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COILED TUBING PERFORMANCE FOR HORIZONTAL AND DEVIATED WELLS IN SELECTED NIGER DELTA RESERVOIRS

Akpoturi Peters
Department of Petroleum Engineering
Federal University of Petroleum Resources, Effurun, Delta State.
Email: petersakpoturi1212@gmail.com

ABSTRACT

Generally Coiled Tubing operation has been on steady increase for post drilling completion operations such as well clean-up, balance/under balance washing, stimulation, production logging and testing especially in horizontal wells. In order to establish the feasibility of CT- assisted operations, a comprehensive engineering analysis which predicts the CT mechanical performance and its penetration limit is carried out. The predictive mathematical technique procedure was applied to a typical two-dimensional horizontal well (i.e. with a Constant azimuth) along three major paths: (i) Identification of the well and Coiled Tubing mechanical data. (ii) Estimation of the CT hydraulic limit. (iii) Prediction of the limit of penetration (LOP) of CT in the horizontal well completion with a sensitive analysis of the LOP based on variable pipe frictional coefficients. This paper presents the theoretical analysis of the system hydraulics and Coiled Tubing forces based on the well/completion configuration, Coiled Tubing dimensions, and the completion fluid/formation type.. Case histories which validation of the technique with actual field data recorded during horizontal well completion operations were also correlated and recorded.

INTRODUCTION

1_1 /4" Coiled Tubing has been routinely used to successful carry out pumping services and stiff wire line applications due to the access restrictions of the existing small completion tubing (2-3/8' and 2- 7/8") bores. The various applications of the CT operations is listed below;

PUMPING SERVICES

- Acid Washing/Stimulation
- Fill Cleanouts/Sand Removal
- Repair/Remedial Operations-
SCON/Cementing

STIFF WIRELINE APPLICATIONS

- Production Logging Data Acquisition -PLT

In order to overcome the increased challenges associated with horizontal wells such as post-well clean-up and evaluation, CT is being utilized for clean out/washing and PLT logging in these well. Currently, many horizontal wells are being designed with extra which long horizontal completion sections (> 3000 feet) for maximum well developed ultimate recovery. It is against this background that this paper focuses on CT performance for horizontal wells. The results are presented in a spreadsheet format which incorporates the coiled tubing/well mechanical and completion fluid data. Attempt has been made to validate the CT force analytical model based on a industry accepted frictional factor of 0.3 with the actual CT performance data observed in a horizontal well operation.

METHODOLOGY

a. Procedure and Equations;

The pre-set CT/wellbore fluid/mechanical data are first identified prior to a comprehensive analysis of the hydraulic and mechanical load limitations during completion. The CT force analysis includes the risk of buckling, axial and hook load effects and the corresponding compressive stress for the vertical, curved, tangent and horizontal well sections.

The analytical procedure requires a careful and sequential consideration in order to show the difference in CT performance with changing wellbore conditions from the top of the well to the bottom or vice-versa.

See Appendix I, The CT penetration limits were estimated using the latest available industry technique and sets of new analytical equations developed for predicting buckling of coiled tubing, hook load transmission, axial compressive load and maximum horizontal penetration length – (1,2,5).

CT/ Well Data and Hydraulic Limit

The pre-identified CT/well mechanical and wellbore fluid data are combined to accurately predict the maximum system well pressure loss/requirement and hence, the fluid hydraulic capacity for successfully washing out sand cuttings from the bottom-horizontal- hole section.

The well system pressure loss is defined by the fluid/particle density, fluid pump rate, and the annular cross-sectional area between the CT and the slotted liner/production tubing wellbore. The minimum fluid pump rate is determined by the terminal particle settling velocity (TPSV) required to ensure that the solid/sand particles remain in suspension and in motion while circulating out of the wellbore. Since maximum system pressure loss during the completion phase is expected while circulating with the highest density fluid, the limit is not established with the light-weight nitrified fluid designed for the under balance washing/circulation operation. The limit is therefore better estimated while circulating out the formation sand/solid particles with an incompressible Newtonian wash brine fluid.

Assumptions:

- The sand grains are rigid solid particles of uniform geometry with diameter, DrD (120 US Mesh) for the large size particles with a true density of 265
(S.G.).
- The TPSV(horizontal) is at least 10 times the TPSV required in vertical wellbore environment to maintain fluid/particle circulation without settling out of solids.

The minimum effective fluid pump rate (Qmin bpm) required for a successful completion wash program with an exclusively brine fluid utilization is estimated by considering the largest annular area in the well completion configuration i.e. CT/5-1/2 inch SL annulus in the subject wells - See appendix A.

Mechanical Load Limits;

The coiled tubing limitations can be established by mechanical load analysis such as axial compressive load transmitted downhole in addition to the hook/drag load while tripping-in and out of the bottom-hole completion. This analysis are useful in determining the critical compressive loads of the CT in different wellbore environment and hence, the impact of excess load application on the expected tubing buckling behaviour.(5)

CT buckling is usually initiated by the application of axial load in excess of the critical load for the particular wellbore configuration and the tubing first takes the shape of sinusoidal buckling. As additional load is applied, the helical buckling load is reached and helical buckling shape is developed with a smaller buckling pitch length compared to that for sinusoidal buckling (6). There is a significant increase in the frictional drag and the wall contact force during this period such that the load transmitted through the helically buckled CT is highly reduced until a "lock-up' condition is reached (i.e maximum load transmission at which there is no further CT movement downhole).

RESULTS DISCUSSION

Irri-29 (Horizontal Well)

Irri-20 was planned to have a medium range horizontal drainage section length of 3100 ft ah with an average build-up rate of 3.75°/I00 ft and LD/TMD of 8090/11190 ft ah. The use of a tapered 5-1/2"? 4_1/2M slotted liner completion assembly in order to facilitate the installation of the completion liner across the entire horizontal section drilled has resulted in a -27% reduction in radial clearance between the CT 01) and the 4-112 slotted liner ID at the lower end of the horizontal section - See analysis report.

The CT was unable to penetrate further than the depth of —9528 flab due to some possible restriction in the 4-1/2 SL bore.
The estimated maximum circulating pressure for the I- 114", 1.251 lb/ft CT during the planned pumping operation with the non-nitrified low-weight brine (SG. -105) is —3000 psi.

The validation of the CT performance prediction model has been attempted with actual tubing load behavior in the well - See figure 3 and 4. Irri-21 (Horizontal Well) A 1-1/2" tapered —1.8 lb/ft CT was selected for the post rig-completion exercise at Opukushi-22 horizontal well. This was informed by the need to avoid the unexpected incidence of CT hold-up mid-way into the completion liner as in the preceding well. Well trajectory was fairly similar with a planned BUR of 3.9°/I00 ft and LD/TMD of 7929/10430 ft ah.

The CT was successfully ran down to the bottom without any incident of lock-up. This performance was sufficient in eliminating the some of the uncertainties that surrounded the hold-up of the 1-1/4' CT in the preceding well. This has confirmed the PC-based simulator and spreadsheet prediction that there will be no lock-up. Maximum LOP calculated from both techniques was 100% higher than the section penetrated in horizontal section at HUD.

CONCLUSIONS AND RECOMMENDATIONS

Analysis of expected CT hydraulic performance during the planned pumping operations such as well clean-up is critical in order to determine if the operating envelope will fall within the maximum allowable CT working pressure limit.

Analysis of 1-1/4” CT mechanical load behavior in horizontal wells shows that the CT will buckle at the heel end of the horizontal section as the helical buckling load for this well section will be exceeded during CT-assisted completion operation.
The limit of penetration predicted from the 1-1/4” CT axial and hook load distribution while tripping-in is less than the proposed total well measured depth (TMD) for horizontal wells with similar completion configuration (Lw > 3000 ft). A higher capacity-CT e.g. 1-1/2 is recommended for CT-assisted operations to be technically feasible in these long-drainage-section horizontal wells.

Coiled tubing penetration performance in the horizontal well application can be enhanced by adjusting the radial clearance between the tubing and the surrounding wellbore, increasing the wellbore fluid density, or changing out the tubing to a larger size CT unit.

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Appendix-I : FLUID HYDRAULICS EQUATIONS

1. Fluid Velocity and Reynolds Number

$V_i = 17.14Q / D_i^2$

or $V_{ann} = 17.14Q / (D_i^2 - D_o^2)$ ..... (1)

$N_{re} = 124\, D_i V_i \rho_f / \mu_f$ or

$N_{re} = 124\, D_{e(ann)} V_{ann} \rho_f / \mu_f$ ..... (2)

where $D_{e(ann)} \approx (2/3)^{0.5}(D_i - D_o)$

$\approx 0.816(D_i - D_o)$ ....(3)

and $N_{re} < 2000$ (Laminar flow)

$N_{re} > 4000$ (Turbulent flow)

2. Particle Dynamics and Solids Clean-out

$N_{rep} = 124\, D_p V_t \rho_f / \mu_f$ ....(4)

$C_d = g D_p(\rho_s - \rho_f) / 9 V_t \rho_f$ ....(5)

From eqns 3 & 4,

$Cd\, (N_{rep})2 = 1708\, g D_p^3(\rho_s - \rho_f)\rho_f / \mu_f^2$ ....(6)

$\log C_d + 2\log N_{rep} = \log [1708\, g D_p^3(\rho_s - \rho_f)\rho_f / \mu_f^2]$ ....(7)

where Cd and Nrep are determined by the prevailing flow regime in the wellbore section :

- Stokes Law Region : $N_{rep} \leq 0.10$ and $\log C_d = \log(24) - \log N_{rep}$ .....(8)

- **Transition/Intermediate Law Region :**
  $0.10 \leq N_{rep} \leq 500$

and $\log C_d = \log (18.5) - 0.6 \log N_{rep}$ ....(9)

- **Newtons Law Region :** $500 \leq N_{rep} \leq 200{,}000$
  and $\log C_d \approx \log (0.44)$ ....(10)

From eqn. (5),

TPSV(vertical), $V_{t(vert)} = 9\rho_f C_d / gD_p(\rho_s - \rho_f)$ ....(11)

Minimum required TPSV(horizontal),

$V_{t(horz)} \approx 10 V_{t(vert)} = 90\rho_f C_d / gD_p(\rho_s - \rho_f)$ ....(12)

From eqn. (1), Minimum required Circulation Rate for Horizontal well clean-out,

$Qmin = (D_i^2 - D_o^2)\, V_{t(horz)} / 17.14$ ....(13)

3. System Frictional Pressure Loss

Tubing Bore (Turbulent flow) :

$\Delta P/1000\ ft = 380.5\, f \rho_f Q^2 / D_i^5$ ....(14)

where, $*f \approx 0.0072 + (0.636 / N_{re}^{0.355})$...(15a)

or $f \approx 0228\, (N_{re})^{-0.2}$ ....(15b)

Annular Section :

$\Delta P_{lam} = V_{ann} \mu_f \Delta L R_{lam} / [1000(D_i - D_o)^2]$ ....(16)

$\Delta P_{turb} = \rho_f^{0.75} V_{ann}^{1.75} \mu_f^{0.25} \Delta L\, R_{turb} / [6310(D_i - D_o)^{1.25}]$ ....(17)

where,

$R_{lam} = 1 - 0.72E_c(D_o/D_i)^{0.8454} - 1.5E_c^2(D_o/D_i)^{0.1852} + 0.96E_c^3(D_o/D_i)^{0.2527}$ ....(18)

For turbulent flow, $D_o/D_i = 0.01$ is substituted in eqn. (17) instead of actual diameter ratio.

Hence,

$R_{turb} = 1 - 0.015E_c - 0.64E_c^2 + 0.30E_c^3$ ....(19)

where $E_c = f\,(D_o/D_i)$

Assume $E_c \approx 0.50$ to 0.75 for vertical section and
$E_c \approx 0.75$ to 0.95 for horizontal section

Wash tool/Jet :

$\Delta P_{jet} = 0.035 \times Q^2 \rho_f / (nD_j^2)^2$ ....(20)

4. Nomenclature

C_d - Particle drag coefficient (dimensionless)

$D_{e(ann)}$ - Equivalent circular diameter (for annular wellbore flow computations), in.

D_o - O.D. of the CT, in.

D_i - I.D. of the CT bore (or I.D. of surrounding pipe for annular wellbore computations), in.

D_j - Wash tool nozzle port diameter, in.

D_p - Median/Average Particle diameter (D_{50})

$\in$ - Standard steel absolute roughness factor, in (= 0.0018 in).
E_c - Pipe eccentricity (degree of CT decentralisation in concentric annulus), dimensionless.
*f - Moody's frictional factor equation (for approximate values only) developed by Shell Oil. (More accurate estimates available from Moody's frictional factor chart using $\in/D_i$)
n - number of wash tool nozzles.
N_{re} - Reynolds number (dimensionless ratio used to determine flow regimes).
N_{rep} - Particle Reynolds number (dimensionless ratio used to determine flow regimes).
ρ_f - Fluid density, lb/ft^3.
ρ_s - Particle/Formation grain density, lb/ft^3.
Q - Fluid flow rate, bpm.
R_{lam} - Haciislamoglu's eccentricity correction factor (for laminar flow), dimensionless.
R_{turb} - Haciislamoglu's eccentricity correction factor (for turbulent flow), dimensionless.
TPSV - Terminal particle settling velocity, fps.
μ_f - Fluid viscosity, cp.
V_{ann} - Fluid velocity in a annular well section, fps.
V_i - Fluid velocity in a tubing bore section, fps.
$V_{t(vert)}$ - Particle/Fluid velocity in a vertical well section, fps.
$V_{t(horz)}$ - Particle/Fluid velocity in a horizontal well section, fps.

ΔL - Length of wellbore section, ft.
ΔP - Pressure loss, psi.
ΔP_{jet} - Pressure loss at the wash tool nozzles, psi.
ΔP_{lam} - Pressure loss in laminar flow regime, psi.
ΔP_{turb} - Pressure loss in turbulent flow regime, psi.

Appendix-II

CT MECHANICAL LOAD AND STRESS EQUATIONS

A. Basic uniform calculation equations

Moment of Inertia, in^4,

$$I = (\pi/64) \times (D_o^4 - D_i^4) \quad ....(1)$$

Buoyancy factor,

$$f_b = 1.008 - 2.14 \times 10^{-3} \rho_f ....(2)$$ (Single Fluid medium)

Buoyancy factor,
$f_b = 1 - \{[0.433 \times (A_o\rho_o - A_i\rho_i)] / W\}$ ....(3)
(Dual Fluid medium)

Tubular Buoyant weight, lb/ft,
$W_b = W \times f_b$ ....(4)

Axial Compressive stress, psi,
$\sigma_a = F_a / A$ ....(5)

Outer fibre bending stress, psi,
$\sigma_b = rD_o/4I$ ....(6)

Yield stress, psi,
$\sigma_y = \sigma_a + \sigma_b = F_a/A + rD_o/4I$ ....(7)

B. MAURER TECHNIQUE

B.1. Vertical well section evaluation

$A_v = (EIW_b / 3\mu r_v)^{0.5}$ ....(8)

$F_{cr,v} = 2.55\,(EIW_b^2)^{1/3}$ ....(9)

$F_{hel,v} = 5.55\,(EIW_b^2)^{1/3}$
or $F_{hel,v} = 2.18\,F_{cr,v}$ ....(10)

$F_{hel,tv} = 0.14\,(EIW_b^2)^{1/3}$ ....(11)

$F_{hk} = W_b\,d_v - K$ ....(12)
(where K=500/0 lbf while tripping-in well/POH)

$F_a = A_v \tanh(d_v W_b / A_v)$ ....(13)
(at zero hook load condition)

$F_{kop} = F_{a(max)} = A_v \tanh(DW_b / A_v)$
(at zero hook load condition) ....(14)

$d_{bkl,v} = A_v\,[\text{arctanh}(F_{kop} / A_vW_b) - \text{arctanh}(F_{hel,t} / A_vW_b)]$ ....(15)

$d_{hel,v} = D - d_{bkl,v}$ ....(16)

$D_{v(max)} = [115\,\sigma_{y(max)}] / (490 - \rho_f)$ ....(17)

B.2. Curved Wellbore section evaluation

B.2.1 For single continuous curved section :

$A_c = (EI / 3r_cR)^{0.5}$ ....(18)

$Z_c = W_bR / (1+\mu^2)$ ....(19)

$F_{cr} = A_c\{1+[1+(W_bR \sin\theta / A_c)]^{0.5}\}$ ....(20)

$F_{hel} = 3A_c\{1+[1+(W_bR \sin\theta / 2A_c)]^{0.5}\}$ ....(21)

$F_{kop(0)} = [F_{eoc(90)} - Z_c(1-\mu)^2]e^{\mu\pi/2} + Z_c(2\mu)$ ....(22).

****B.2.2 For double curved section (separated by tangent section) :**

$A_{c1} = (EI / 3r_{c1}R_1)^{0.5}$
$A_{c2} = (EI / 3r_{c2}R_2)^{0.5}$ ....(23)

$Z_{c1} = W_bR_1 / (1+\mu^2)$
$Z_{c2} = W_bR_2 / (1+\mu^2)$ ....(24)

$F_{eoc(90^\circ)} = \{[(F_{kop(0)} - Z_{c1}(2\mu)]e^{-\mu\pi/2}\} + Z_{c1}(1-\mu^2)$ ....(25)

B.2.3 (Dual Curved Section with a θ-deg tangent separation)

$F_{kop(t)} = F_{kop(R1)} + (\theta_t/90)\,[F_{eoc(R1)} + F_{kop(R1)}]$ ....(26a)

$F_{eoc(t)} = F_{kop(R2)} + (\theta_t/90)\,[F_{eoc(R2)} + F_{kop(R2)}]$ ....(26b)

$F_{eoc(90)} = \{F_{eoc(t)} + [(1-\theta_t/90) Z_{c2}(1-\mu^2)e^{\mu\pi/2}] - [(1-\theta_t/90).\,2Z_{c2}e^{\mu\pi/2}]\}/[(1-\theta_t/90)e^{\mu\pi/2} + (\theta_t/90)]$..........(27)

B.3. Tangent Well section evaluation

$F_{cr} = (EIW_b \text{ Sin } \theta / 3r_t)^{0.5}$ ....(28)

$F_{hel} = (2*2^{0.5}-1)F_{cr,t}$ ....(29)

$F_a = F_{eoc(45)} - L_t W_b \text{ Sin } \theta$ ....(30)

$*F_{hk} = f(x_t)$ ....(31)

(where x_t is the length along the tangent)

*(interpolated between the hook loads at kop and horizontal entry point)

B.4. Horizonta. well section evaluation

$A_h = (EIW_b / 3r_h)^{0.5}$ ....(32)

$F_{cr} = A_h = (EIW_b / 3r_h)^{0.5}$ ....(33)

$F_{hel} = (2*2^{0.5}-1)\,F_{cr}$ ....(34)

$R = 1800 / (\pi\alpha)$ ....(35)

(for single curved section horizontal well)

$R = R_{eff}$ (for a dual curved section horizontal well as above**)

From eqn. (24)

$R_{eff} = (1+\mu^2)\,[F_{kop(0)} - (F_{eoc(90)}e^{\mu\pi/2}] / [W_b(2\mu) - W_b(1-\mu^2)e^{\mu\pi/2}]$ ....(36)

B.4.1 If no horizontal well buckling

(i.e $F_{eoc(90)} < F_{hel}$)

$F_a = F_{eoc(90)} - W_b\mu l_h$ ....(37)

For hook load evaluation (and with zero bit weight),

$F_{eoc'} = 0 + W_b\mu l_h$ ....(38)

Substitute $F_{eoc'}$ in eqn. (21) with R/Reff for single/dual curved section horizontal wells respectively to obtain $F_{kop'(0)}$

$***F_{hk} = DW_b - \{A_v\,[\arctan(F_{kop'(0)}/A_v)]\}$ ....(39)

B.4.2 If horizontal well buckling occurs

(i.e $F_{eoc(90)} > F_{hel}$)

Buckling section (i.e. where $F_a > F_{hel}$):

Determine total length of buckled section, L_b first, thus :

$F_a = A_h.\tan\{[(\mu\, l_b W_b)/A_h] + \arctan(F_o/A_h)]\}$ ....(40)

Substituting $F_{eoc(90)} = F_a$

and $F_{hel} = F_o$ in eqn. (35)

$F_{eoc(90)} = A_h.\tan\{[(\mu\, L_b W_b)/A_h] + \arctan(F_{hel}/A_h)]\}$ ....(41)

$\therefore L_b = l_{b(max)}$

$= (A_h/\mu W_b)$ [arctan $(F_{eoc(90)}/A_h)$
- arctan (F_{hel}/A_h)] ....(42)

(where l_b is the distance measured from the Neutral Position, NP at which helical buckling stops, towards the entry point of the horizontal section e.g.
at MD = 8000' ah, KOP = 7900' ah,
NP = 7900 + L_b,
and l_b = NP - MD = (7900 + L_b) - 8000

For hook load evaluation (and with zero bit weight),
$F_{eoc'} = A_h \cdot \tan \{[(-\mu\, l_b W_b)/A_h]$
$+ \arctan(F_{hel}/A_h)\}$ ....(43)

where l_b is the distance from the neutral point (as illustrated above), i.e. at KOP, $l_b = L_b$
Substitute $F_{eoc'}$ in eqn. (21) with R/Reff for single/dual curved section horizontal wells respectively to obtain $F_{kop'(0)}$
***$F_{hk} = DW_b - \{A_v$ [arctan $(F_{kop'(0)}/A_v)]\}$ ....(44)

B.4.3 Non-Buckling section
(i.e. where $F_a < F_{hel}$):

$F_a = F_{hel} - W_b\, l_{nb}$ ....(45)

(where l_{nb} is the distance measured from the neutral position at which helical buckling stops towards the tail end of the horizontal section e.g at MD = 8500' ah, NP = (7900+L_b), and l_{nb} = 8500 - (7900+L_b))

$L_{nb} = l_{nb(max)}$
$= F_{hel} / (\mu W_b)$ ....(46)

$L_{h(max)} = L_b + L_{nb}$
$L_{h(max)} = (A_h/\mu W_b)$ [arctan $(F_{eoc(90)}/A_h)$ - arctan $(F_{hel}/A_h)] + [F_{hel} / (\mu W_b)]$ ....(47)

For hook load evaluation,
$F_{eoc'} = F_{hel} + W_b \mu l_{nb}$ ....(48)

Substitute $F_{eoc'}$ in eqn. (21) with R/Reff for single/dual curved section horizontal wells respectively to obtain $F_{kop'(0)}$
***$F_{hk} = DW_b - \{A_v$ [arctan $(F_{kop'(0)}/A_v)]\}$ ....(49)

***Note that for hook load evaluation while tripping-in, the equation factor, A_v (from vertical section) remains the same for all wellbore sections.

B.4.4 At lock-up condition

$\pi/2 = [(\mu\, l_b W_b)/A_h] + \arctan(F_o/A_h)]$ ......(50)

C. CRITI-CAL TECHNIQUE
C.1 Helical Buckling Force and Lock-up

$F_{cr} = \sqrt{(2F_{1nb}EI/3r)}$ ....(51)

For $F < F_{cr}$:
$F_{1nb} = \sqrt{[(W_b \sin\theta + F_c a_i)^2 + (F_c \sin\theta a_\phi)^2]}$ ......(52)

For $F > F_{cr}$:

$$F_{1hb} = 3F^2r/EI \qquad \text{...........(53)}$$

At critical buckling load,

$$F_{cr}^2 = (2EI/3r) \cdot \sqrt{[(W_b Sin\theta + F_c a_i)^2 + (F_c Sin\theta a_\phi)^2]} \qquad \text{...........(54)}$$

(Solved by Iteration)

$$F_{in}(L) = F_{out} - \int (W_b Cos\theta - K_f F_{1c}) \cdot ds \qquad \text{..(55)}$$

$$P = (\pi/3)\sqrt{(EI/2F_a)} \qquad \text{...........(56)}$$

D. Nomenclature :

a_i - Inclination Build Rate, rad/ft.

A - Tubing wall cross-sectional area, in^2..

A_c - Equation factor in curved well section

A_h - Equation factor in horizontal well section

A_i - CT bore/internal area, in^2.

A_o - CT annular area, in^2.

A_t - Equation factor in tangent well section

A_v - Equation factor in vertical well section

$d_{blk,v}$ - buckled vertical section height/length, ft

dhel,v - Top of helical buckling in the vertical section, ft.

D - Maximum vertical depth prior to kick-off (KOP), ft ah.

D_i - CT ID., in.

D_o - CT OD., in.

$D_{v(max)}$ - Maximum vertical section operable (at zero bit weight), ft

E - Youngs Modulus (for steel), psi.

EI - Stiffness of Coiled Tubing, $lbin^2$.

f_b - Buoyancy factor based on uniform density brine fluid (SG. - 1.05), dimensionless

f_b - Buoyancy factor based on different internal and annular fluid densities (Assume Nitrified brine fluid (SG. - 0.90) as internal fluid, and brine fluid (SG. - 1.05) as annular fluid), dimensionless

F_a - Axial Load transmitted at 0 hook load condition, lbf.

F_{cr} - Critical Buckling Load, lbf

F_{hk} - Hook Load transmitted while tripping-in, lbf.

F_{hel} - Helical Buckling Load, lbf

F_{1c} - Contact Force per unit length, lb/ft.

F_{1nb} - Contact Force per unit length (for a non-buckled pipe), lb/ft.

F_{1hb} - Contact Force per unit length (for a helically buckled pipe), lb/ft.

$F_{kop(0)}$ - Kick-off point from the vertical section (at $\theta = 0$), lbf

$F_{kop(t)}$ - Kick-off point from the tangent section (at θ_t), lbf

$F_{eoc(90^\circ)}$- Pseudo load value derived for end of a pre-tangent build-up or the first curved section (at $\theta = 90$) used for intrapolating the load (e.g. $F_{kop(t)}$

at start of the tangent section, lbf.

$F_{eoc(90)}$ - Actual load at end of build-up or curved section (at $\theta = 90$), lbf.

$F_{eoc(t)}$ - Actual load at end of tangent section separating 2 curved sections (at θ_t), lbf.

I - Moment of Inertia, in^4.

K - Initial negative hook load recording while RIH (due to stripper friction, reel back tension and wellhead pressure).

L_b - Total length of buckled section, ft.

$L_{h(max)}$ - Maximum Horizontal section possible, ft.

l_{nb} - Non-buckled horizontal section length, ft.

L_{nb} - Maximum Non-buckling Horizontal section length, ft.

NP - Neutral point at which helical buckling stops, ft ah.

p - Pitch Length of Helix, ft.

r - radial clearance, in [= $(D_i$-$D_o)/2$] for the corresponding wellbore section.

R - Radius of curvature, ft. for corresponding curved wellbore section.

R_{eff} - Effective Radius of curvature, ft. (for dual-curved-section horizontal well based on $F_{kop(0)}$ and $F_{eoc(90)}$ - i.e. true axial load at horizontal section entry)

W - Weight per unit CT length, lb/ft.

x_t - Length along the tangent, ft

Z_c - Equation factor in corresponding curved wellbore section, c1, c2, etc.

6.1 Symbols

$f(\ )$ - function of ( )

α - Rate of angle build-up in curved wellbore section (degree/100 ft).

π - (22/7)

ρ_i - Density of internal drilling/workover fluid, lb/ft^3

ρ_f - Density of drilling/workover fluid, lb/ft^3

ρ_o - Density of external drilling/workover fluid, lb/ft^3

$\sigma_{y(max)}$ - Maximum Yield strength of CT material, (70,000 psi).

μ - Friction factor, dimensionless (assume = 0.3 for RIH and 0.18 for POH)

APPENDIX A
OPUKUSHI-20 CT-CLEAN-UP/WASHING FLUID PUMPING DATA (WITH 1-1/4" CT)

Sand/Wash Fluid Data

Formation Sand	E1.0A
Particle Diameter, Dp, in	0.0049
Sand Grain Density, SG	2.65
Brine SG	1.05

RESULTS

Flow Regime - Intermediate law	
Nrep	1.685
Cd	1.131
$TPSV_{(vertical)}$	0.0444 fps

Well Completion system frictional pressure loss

Well Section	Press loss, ΔP psi/1000	Length, ft	Press. loss, ΔP, psi	Remarks	N_{re}	Friction factor, *f*.
CT (bore)	179.2	11190	2005		76080	0.025
CT (wash tool/jet)	-	-	50	**Estimated	-	-
Sub-total pressure loss, psi = =>			2055			
	Fluid velocity	Length	ΔP, psi		N_{re}	R_{turb}
CT/4-1/2" SL ann.	0.730	1550	0.7	$\epsilon_h = 0.85$ (horz. section)	12480	0.71
CT/5-1/2" SL ann.	0.444	1550	0.2	Min. $V_{t(horz.)}$ reqd. at this section ~ 0.444 fps	10210	0.71
CT/4-1/2" tbg. ann.	0.745	8090	4.2	$\epsilon_v = 0.65$ (vertical section)	12560	0.80
Total Frictional Pressure loss, psi = =>			~ 2060$^+$			

***See Appendix for analytical equations.**
$^+$Max. CT working/circulating pressure, 5000 psi
****Assumption (Actual Estimates dependent on wash tool/jet configuration).**

1-1/4" CT Axial/Hook Load Sensitivity on Frictional Factor

Frictional Factor = =>	**0.2**	**0.3**	**0.4**	**0.5**
Axial Load at KOP*, lbf	1522	1243	1077	963
Hook Load at KOP, lbf	4998	4998	4998	4998
Estimated **LOP, ft ah	14500	11050	9600	8500

*KOP - Kick Off Point
**LOP - Limit of Penetration