$$

$$I = \frac{\pi}{64}\left(D^4 - d^4\right)$$

$$I = \frac{\pi}{64}\left((2.875\,pg)^4 - (2.441\,pg)^4\right) \rightarrow I = 1.611\,pg^4$$

$$r = \frac{d_{csg} - D_{tbg}}{2}$$

$$r = \frac{6.094\,pg - 2.875\,pg}{2}$$

$$r = 1.6095\,pg$$

Tal que, determinando la fuerza ficticia F_f; a partir de:

$$F_f = A_P(\Delta P_i - \Delta P_o)$$

$$F_f = 8.295\ pg^2\left(9{,}004\ \frac{lb}{pg^2} - 1{,}000\ \frac{lb}{pg^2}\right)$$

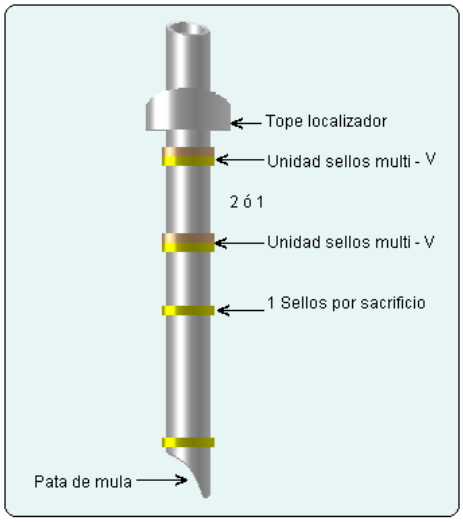
$$F_f \cong 66{,}394\ lbs_f$$

$$\Delta L_{bHYD} = -\frac{r^2\ F_f^2}{96\ E\ I\ w}$$

$$\Delta L_{bHYD} = -\frac{(1.6095\ pg)^2\ (66{,}394\ lb)^2}{96\left(30x10^6\ \frac{lb}{pg^2}\right)(1.611\ pg^4)\left(0.640\ \frac{lb}{pg}\right)} \rightarrow \Delta L_{bHYD} = -3.84\ \text{pies}$$

Solución:

e) Determinar la longitud de sello.



$$\Delta L_{total} = \Delta L_T + \Delta L_B + \Delta L_P + \Delta L_{bmec} + \Delta L_{bHYD}$$

$$\Delta L_{total} = -1.38\ \text{pies} - 2.89\ \text{pies} - 5.65\ \text{pies} + 0\ \text{pies} - 3.84\ \text{pies}$$

$$\Delta L_{total} = -13.76\ \text{pies}$$

Concluyendo, para ello se requiere un mínimo de 20 pies de longitud de sellos.

RESUMIENDO:

EFECTO	SIGNO	ΔL (pies)	FUERZA
Temperatura	-	1.38	No existe
Ballooning	-	2.89	No existe
Pistón	-	5.65	Si existe
Buckling	-	3.84	No existe

Solución:

f) Determinar el diagrama de Cargas axiales (**Tensión - Compresión**) será:

Finalmente representamos el diagrama de **Tensión – Compresión**, se obtiene:

1. $W_{tbgaire} = Wn * L$

$$W_{tbgaire} = \left(6.5\ \frac{lb}{pie}\right) * 10{,}000\ \text{pies}$$

$$W_{tbgaire} = 65{,}000\ lbs$$

2. $W_{tbgflotada} = W_{tbgaire} - F_{flotación}$

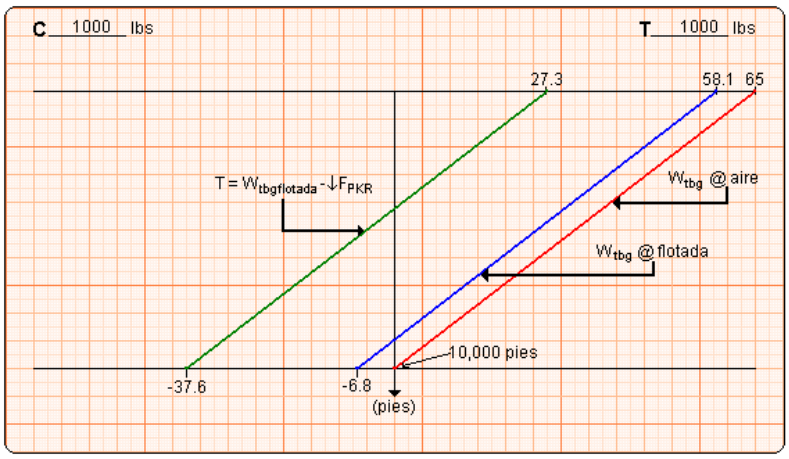
$F_{flotación} = P_i * As$

$P_i = 0.052 * \rho_o * Prof$

$P_i = 0.052 * 7.3 \frac{lb}{gal} * 10{,}000 \text{ pies} \rightarrow P_i = 3{,}796 \frac{lb}{pg^2}$

$F_{flotación} = 3{,}796 \frac{lb}{pg^2} * 1.8112\, pg^2 \rightarrow F_{flotación} = 6{,}878 \text{ lbs}_f$

$W_{tbgflotada} = 65{,}000 \text{ lbs}_f - 6878 \text{ lbs}_f \rightarrow W_{tbgflotada} = 58{,}122 \text{ lbs}_f$



3. $T = W_{tbgflotada} - \downarrow F_{PKR}$

Como la $\downarrow F_{PKR} = 0 \text{ lbs}_f$, entonces tomamos el valor de la fuerza del efecto Pistón.

$\Delta F_P = 30{,}754 \text{ lb}_f$

$T = 58{,}122 \text{ lbs}_f - 30{,}754 \text{ lbs}_f$

$T = 27{,}368 \text{ lbs}_f$

Solución:

g) Determinar la profundidad donde se localizan dichos efectos

$(T - C) = P_o A_o - P_i A_i$

Se tiene:

1. $(T-C)_{sup} = P_{csg}\, A_o - P_{th}\, A_i$

$$(T-C)_{sup} = 1{,}000\ \frac{lb}{pg^2}\left(6.492\ pg^2\right) - 5{,}000\ \frac{lb}{pg^2}\left(4.68\ pg^2\right)$$

$$(T-C)_{sup} = 16{,}907\ lbs_f$$

$$(T-C)_{sup} = 16{,}907\ lbs_f$$

Ahora:

2. $(T-C)_{fon} = P_{csg1}\, A_o - P_{t_{bg1}}\, A_i$

$$(T-C)_{fon} = 4{,}796\ \frac{lb}{pg^2}\left(6.492\ pg^2\right) - 12{,}800\ \frac{lb}{pg^2}\left(4.68\ pg^2\right)$$

$$(T-C)_{fon} = \left(31{,}136\ lbs_f\right) - \left(59{,}904\ lbs_f\right)$$

$$(T-C)_{fon} \cong -28{,}768\ \ lbs_f$$

Por lo que resumiendo:

(T – C)

Superficie =	16,907 lbs_f	@	10,000 pies
Fondo =	-28,768 lbs_f	@	10,000 pies

3. Tal que la intercepción esta dada por:

$$T_1 - \frac{W_{aire}}{L} D_d = -\frac{(T-C)_f}{L} D_d$$

$$27{,}368\ lbs_f - \frac{65{,}000\ lbs_f}{10{,}000\ pies} D_d = -\left(-16{,}907\ lbs_f\right) + \frac{\left(\left(-28{,}768\ lbs_f\right) + \left(-16{,}907\ lbs_f\right)\right)}{10{,}000\ pies} D_d$$

$$27{,}368\ lbs_f - 6.5\ \frac{lbs_f}{pies} D_d = 16{,}907 lbs_f + 1.1861\ \frac{lbs_f}{pies} D_d$$

$$-6.5\ \frac{lbs_f}{pies} D_d - 1.1861\ \frac{lbs_f}{pies} D_d = 16{,}907\ lbs_f - 27{,}368\ lbs_f$$

$$-7.6861\ \frac{lbs_f}{pie} D_d = -10{,}461\ lbs_f \ \rightarrow\ D = \frac{-10{,}461 lbs_f}{-7.6861\ \frac{lbs_f}{pies}} \ \rightarrow\ D = 1{,}361 pies$$

Solución:

h) Determinar la resistencia del aparejo de producción.

$$\sigma_{tbg} = \frac{W_{tbgaire} - F_{flotación} - \uparrow F}{As}$$

$$\sigma_{tbg} = \frac{65{,}000\ lbs_f - 6{,}878 lbs_f - 30{,}754\ lbs_f}{1.812\ \ pg^2} \rightarrow \sigma_{tbg} \cong 15{,}104\ psi$$