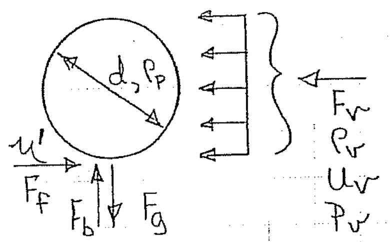
Subject: TRANSPORT AND EFFECTS OF SAND IN PRODUCED GAS



PROJECTED AREA OF SPHERE = AREA OF CIRCLE

$$A = \frac{\pi d^2}{4}$$

VOLUME OF SPHERE $V = \frac{4}{3}\pi\left(\frac{d}{2}\right)^3 = \frac{\pi d^3}{6}$

AVAILABLE DYNAMIC PRESSURE OF GAS STREAM:

$$P_v = \frac{1}{2}\rho_v U_v^2$$

PARTICLE BUOYANT FORCE: $F_b = \frac{\rho_v g \pi d^3}{6}$

PARTICLE WEIGHT: $F_g = \frac{\rho_p g \pi d^3}{6}$

PARTICLE FRICTION FORCE: $F_f = \mu'(F_g - F_b) = \frac{\mu' g \pi d^3}{6}(\rho_p - \rho_v)$

FORCE EXERTED BY GAS: $F_v = P_v A = \frac{1}{2}\rho_v U_v^2 \frac{\pi d^2}{4} = \frac{\rho_v U_v^2 \pi d^2}{8}$

EQUILIBRIUM: $F_f = F_v; \quad \frac{\mu' g \pi d^3}{6}(\rho_p - \rho_v) = \frac{\rho_v U_v^2 \pi d^2}{8}$

$$\therefore \frac{4}{3}\mu' g d = \frac{\rho_v U_v^2}{(\rho_p - \rho_v)}$$

$$\therefore U_v^2 = \frac{4}{3}\mu' g d \frac{(\rho_p - \rho_v)}{\rho_v}$$

$$\therefore U_v = \sqrt{\frac{4}{3}\mu' g \frac{(\rho_p - \rho_v)}{\rho_v} d}$$

TYPICAL VALUES FOR μ' (ROCK ON STEEL) RANGE FROM $\mu' = 0.4$ TO $\mu' = 0.7$

VERTICAL FLOW: $F_f = 0; \quad P_v A = F_g - F_b$ (AT STAGNATION FLOW)

$$\therefore \frac{1}{2}\rho_v U_v^2 \frac{\pi d^2}{4} = \frac{g \pi d^3}{6}(\rho_p - \rho_v)$$

$$\therefore \frac{\rho_v U_v^2}{8} = \frac{g}{6}(\rho_p - \rho_v) d$$

$$\therefore U_v = \sqrt{\frac{4}{3} g \frac{(\rho_p - \rho_v)}{\rho_v} d} \quad \text{(STAGNATION CASE)}$$

QUALITATIVE RATIONALIZATION OF THE COMBINED EFFECTS OF STAGNATION FORCES AND FRICTION FORCES ON THE PARTICLE

TO THIS POINT, A "ROCK TO PIPE" (SOLID TO SOLID) COEFFICIENT OF SLIDING (AND/OR ROLLING) STATIC FRICTION, μ', HAS BEEN ASSUMED IN A HORIZONTAL DIRECTION. HOWEVER, THE ACTUAL RETARDING FRICTION FORCE AT THE POINT OF CONTACT BETWEEN THE PARTICLE AND THE PIPE WALL WILL BE REDUCED IF THE GAS STREAM CAN FLOW AROUND AND OVER THE PARTICLE, AS WILL BE THE CASE FOR ANY PARTICLE DIAMETER SMALLER THAN THE PIPE DIAMETER. THE ACCELERATION OF GAS ABOVE THE PARTICLE COMBINED WITH MORE COMPLETE CONVERSION TO DYNAMIC PRESSURE BELOW THE TOP OF THE PARTICLE WILL TEND TO PRODUCE A LIFT FORCE. THE RAREFACTION OF THE GAS IN THE REGIONS OF STREAM ACCELERATION WILL REDUCE THE PARTICLE BUOYANCY SOMEWHAT, BUT IN COMBINATION WITH THE EFFECTS GIVING RISE TO LIFT, THE OVERALL RESULT EXPECTED IS AN APPARENT REDUCTION IN THE NORMAL FORCE AND THE RETARDING SOLID-TO-SOLID FRICTION FORCE. SINCE THE PARTICLE MASS AND GRAVITATIONAL ACCELERATION ARE CONSTANT, THE HORIZONTAL RETARDING FORCE CAN BE THOUGHT OF AS BEING REDUCED AS A FUNCTION OF AN EFFECTIVE OVERALL FRICTION PARAMETER THAT VARIES INVERSELY WITH THE GAS STREAM VELOCITY. DEFINING THE LIFT FORCE AS F_e AND FRICTION PARAMETER AS C:

$$F_f = C\,(F_g - F_b - F_e) = F_v = \frac{\rho_v u_v^2 \pi d^2}{8}\ ; \quad (F_g - F_b - F_e) = F_N$$

$$C\,F_N = \frac{\rho_v \pi d^2}{8} u_v^2\ ; \quad \text{LET VARIATIONS IN } F_b, F_e \text{ OCCUR IN } C$$

$$C_{(VARIABLE)}\,F_{N\,(CONSTANT)} = \frac{\rho_v \pi d^2 u_v^2}{8}\ ; \quad \text{LET } C = \frac{1}{C'}$$

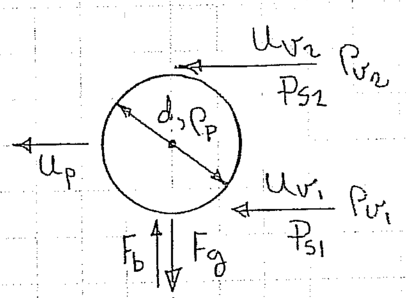
$$\frac{1}{C'} F_N = \frac{\rho_v \pi d^2}{8} u_v^2\ ; \quad \text{LET } F_N \text{ RELATE TO NON-ACCELERATED GAS}$$

$$\frac{1}{C'}(F_g - F_b) = \frac{g\pi d^3(\rho_p - \rho_v)}{C'6} = \rho_v U_v^2 \frac{\pi d^2}{8}$$

$$\frac{gd(\rho_p - \rho_v)}{6C'} = \frac{\rho_v U_v^2}{8}\ ; \quad U_v^2 = \frac{8gd(\rho_p - \rho_v)}{6C'\rho_v}$$

$$\therefore\ U_v = \sqrt{\frac{4gd(\rho_p - \rho_v)}{3\rho_v C'}} \quad \text{(DRAG CASE)}$$

THIS RESULT IS THE SAME AS EQUATION 7.1 IN GPSA, WHERE THE VARIABLE EFFECTIVE OVERALL FRICTION PARAMETER IN HORIZONTAL FLOW CORRESPONDS TO THE DRAG COEFFICIENT IN VERTICAL FLOW. HOWEVER, THE GAS STREAM VELOCITY U_v AND THE DRAG COEFFICIENT C' DERIVED FOR THE HORIZONTAL FLOW CASE ABOVE CANNOT BE THE SAME AS THOSE FOR VERTICAL FLOW IN GPSA FOR THE PARTICLE FREE SETTLING VELOCITY. RATHER, THE GAS STREAM VELOCITY FOR HORIZONTAL FLOW ABOVE MUST BE A DIFFERENCE BETWEEN THE STREAMLINE VELOCITIES TANGENTIAL TO THE BOTTOM AND TOP OF THE PARTICLE SUCH THAT LIFT AND BUOYANCY ARE IN EQUILIBRIUM WITH THE WEIGHT OF THE PARTICLE.



LET $U_{v1} = U_p$ SO $U_{v1} - U_p = 0$

LET $\rho_{v2} \cong \rho_{v1} \cong \rho_v$

$$P_{s1} + \frac{\rho_v U_{v1}^2}{2} = P_{s2} + \frac{\rho_v U_{v2}^2}{2}$$

$$P_{s1} - P_{s2} = \frac{\rho_v}{2}(U_{v2}^2 - U_{v1}^2)$$

RELATIVE TO PARTICLE WHEN $U_{v1} = U_p$:

$$P_{s1} - P_{s2} = \frac{\rho_v}{2}(\Delta U_v)^2$$

$$\Delta U_v = \sqrt{\frac{2(P_{s1} - P_{s2})}{\rho_v}}$$

IN OTHER WORDS, THE PARTICLE STAYS SUSPENDED WHEN THE DYNAMIC PRESSURE GRADIENT × PROJECTED AREA = WEIGHT.

GPSA EQUATIONS:

$$U_v = \sqrt{\frac{4\,g\,d\,(\rho_p - \rho_v)}{3\,\rho_v\,C'}}$$ GPSA EQATION 7-1

$$Re = \frac{1488\,d\,U_v\,\rho_v}{\mu}$$ GPSA EQUATION 7-2

$$C'Re^2 = \frac{(0.95)(10^8)\,\rho_v\,d^3\,(\rho_p - \rho_v)}{\mu^2}$$ GPSA EQUATION 7-3

KEEPING THE UNITS USED IN GPSA AND SUBSTITUTING 7-1 INTO 7-2:

$$Re = \frac{1488\,d\,\rho_v}{\mu}\sqrt{\frac{4gd(\rho_p-\rho_v)}{3\rho_v C'}} = \sqrt{\frac{(4)(1488^2)d^3\rho_v^2(\rho_p-\rho_v)g}{3\,\rho_v\,C'\,\mu^2}}$$

$$Re = \sqrt{\frac{(4)(1488^2)}{3C'}\,\frac{d^3\rho_v(\rho_p-\rho_v)g}{\mu^2}}\;;\quad Re^2 = \frac{(4)(1488^2)}{3C'}\,\frac{d^3\rho_v(\rho_p-\rho_v)g}{\mu^2}$$

$$C'Re^2 = \frac{(4)(1488^2)}{3}\,\frac{d^3\rho_v(\rho_p-\rho_v)g}{\mu^2} = \frac{(4)(1488^2)(32.2)}{3}\,\frac{d^3\rho_v(\rho_p-\rho_v)}{\mu^2}$$

$$C'Re^2 = 95060582.4\,\frac{d^3\rho_v(\rho_p-\rho_v)}{\mu^2} \cong (0.95)(10^8)\frac{d^3\rho_v(\rho_p-\rho_v)}{\mu^2}$$

THIS IS THE SAME AS GPSA EQUATION 7-3.

VERIFICATION OF GPSA EQUATION 7-1 IS NOT NECESSARY SINCE THE IDENTICAL EQUATION WAS DERIVED FROM FIRST PRINCIPLES WITHOUT DEPENDANCE UPON A PARTICULAR SET OF UNITS. HOWEVER, FOR THE PURPOSE OF EXAMPLE:

$g = 32.2\ \frac{ft}{s^2} = 9.81456\ \frac{m}{s^2}$

$d = 1\ ft = 0.3048\ m$

$\rho_p = 124.8\ \frac{lb}{ft^3} = 1998.76209\ \frac{kg}{m^3}$

$\rho_v = 5\ \frac{lb}{ft^3} = 80.07861\ \frac{kg}{m^3}$

$C' = 1 = 1$ (DIMENSIONLESS)

$$U_v = \sqrt{\frac{(4)(32.2)(1)(124.8-5)}{(3)(5)(1)}} = 32.0730832111\ \frac{ft}{s}$$

$$U_v = \sqrt{\frac{(4)(9.81456)(0.3048)(1998.76209-80.07861)}{(3)(80.07861)(1)}} = 9.775875723\ \frac{m}{s}$$

$$\frac{9.775875723}{32.0730832111}\ \frac{m}{s}\,\frac{s}{ft} = 0.3048\ \frac{m}{ft}\;;$$ ∴ GPSA EQUATION 7-1 IS VERIFIED.

$$Re = 1488\, d\,(ft)\, \rho_v \left(\frac{lb}{ft^3}\right) U_v \left(\frac{ft}{s}\right) \frac{1}{\mu} \left(\frac{1}{cP}\right) = 1488\, d \rho_v U_v \left(\frac{lb}{ft\,s}\right)\left(\frac{1}{cP}\right)$$

$$1\ cP = \frac{1}{1000}\ Pa \cdot s = \frac{1}{1000}\ \frac{kg\ m\ s}{m^2\ s^2} = \frac{2.205}{1000}\ \frac{lb}{m s} = \frac{2.205}{(1000)(3.28084)}\ \frac{lb}{ft\,s}$$

$$1\ cP = 6.72084 \times 10^{-4}\ \frac{lb}{ft\,s}\ ;\quad 1\ \frac{lb}{ft\,s} = \frac{1}{6.72084 \times 10^{-4}}\ cP = 1488\ cP$$

∴ TO CONVERT FROM VISCOSITY IN $\frac{lb}{ft\,s}$ TO VISCOSITY IN cP, MULTIPLY BY 1488.

SINCE GPSA ASSUMES VISCOSITY, μ, IN UNITS OF cP IN THE DENOMINATOR OF THE REYNOLDS NUMBER, THE NUMERATOR IS MULTIPLIED BY A COEFFICIENT TO CORRECT FOR THE MIXED UNITS. THEREFORE:

FOR GPSA UNITS: $Re = 1488 \frac{\rho_v U_v d}{\mu}$ ∴ GPSA EQUATION 7-2 IS VERIFIED.

FOR CONVENTIONAL UNITS: $Re = \frac{\rho_v U_v d}{\mu}$

WITHOUT USING A COEFFICIENT TO CORRECT FOR MIXED UNITS, GPSA EQUATION 7-3 CAN BE REWRITTEN:

$$C' Re^2 = C' \frac{\rho_v^2 U_v^2 d^2}{\mu^2} = \frac{C' \rho_v^2 d^2}{\mu^2} \frac{4 g d (\rho_p - \rho_v)}{3 \rho_v C'} = \frac{4g}{3} \frac{\rho_v d^3 (\rho_p - \rho_v)}{\mu^2}$$

$$C' Re^2 = \frac{4 g d^3 \rho_v (\rho_p - \rho_v)}{3 \mu^2}$$ FOR CONVENTIONAL UNITS

CORRECTING FOR THE VISCOSITY UNITS ADOPTED BY GPSA:

$$C' Re^2 = \frac{(1488)^2\, 4 g d^3 \rho_v (\rho_p - \rho_v)}{3 \mu^2}$$ FOR GPSA UNITS

ASSUME THE VALUES FROM THE PREVIOUS EXAMPLE WITH A GAS HAVING A VISCOSITY $\mu = 1\ cP = 0.001\ Pa \cdot s = 6.72084 \times 10^{-4}\ \frac{lb}{ft\,s}$.

$$C' Re^2 = \frac{(4)(9.81456)(0.3048)^3(80.07861)(1998.76209 - 80.07861)}{(3)(0.001)^2} = 56934344034.2$$

$$C' Re^2 = \frac{(1488)^2(4)(32.2)(1)^3(5)(124.8 - 5)}{(3)(1)^2} = 56941288857.6$$

$$\%\ ERROR = \frac{(100)(569.413 - 569.343)}{569.343} = 0.0123\%$$ ∴ GPSA EQUATION 7-3 IS VERIFIED.

SIMILAR RATIONALE IS APPLIED TO DEMONSTRATE THAT GPSA EQUATION 7-4 AND GPSA EQUATION 7-6 ARE VALID, AGAIN USING VALUES FROM THE EXAMPLE:

GPSA EQUATION 7-4: $U_v = 1.74\sqrt{\dfrac{g\,d\,(P_P - P_v)}{P_v}}$

$$U_v = 1.74\sqrt{\frac{(9.81456)(0.3048)(1998.8-80.1)}{80.1}} = 14.73\ \frac{m}{s}$$

$$U_v = 1.74\sqrt{\frac{(32.2)(1)(124.8-5)}{5}} = 48.33\ \frac{ft}{s}$$

$$\frac{14.73}{48.33} = 0.30478\ \frac{m}{ft} \cong 0.3048\ \frac{m}{ft};\ \text{VERIFIED.}$$

GPSA EQUATION 7-6: $U_v = \dfrac{1488\,g\,d^2(P_P - P_v)}{18\,\mu}$ WHEN IN GPSA UNITS

$$U_v = \frac{g\,d^2(P_P - P_v)}{18\,\mu}\quad \text{WHEN IN CONVENTIONAL UNITS}$$

$$U_v = \frac{(1488)(32.2)(1)^2(124.8-5)}{(18)(1)} = 318891.63\ \frac{ft}{s}$$

$$U_v = \frac{(9.81456)(0.3048)^2(1998.8-80.1)}{(18)(0.001)} = 97193.08\ \frac{m}{s}$$

$$\frac{97193.08}{318891.63} = 0.30478\ \frac{m}{ft} \cong 0.3048\ \frac{m}{ft};\ \text{VERIFIED.}$$

GPSA EQUATION 7-5: $d = K_{CR}\left[\dfrac{\mu^2}{g\,P_v(P_P - P_v)}\right]^{0.33} \cong K_{CR}\left[\dfrac{\mu^2}{g\,P_v(P_P - P_v)}\right]^{\frac{1}{3}}$

$$d^3 = K_{CR}^3\ \frac{\mu^2}{g\,P_v(P_P - P_v)}\quad \text{SO}\quad K_{CR}^3 = \frac{g\,d^3 P_v(P_P - P_v)}{\mu^2}$$

$$K_{CR} = \left[\frac{g\,d^3 P_v(P_P - P_v)}{\mu^2}\right]^{\frac{1}{3}}\quad \text{WHEN IN GPSA UNITS}$$

$$K_{CR} = \left[\frac{g\,d^3 P_v(P_P - P_v)}{(1488)^2\,\mu^2}\right]^{\frac{1}{3}}\quad \text{WHEN IN CONVENTIONAL UNITS}$$

$$K_{CR} = \left[\frac{(32.2)(1)^3(5)(124.8-5)}{(1)^2}\right]^{\frac{1}{3}} = 26.8181$$

$$K_{CR} = \left[\frac{(9.81456)(0.3048)^3(80.1)(1998.8-80.1)}{(1488)^2(0.001)^2}\right]^{\frac{1}{3}} = 26.8194$$

SIMILARLY, FOR DETERMINATION OF THE PARTICLE SIZE:

GPSA UNITS: $d = K_{CR}\left[\frac{\mu^2}{g\rho_v(\rho_p-\rho_v)}\right]^{\frac{1}{3}}$

CONVENTIONAL UNITS: $d = K_{CR}\left[\frac{(1488)^2\mu^2}{g\rho_v(\rho_p-\rho_v)}\right]^{\frac{1}{3}}$

$$d = K_{CR}\left[(1488)^2\right]^{\frac{1}{3}}\left[\frac{\mu^2}{g\rho_v(\rho_p-\rho_v)}\right]^{\frac{1}{3}}$$

$$d = (1488)^{2/3} K_{CR}\left[\frac{\mu^2}{g\rho_v(\rho_p-\rho_v)}\right]^{\frac{1}{3}}$$

$$d \cong 130.34\ K_{CR}\left[\frac{\mu^2}{g\rho_v(\rho_p-\rho_v)}\right]^{1/3}$$

$$d = K_{CR}\left[\frac{(1)^2}{(32.2)(5)(124.8-5)}\right]^{\frac{1}{3}} = 0.037288\ K_{CR}$$

$$d = 130.34\ K_{CR}\left[\frac{(0.001)^2}{(9.81456)(80.1)(1998.8-80.1)}\right]^{\frac{1}{3}} = 0.011365\ K_{CR}$$

$$\frac{0.011365\ K_{CR}\ m}{0.037288\ K_{CR}\ ft} = 0.30479\ \frac{m}{ft} \cong 0.3048\ \frac{m}{ft}$$

∴ GPSA EQUATION 7-5 IS VERIFIED.

GPSA FIGURE 7-4 INTERMEDIATE LAW: $U_v = \frac{3.54\, g^{0.71} d^{1.14}(\rho_p-\rho_v)^{0.71}}{\rho_v^{0.29}\mu^{0.43}}$

FROM EXAMPLE USING GPSA UNITS:

$$U_v = \frac{3.54\,(32.2)^{0.71}(1)^{1.14}(124.8-5)^{0.71}}{(5)^{0.29}(1)^{0.43}} = 780.88\ \frac{ft}{s}$$

ADJUSTING FOR CONVENTIONAL UNITS:

$$U_v = \frac{1}{(1488)^{0.43}}\ \frac{3.54\, g^{0.71} d^{1.14}(\rho_p-\rho_v)^{0.71}}{\rho_v^{0.29}\mu^{0.43}}$$

$$U_v \cong \frac{0.153\, g^{0.71} d^{1.14}(\rho_p-\rho_v)^{0.71}}{\rho_v^{0.29}\mu^{0.43}}$$

$$U_v = \frac{0.153\,(9.81456)^{0.71}(0.3048)^{1.14}(1998.8-80.1)^{0.71}}{(80.1)^{0.29}(0.001)^{0.43}} = 234.20\ \frac{m}{s}$$

$$\frac{234.20}{780.88} = 0.29992\ \frac{m}{ft}\ ;\quad \%\ \text{ERROR} = \frac{(100)(0.3048-0.29992)}{0.29992} = 1.63\%$$

THIS IS REASONABLY CLOSE. ∴ GPSA FIGURE 7-4 INTERMEDIATE LAW IS VERIFIED.

Subject: TRANSPORT AND EFFECTS OF SAND IN PRODUCED GAS

GPSA FIGURE 7-3 IS ANALYZED IN AN ATTEMPT TO FIND A FUNCTION THAT DEFINES THE DRAG COEFFICIENT AS A FUNCTION OF REYNOLDS NUMBER ALONE. A SUITABLE EQUATION IS FIT USING A SHAREWARE PROGRAM.

$C'Re^2$	C'	$Re = \sqrt{\frac{C'Re^2}{C'}}$	$C'Re^2$	C'	$Re = \sqrt{\frac{C'Re^2}{C'}}$
0.1	4000	0.005	6000	1.2	70.711
1	400	0.050	7000	1.15	78.019
10	60	0.408	8000	1.1	85.280
20	35	0.756	9000	1.05	92.582
30	26	1.074	10000	1	100.000
40	20	1.414	20000	0.81	157.135
50	17	1.715	30000	0.725	203.419
60	15	2.000	40000	0.685	241.649
70	13	2.320	50000	0.64	279.508
80	11.5	2.638	60000	0.61	313.625
90	10.5	2.928	70000	0.595	342.997
100	9.75	3.203	80000	0.585	369.800
200	6.1	5.726	90000	0.57	397.360
300	4.8	7.906	100000	0.56	422.577
400	4	10.000	200000	0.5	632.456
500	3.5	11.952	300000	0.49	782.461
600	3.15	13.801	400000	0.47	922.531
700	3	15.275	500000	0.45	1054.093
800	2.95	16.468	600000	0.445	1161.169
900	2.9	17.617	700000	0.44	1261.312
1000	2.85	18.732	800000	0.435	1356.127
2000	1.95	32.026	900000	0.43	1446.728
3000	1.5	44.721	1000000	0.425	1533.930
4000	1.4	53.452	10000000	0.41	4938.648
5000	1.3	62.017	100000000	0.4	15811.388

USING SHAREWARE PROGRAM "XYMATH.EXE", AN EQUATION IS DETERMINED.

$$\ln C' = k_1 + k_2 \ln Re + \frac{k_3}{Re} + \frac{k_4}{Re^2} + k_5 (\ln Re)^2$$

$k_1 = 3.3639336472$
$k_2 = -0.9853444154$
$k_3 = -0.0456173473$
$k_4 = 0.0001810592151$
$k_5 = 0.0559105549$

RE-WRITING THIS EQUATION TO OBTAIN C' DIRECTLY:

$$C' = e^{\left[k_1 + k_2 \ln Re + \frac{k_3}{Re} + \frac{k_4}{Re^2} + k_5 (\ln Re)^2\right]}$$

WITH THE DATA GIVEN AS READ FROM THE CURVE IN GPSA FIGURE 7-3, THIS EQUATION PRODUCES AN AVERAGE ERROR OF 1.95 %. AS A RANDOM CHECK, ASSUME A DRAG COEFFICIENT $C' = 20$. FROM GPSA FIGURE 7-3, $C'Re^2 = 40$, FROM WHICH $Re = \sqrt{2}$. FROM THE EQUATION DERIVED ABOVE:

$$C' = e^{\left[k_1 + k_2 \ln \sqrt{2} + \frac{k_3}{\sqrt{2}} + \frac{k_4}{2} + k_5 (\ln \sqrt{2})^2\right]} = 20.027 \cong 20.$$

IN ALL OF THE FOREGOING, THE VELOCITY AND REYNOLDS NUMBER ARE DETERMINED RELATIVE TO THE PARTICLE'S DIMENSIONS AND FRAME OF REFERENCE. TO KEEP THE PARTICLE FROM SETTLING OUT OF THE GAS STREAM, GAS MUST SLIP AROUND IT. IN OTHER WORDS, WITHOUT THE GAS TRAVELLING FASTER THAN THE PARTICLE, THERE CAN BE NO LIFT OR DRAG EFFECTS. THEREFORE, THE VELOCITY CAN BE THOUGHT OF AS A "SLIP VELOCITY" THAT IS EQUAL TO THE FREE SETTLING TERMINAL VELOCITY OF THE PARTICLE. SUBTRACTING THIS "SLIP VELOCITY" FROM THE ACTUAL ABSOLUTE VELOCITY OF THE GAS FLOWING IN THE PIPE WILL YIELD THE ACTUAL ABSOLUTE VELOCITY OF THE PARTICLE RELATIVE TO A STATIONARY FRAME OF REFERENCE. THE ACTUAL ABSOLUTE VELOCITY OF THE PARTICLE IS OF THE MOST INTEREST IN CONSIDERATION OF THE EFFECTS OF ABRASION. IN THE ANALYSIS THAT FOLLOWS, THE ACTUAL FLOW PATTERNS AND PRESSURE DROPS IN THE PIPE ARE NOT CONSIDERED AS RELEVANT AS THE PARTICLE VELOCITY DISTRIBUTION.

THE VELOCITY OF THE CLEAN GAS FLOWING IN THE PIPE IS CORRECTED FOR SOLIDS LOADING.

LET $E = \dfrac{\text{MASS FLOW RATE OF PARTICLES}}{\text{MASS FLOW RATE OF PARTICLES + MASS FLOW RATE OF CLEAN GAS}}$

LET $E_Q = \dfrac{\text{VOLUME FLOW RATE OF PARTICLES}}{\text{VOLUME FLOW RATE OF PARTICLES + VOLUME FLOW RATE OF CLEAN GAS}}$

$$E = \frac{\dot{m}_p}{\dot{m}_p + \dot{m}_g} \; ; \quad 1-E = \frac{\dot{m}_p + \dot{m}_g}{\dot{m}_p + \dot{m}_g} - \frac{\dot{m}_p}{\dot{m}_p + \dot{m}_g} = \frac{\dot{m}_g}{\dot{m}_p + \dot{m}_g}$$

$$E_Q = \frac{\dfrac{\dot{m}_p}{\rho_p}}{\dfrac{\dot{m}_p}{\rho_p} + \dfrac{\dot{m}_g}{\rho_g}} \; ; \quad 1-E_Q = \frac{\dfrac{\dot{m}_p}{\rho_p} + \dfrac{\dot{m}_g}{\rho_g}}{\dfrac{\dot{m}_p}{\rho_p} + \dfrac{\dot{m}_g}{\rho_g}} - \frac{\dfrac{\dot{m}_p}{\rho_p}}{\dfrac{\dot{m}_p}{\rho_p} + \dfrac{\dot{m}_g}{\rho_g}} = \frac{\dfrac{\dot{m}_g}{\rho_g}}{\dfrac{\dot{m}_p}{\rho_p} + \dfrac{\dot{m}_g}{\rho_g}}$$

$$Q_g = Q_{go} \frac{1}{1-E_Q} = Q_{go} \frac{\left(\dfrac{\dot{m}_p}{\rho_p} + \dfrac{\dot{m}_g}{\rho_g}\right)}{\left(\dfrac{\dot{m}_g}{\rho_g}\right)} = Q_{go} \frac{\rho_g}{\dot{m}_g}\left(\frac{\dot{m}_p}{\rho_p} + \frac{\dot{m}_g}{\rho_g}\right)$$

$$Q_g = Q_{go}\left(\frac{\rho_g \dot{m}_p}{\rho_p \dot{m}_g} + 1\right) = Q_{go}\left(\frac{Q_p}{Q_g} + 1\right) = Q_{go}\left(\frac{Q_p + Q_g}{Q_g}\right) = Q_{go}\left(\frac{\dot{m}_p}{\rho_p Q_g} + 1\right)$$

THERE ARE THUS THREE FORMS FOR THE EQUATION FOR GAS VELOCITY CORRECTION AS A FUNCTION OF SOLIDS LOADING:

$U_g = U_{go}\left(\dfrac{Q_p + Q_g}{Q_g}\right)$ FOR WHEN VOLUMETRIC FLOW RATES ARE GIVEN

$U_g = U_{go}\left(\dfrac{\rho_g \dot{m}_p}{\rho_p \dot{m}_g} + 1\right)$ FOR WHEN MASS FLOW RATES ARE GIVEN

$U_g = U_{go}\left(\dfrac{\dot{m}_p}{\rho_p Q_g} + 1\right)$ FOR RATES GIVEN IN $\left(\dfrac{\text{MASS FLOW RATE OF PARTICLES}}{\text{VOLUMETRIC FLOW RATE OF CLEAN GAS}}\right)$

NOTE THAT IT IS THE CORRECTED CLEAN GAS VELOCITY THAT IS USED TO ESTABLISH THE TRUE PARTICLE VELOCITY AND PIPE FLOW REYNOLDS NUMBER.

$$U_{go}\left(\frac{\dot{m}_p}{\rho_p Q_g} + 1\right) - U_v = U_p \; ; \quad Re_g = \frac{\rho_g D}{\mu} U_{go}\left(\frac{\dot{m}_p}{\rho_p Q_g} + 1\right)$$

$$U_{go}\left(\frac{\dot{m}_p}{\rho_p Q_g} + 1\right) - \sqrt{\frac{4gd(\rho_p - \rho_v)}{3\rho_v C'}} = U_p$$

WHERE Re_g = PIPE FLOW REYNOLDS NUMBER AND D = PIPE INTERNAL DIAMETER.

IT MAY BE USEFUL TO DEFINE REYNOLDS NUMBER RATIOS AS FOLLOWS:

$$\frac{Re_g}{Re} = \frac{\text{REYNOLDS NUMBER OF GAS FLOW IN PIPE}}{\text{REYNOLDS NUMBER OF PARTICLE TERMINAL VELOCITY}}$$

$$\frac{Re_g}{Re} = \frac{\rho_g D U_{go}}{\mu (1-E_Q)} \frac{\mu}{\rho_v d \sqrt{\frac{4gd(\rho_P-\rho_v)}{3\rho_v C'}}} = \frac{D U_{go}}{d(1-E_Q)} \frac{1}{\sqrt{\frac{4gd(\rho_P-\rho_v)}{3\rho_v C'}}}$$

$$\left(\frac{Re_g}{Re}\right)^2 = \frac{D^2 U_{go}^2 \, 3\rho_v C'}{d^2(1-E_Q)^2 4gd(\rho_P-\rho_v)} \quad \text{SO} \quad \frac{Re_g}{Re} = \frac{D U_{go}}{d(1-E_Q)}\sqrt{\frac{3\rho_v C'}{4gd(\rho_P-\rho_v)}}$$

IN THE ABOVE, IT IS ASSUMED THAT THE EFFECTS OF GAS RAREFACTION AROUND THE PARTICLE DO NOT SIGNIFICANTLY ALTER THE DENSITY AND VISCOSITY OF THE GAS, i.e., $\rho_g = \rho_v$ AND $\mu_g = \mu_v = \mu$. THE REYNOLDS NUMBER OF THE GAS FLOWING IN THE PIPE AT ITS CORRECTED VELOCITY CAN THEN BE GIVEN BY:

$$Re_g = Re \frac{D U_{go}}{d(1-E_Q)}\sqrt{\frac{3\rho_v C'}{4gd(\rho_P-\rho_v)}} = \frac{Re\, D\, 4Q_{go}}{d(1-E_Q)\pi D^2}\sqrt{\frac{3\rho_v C'}{4gd(\rho_P-\rho_v)}}$$

$$Re_g = \frac{4 Re\, Q_{go}}{\pi D d(1-E_Q)}\sqrt{\frac{3\rho_v C'}{4gd(\rho_P-\rho_v)}}$$

THIS IS ONLY VALID WHEN THERE IS A SINGLE UNIQUE PARTICLE DIAMETER d, OR IF d REPRESENTS AN AVERAGE PARTICLE DIAMETER.

RECALLING THAT $\frac{1}{1-E_Q} = \left(\frac{Q_P + Q_g}{Q_g}\right) = \left(\frac{\rho_g \dot{m}_P}{\rho_P \dot{m}_g} + 1\right) = \left(\frac{\dot{m}_P}{\rho_P Q_g} + 1\right)$:

$$Re_g = \frac{4 Re\, Q_{go}}{\pi D d}\left(\frac{Q_P + Q_g}{Q_g}\right)\sqrt{\frac{3\rho_v C'}{4gd(\rho_P-\rho_v)}}$$

$$Re_g = \frac{4 Re\, Q_{go}}{\pi D d}\left(\frac{\rho_g \dot{m}_P}{\rho_P \dot{m}_g} + 1\right)\sqrt{\frac{3\rho_v C'}{4gd(\rho_P-\rho_v)}}$$

$$Re_g = \frac{4 Re\, Q_{go}}{\pi D d}\left(\frac{\dot{m}_P}{\rho_P Q_g} + 1\right)\sqrt{\frac{3\rho_v C'}{4gd(\rho_P-\rho_v)}}$$

NOTE THAT THE EQUATIONS DERIVED ABOVE ASSUME CONVENTIONAL, UNMIXED UNITS. IN FACT, ALL EQUATIONS USED IN ACTUAL SPECIFIC CALCULATIONS SHOULD - AND WILL - USE CONVENTIONAL, UNMIXED UNITS.

∴ PARTICLE SIZE CONVERSION:
1 MICRON = 3.28084×10^{-6} ft
1 MICRON = 3.93701×10^{-5} in
1 MICRON = 1×10^{-6} m = 1×10^{-3} mm

Subject: TRANSPORT AND EFFECTS OF SAND IN PRODUCED GAS

FROM DATA CONTAINED IN THE REPORT ENTITLED:

"WELLHEAD SAND PRODUCTION & HANDLING"

THE FOLLOWING INFORMATION IS ASSUMED AS CORRECT:

PARTICLE DIAMETER μM	CUMULATIVE VOLUME %	PARTICLE DIAMETER RANGE μM - μM	GROUP VOLUME %
1	0.36	0 - 1	0.36
5	1.76	1 - 5	1.40
10	2.62	5 - 10	0.86
20	3.79	10 - 20	1.17
50	7.89	20 - 50	4.10
100	24.30	50 - 100	16.41
200	39.60	100 - 200	15.30
400	59.10	200 - 400	19.50
1000	100.00	400 - 1000	40.90

GAS TO WATER RATIO: $GWR = \frac{1\ MMSCF}{5\ bbl}$

SAND TO WATER RATIO: SWR = 0.02 - 0.05

(THIS SAND IS PART OF THE WATER CONSIDERED IN GWR.)

THE FOLLOWING DATA ARE ASSUMED IN ORDER TO ESTIMATE THE PARTICLE DENSITY (S.G. RELATIVE TO WATER):

ANDESITE	S.G. = 2.5-2.8	LIMESTONE	S.G. = 2.3-2.7
BASALT	S.G. = 2.8-3.0	MARBLE	S.G. = 2.4-2.7
COAL	S.G. = 1.1-1.4	MICA SCHIST	S.G. = 2.5-2.9
DIABASE	S.G. = 2.6-3.0	PERIDOTITE	S.G. = 3.1-3.4
DIORITE	S.G. = 2.8-3.0	QUARTZITE	S.G. = 2.6-2.8
DOLOMITE	S.G. = 2.8-2.9	RHYOLITE	S.G. = 2.4-2.6
GABBRO	S.G. = 2.7-3.3	ROCK SALT	S.G. = 2.5-2.6
GNEISS	S.G. = 2.6-2.9	SANDSTONE	S.G. = 2.2-2.8
GRANITE	S.G. = 2.6-2.7	SHALE	S.G. = 2.4-2.8
GYPSUM	S.G. = 2.3-2.8	SLATE	S.G. = 2.7-2.8

(DATA FROM http://geology.about.com/cs/rock_types/a/aarockspecgrav.htm)

BASED ON THE ABOVE DATA, IT IS REASONABLE TO ASSUME S.G. = 2.7.

REPRESENTATIVE CASE:

GAS MOLECULAR WEIGHT = 17.35
GAS COMPRESSIBILITY = 0.766
GAS TEMPERATURE = 10 °C
GAS VISCOSITY = 0.013 cP
GAS PRESSURE = 24000 kPag
GAS PIPING = 3" NPS XXH
GAS FLOW RATE = 3 MMSCFD

HYSIS DATA: $\mu_g = 0.013$ cP, $\rho_g = 236.1 \frac{kg}{m^3}$

$$\frac{P}{zRT} = \frac{PM}{z\bar{R}T} = \rho = \frac{(24101325)(17.35)}{(0.766)(8314)(283.15)} = 231.9 \frac{kg}{m^3}$$

$$\frac{3\times10^6\ ft^3}{24\times60\times60\ s} \times \frac{0.3048^3\ m^3}{1\ ft^3} = Q_s = 0.983 \frac{m^3}{s}$$ AT STANDARD CONDITIONS

$$\frac{\pi D^2}{4} = \frac{\pi}{4}(0.0584)^2 = A = 0.002679\ m^2$$

$$\frac{P_s}{zRT_s} = \frac{P_s M}{z\bar{R}T_s} = \frac{(101325)(17.35)}{(0.98)(8314)(273.15)} = \rho_s = 0.7899 \frac{kg}{m^3}$$ (STANDARD)

$$\dot{m} = Q_s \rho_s = 0.983 \frac{m^3}{s} \times 0.7899 \frac{kg}{m^3} = 0.7765 \frac{kg}{s}$$ (STANDARD)

$$\frac{\dot{m}}{\rho} = Q = 0.7765 \frac{kg}{s} \times \frac{1}{231.9} \frac{m^3}{kg} = 0.00334843 \frac{m^3}{s}$$ (FLOWING)

$$\frac{Q}{A} = u = \frac{0.003348}{0.002679} = 1.24972 \frac{m}{s}$$

$$Re_g = \frac{\rho u D}{\mu} = \frac{(231.9)(1.24972)(0.0584)}{0.013\times10^{-3}} = 1301916$$

ASSUME A PARTICLE SIZE OF 1000 MICRONS AND THE DENSITY OF QUARTZITE; $d = 0.001$ m AND $\rho_p = 2700 \frac{kg}{m^3}$.

$$C'Re^2 = \frac{4gd^3\rho_v(\rho_p-\rho_v)}{3\mu^2} = \frac{(4)(9.80665)(0.001)^3(231.9)(2700-231.9)}{(3)(0.013\times10^{-3})^2}$$

$C'Re^2 = 44282915.7033$; CLEARLY $C' \cong 0.4$

$$Re = \sqrt{\frac{C'Re^2}{C'}} = \sqrt{\frac{44282915.7033}{0.4}} = 10521.7531 = 10522$$

$$u_v = \sqrt{\frac{4gd(\rho_p-\rho_v)}{3\rho_v C'}} = \sqrt{\frac{(4)(9.80665)(0.001)(2700-231.9)}{(3)(231.9)(0.4)}} = 0.58984 \frac{m}{s}$$

SINCE $U > U_v$, THE PARTICLE WILL BE CARRIED IN THE GAS STREAM AND WILL NOT SETTLE IN THE PIPE.

VERIFICATION USING GPSA EQUATIONS AND UNITS:

$$C'Re^2 = \frac{(0.95\times10^8)(14.479)(0.003281)^3(168.583-14.479)}{(0.013)^2} = 44300443$$

$$C' = 0.4,\ Re = \sqrt{\frac{44300443}{0.4}} = 10524$$

$$U_v = \sqrt{\frac{(4)(32.2)(0.003281)(168.583-14.479)}{(3)(14.479)(0.4)}} = 1.93601\ \frac{ft}{s}$$

$$1.93601 \times 0.3048 = 0.59010\ \frac{m}{s}\quad \therefore\ \text{RESULTS VERIFIED}$$

THE ACTUAL PARTICLE VELOCITY $U_p = U - U_v = 1.24972 - 0.59010\ \frac{m}{s}$

$U_p = 0.65988\ \frac{m}{s}$ (NOT CORRECTED FOR SOLIDS LOADING %)

AN EQUATION SIMILAR TO THE ONE DETERMINED ON PAGE 9 IS HERE DETERMINED, BASED ON THE DATA PRESENTED ON PAGE 8. THE EQUATION BELOW RELATES THE QUANTITY $C'Re^2$ TO C', CONSISTENT WITH GPSA FIGURE 7-3. THE EQUATION DIFFERS SOMEWHAT FROM THE ONE DETERMINED PREVIOUSLY.

$$\ln C' = K_6 + K_7(C'Re^2) + K_8 \ln(C'Re^2) + \frac{K_9}{(C'Re^2)} + K_{10}[\ln(C'Re^2)]^2$$

$K_6 = 6.0933348735$

$K_7 = -7.0985285430 \times 10^{-9}$

$K_8 = -0.9794536944$

$K_9 = -0.02440312772$

$K_{10} = 0.03457498950$

RE-WRITING THIS EQUATION TO OBTAIN C' DIRECTLY:

$$C' = e^{\left[K_6 + K_7(C'Re^2) + K_8\ln(C'Re^2) + \frac{K_9}{(C'Re^2)} + K_{10}(\ln(C'Re^2))^2\right]}$$

WITH THE DATA GIVEN AS READ FROM THE CURVE IN GPSA FIGURE 7-3, THIS EQUATION PRODUCES AN AVERAGE ERROR OF 3.39 %, WHICH IS ADEQUATE TO COMPUTE C' WHEN Re IS NOT DIRECTLY KNOWN.

Subject: TRANSPORT AND EFFECTS OF SAND IN PRODUCED GAS

FOR THE WELL, AN ANALYSIS OF THE ACTUAL SAND COMPOSITION HAS BEEN PROVIDED BY CORE LABORATORIES. ATTEMPTS TO FIT AN EQUATION TO THE CURVE WITH A HIGH LEVEL OF ACCURACY HAVE BEEN UNSUCCESSFUL. POLYNOMIAL FITS OF BOTH 5-DEGREE (6 TERMS) AND 18-DEGREE (19 TERMS) BOTH PRODUCED LOCAL MAXIMA AND MINIMA THAT DEPRESSED THE CURVE BELOW THE ABSCISSA, WHICH IS INVALID. IN GENERAL, THE BEST CURVE DESCRIBING THE PARTICLE SIZE DISTRIBUTION FOR THE SAMPLE IS AN S-CURVE OR ADJUSTED SIGMOID FUNCTION RELATING PARTICLE SIZE TO CUMULATIVE VOLUME. THE GRAPHING FEATURES OF MICROSOFT EXCEL WERE USED TO ADJUST THE VARIABLES IN SUCH A FUNCTION UNTIL A CURVE WAS PRODUCED THAT, WHEN SUPERIMPOSED OVER THE CURVE FOR THE ACTUAL DATA, PROVIDED A REASONABLY CLOSE FIT WITH AN AVERAGE ERROR OF APPROXIMATELY ±35%. ACCORDINGLY:

$$\frac{V_{CUMULATIVE}}{V_{TOTAL\ SAND}} = \frac{1}{1+e^{-k_{11}(\ln d - k_{12})}}$$ WHERE $k_{11} = 1.50$ AND $k_{12} = 5.35$

$$\therefore \frac{V_{CUMULATIVE}}{V_{TOTAL\ SAND}} = \frac{1}{1+e^{-1.50(\ln d - 5.35)}}$$; d = PARTICLE DIAMETER (MICRONS)

FOR DETAILED CALCULATIONS USING MICROSOFT EXCEL, THE ABOVE EQUATION IS SIMPLY REPLACED BY A DATA TABLE LOOK-UP FUNCTION.

$$\therefore \frac{V_{CUMULATIVE}}{V_{TOTAL\ SAND}} = \Psi(d, V_{CUMULATIVE}) \cong \frac{1}{1+e^{-1.50(\ln d - 5.35)}}$$

FOR THE PURPOSE OF SIMPLIFYING THE NOMENCLATURE, THE FUNCTION $\Psi(d, V_{CUMULATIVE}) = \Psi$.

$\therefore$ FOR EACH CRITICAL PARTICLE SIZE d (i.e., THE MAXIMUM SIZE OF PARTICLE THAT CAN BE CARRIED IN THE GAS STREAM, NEGLECTING THE MOVING BED FLOW PATTERN MODE OF TRANSPORT):

FRACTION OF SAND VOLUME CARRIED = Ψ

FRACTION OF SAND VOLUME SETTLED = $1 - \Psi$

AN EXAMPLE CALCULATION FOLLOWS FOR THE INLET SEPARATOR TO ILLUSTRATE THE CALCULATION METHOD AND TO SERVE AS VERIFICATION FOR THE SPREADSHEET RUNS.

EXAMPLE: INLET SEPARATOR

ASSUMPTIONS:

I.D. = 1486 mm	=	D_1
OUTLET MESH PAD = 478 mm-ϕ = 0.478 m	=	D_2
PRESSURE = 1034 kPag = 1135325 Pa	=	P
TEMPERATURE = 10 °C = 283.15 °K	=	T
FLOW RATE = 10 MMSCFD = 3.275 $Sm^3 s^{-1}$	=	Q_{g0} (STD)
GAS M.W. = 17.35	=	MW
GAS Z = 0.98	=	Z
GAS μ = 0.013 cP = 1.3×10^{-5} Pa·s	=	μ
SAND ρ = 2700 $\frac{kg}{m^3}$	=	ρ_p
$\frac{\text{SAND}}{\text{GAS + SAND}}$ VOLUME FRACTION = 0.03	=	E_a

$$\rho_g \cong \rho_{g0} = \frac{PM}{ZRT} = \frac{(1135325)(17.35)}{(0.98)(8314)(283.15)} = 8.538 \frac{kg}{m^3} = \rho_v$$

AT STANDARD CONDITIONS: $\frac{P_{ST}\,M}{Z_{ST}\,R\,T_{ST}} = \frac{(101325)(17.35)}{(0.98)(8314)(273.15)} = 0.790 \frac{kg}{Sm^3}$

$$\dot{m}_g = 0.790 \frac{kg}{Sm^3} \times 3.275 \frac{Sm^3}{s} = 2.587 \frac{kg}{s}$$

$$Q_g = \frac{Q_{a0}}{1-E_a}\,\frac{\rho_a(STD)}{\rho_g(FLOWING)} = \frac{3.275}{1-0.03}\times\frac{0.790}{8.538} = 0.3124 \frac{m^3}{s}$$

$$\frac{4Q_g}{\pi D_2^2} = U_g(\text{MESH PAD}) = \frac{(4)(0.3124)}{(\pi)(0.478)^2} = U_g = 1.741 \frac{m}{s}$$

FOR PARTICLE EQUILIBRIUM: $U_g = U_v = 1.741 \frac{m}{s} = \sqrt{\frac{4g(\rho_p-\rho_v)d}{3\rho_v C'}}$

$$Re_p = \frac{\rho_v U_v d}{\mu} = \frac{(8.538)(1.741)(d)}{1.3\times10^{-5}} = 1143435\,d$$

$$C'Re_p^2 = C'\left(\frac{\rho_v U_v d}{\mu}\right)^2 = \frac{C'\rho_v^2 U_v^2 d^2}{\mu^2}\,;\quad U_v^2 = \frac{4g(\rho_p-\rho_v)d}{3\rho_v C'}$$

$$C'Re_p^2 = \left(\frac{C'\rho_v^2 d^2}{\mu^2}\right)\left(\frac{4g(\rho_p-\rho_v)d}{3\rho_v C'}\right) = \frac{4g\rho_v d^3(\rho_p-\rho_v)}{3\mu^2}$$

THE "GOAL SEEK" FEATURE OF MICROSOFT EXCEL IS USED TO CONVERGE TOWARDS A UNIQUE SOLUTION IN WHICH:

(1.) $C'Re^2 = \dfrac{4gP_v(P_P - P_v)}{3\mu^2} d^3$

(2.) $f(C'Re^2) = f\left(\dfrac{4gP_v(P_P-P_v)}{3\mu^2} d^3\right) = e^{\left[K_6 + K_7(C'Re^2) + K_8 \ln(C'Re^2) + \frac{K_9}{(C'Re^2)} + K_{10}(\ln(C'Re^2))^2\right]}$

i.e., $C' = e^{\left[K_6 + K_7(C'Re^2) + K_8 \ln(C'Re^2) + \frac{K_9}{(C'Re^2)} + K_{10}(\ln(C'Re^2))^2\right]}$

(3.) $U_g - U_v = 0 = \left(\dfrac{4Q_g}{\pi D_2^2} - \sqrt{\dfrac{4gd(P_P - P_v)}{3P_v C'}}\right) = \left(1.741 - \sqrt{\dfrac{4gd(P_P-P_v)}{3P_v C'}}\right)$

i.e., $U_v = \sqrt{\dfrac{4gd(P_P - P_v)}{3P_v C'}}$

CONVERGENCE IS ACHIEVED AT $d = 396 \times 10^{-6}$ m = 396 MICRONS, WHICH CAN BE VERIFIED BY CHECKING:

(1.) $C'Re^2 = \dfrac{(4)(9.80665)(8.538)(2700-8.538)}{(3)(1.3\times10^{-5})^2} (396\times10^{-6})^3 = 110409$

(2.) $C' = e^{\left[K_6 + K_7(110409) + K_8 \ln(110409) + \frac{K_9}{(110409)} + K_{10}(\ln(110409))^2\right]}$

WHERE:
$K_6 = 6.0933348735$
$K_7 = -7.0985285430 \times 10^{-9}$
$K_8 = -0.9794536944$
$K_9 = -0.02440312772$
$K_{10} = 0.03457498950$

FROM WHICH $C' = 0.53858240$

(3.) $U_v = \sqrt{\dfrac{(4)(9.80665)(396\times10^{-6})(2700-8.538)}{(3)(8.538)(0.53858240)}} \cong 1.741 \ \dfrac{m}{s}$

$\therefore U_g - U_v = 1.741 - 1.741 = 0$

FINALLY, INSTEAD OF USING THE APPROXIMATION GIVEN BY THE ADJUSTED SIGMOID FUNCTION, THE MICROSOFT EXCEL TABLE LOOK-UP FEATURE IS USED TO OBTAIN:

$\psi = 63.07$ % SOLIDS ARE CARRIED OVER INTO THE MESH PAD.
$1 - \psi = 36.93$ % SOLIDS SETTLE OUT IN THE INLET SEPARATOR.

— END OF EXAMPLE —

Prediction Of Critical Particle Size and Sand Settlement In Piping
Based On Site-Specific Core-Lab Analysis Of Solids Composition

d (microns) = Theoretical maximum size of particle carried in gas stream, microns
% Carried = Total percent of solids (based on Core Lab analysis) carried in gas stream, %
% Settled = Total percent of solids (based on Core Lab analysis) predicted to settle out of gas stream, %

kPag	MMSCFD	NPS	SCH	d (microns)	% Carried	% Settled
24000	3	2	xxs	2510	100.00	0.00
24000	3	2	160	2510	100.00	0.00
24000	3	2	80	2510	100.00	0.00
24000	3	2	40	2298	100.00	0.00
24000	3	3	xxs	1966	100.00	0.00
24000	3	3	160	1710	100.00	0.00
24000	3	3	80	1586	100.00	0.00
24000	3	3	40	1406	99.99	0.01
24000	3	4	xxs	1326	99.99	0.01
24000	3	4	160	1102	99.94	0.06
24000	3	4	80	736	91.78	8.22
24000	3	4	40	574	82.95	17.05
24000	3	6	xxs	252	46.80	53.20
24000	3	6	160	208	41.86	58.14
24000	3	6	80	153	33.47	66.53
24000	3	6	40	134	31.45	68.55
24000	3	8	xxs	98	24.25	75.75
24000	3	8	160	100	24.25	75.75
24000	3	8	80	78	16.09	83.91
24000	3	8	40	71	13.76	86.24
24000	3	10	xxs	59	10.17	89.83
24000	3	10	160	62	11.78	88.22
24000	3	10	80	50	7.88	92.12
24000	3	10	40	46	7.06	92.94
24000	3	12	xxs	31	4.92	95.08
24000	3	12	160	45	7.06	92.94
24000	3	12	80	37	5.82	94.18
24000	3	12	40	34	5.34	94.66

Prediction Of Critical Particle Size and Sand Settlement In Piping
Based On Site-Specific Core-Lab Analysis Of Solids Composition

d (microns) = Theoretical maximum size of particle carried in gas stream, microns
% Carried = Total percent of solids (based on Core Lab analysis) carried in gas stream, %
% Settled = Total percent of solids (based on Core Lab analysis) predicted to settle out of gas stream, %

kPag	MMSCFD	NPS	SCH	d (microns)	% Carried	% Settled
24000	3.884	2	xxs	3688	100.00	0.00
24000	3.884	2	160	3050	100.00	0.00
24000	3.884	2	80	2453	100.00	0.00
24000	3.884	2	40	2228	100.00	0.00
24000	3.884	3	xxs	2053	100.00	0.00
24000	3.884	3	160	1936	100.00	0.00
24000	3.884	3	80	1721	100.00	0.00
24000	3.884	3	40	1640	100.00	0.00
24000	3.884	4	xxs	1710	100.00	0.00
24000	3.884	4	160	1453	100.00	0.00
24000	3.884	4	80	1166	99.94	0.06
24000	3.884	4	40	1010	99.65	0.35
24000	3.884	6	xxs	418	63.07	36.93
24000	3.884	6	160	329	55.49	44.51
24000	3.884	6	80	225	44.27	55.73
24000	3.884	6	40	192	39.59	60.41
24000	3.884	8	xxs	135	31.45	68.55
24000	3.884	8	160	138	31.45	68.55
24000	3.884	8	80	104	24.25	75.75
24000	3.884	8	40	93	21.48	78.52
24000	3.884	10	xxs	77	16.09	83.91
24000	3.884	10	160	82	18.71	81.29
24000	3.884	10	80	64	11.78	88.22
24000	3.884	10	40	58	10.17	89.83
24000	3.884	12	xxs	38	5.82	94.18
24000	3.884	12	160	57	10.17	89.83
24000	3.884	12	80	46	7.88	92.12
24000	3.884	12	40	42	7.06	92.94

Prediction Of Critical Particle Size and Sand Settlement In Piping
Based On Site-Specific Core-Lab Analysis Of Solids Composition

d (microns) = Theoretical maximum size of particle carried in gas stream, microns
% Carried = Total percent of solids (based on Core Lab analysis) carried in gas stream, %
% Settled = Total percent of solids (based on Core Lab analysis) predicted to settle out of gas stream, %

kPag	MMSCFD	NPS	SCH	d (microns)	% Carried	% Settled
24000	8	2	xxs	2951	100.00	0.00
24000	8	2	160	2658	100.00	0.00
24000	8	2	80	2510	100.00	0.00
24000	8	2	40	2510	100.00	0.00
24000	8	3	xxs	2651	100.00	0.00
24000	8	3	160	2510	100.00	0.00
24000	8	3	80	2155	100.00	0.00
24000	8	3	40	2154	100.00	0.00
24000	8	4	xxs	2510	100.00	0.00
24000	8	4	160	2235	100.00	0.00
24000	8	4	80	1899	100.00	0.00
24000	8	4	40	1787	100.00	0.00
24000	8	6	xxs	1476	100.00	0.00
24000	8	6	160	1328	99.99	0.01
24000	8	6	80	1035	99.65	0.35
24000	8	6	40	841	97.36	2.64
24000	8	8	xxs	462	67.62	32.38
24000	8	8	160	483	72.60	27.40
24000	8	8	80	299	52.34	47.66
24000	8	8	40	254	46.80	53.20
24000	8	10	xxs	189	39.59	60.41
24000	8	10	160	206	41.86	58.14
24000	8	10	80	147	33.47	66.53
24000	8	10	40	129	31.45	68.55
24000	8	12	xxs	74	16.09	83.91
24000	8	12	160	126	29.27	70.73
24000	8	12	80	95	21.48	78.52
24000	8	12	40	86	18.71	81.29

Prediction Of Critical Particle Size and Sand Settlement In Piping
Based On Site-Specific Core-Lab Analysis Of Solids Composition

d (microns) = Theoretical maximum size of particle carried in gas stream, microns
% Carried = Total percent of solids (based on Core Lab analysis) carried in gas stream, %
% Settled = Total percent of solids (based on Core Lab analysis) predicted to settle out of gas stream, %

kPag	MMSCFD	NPS	SCH	d (microns)	% Carried	% Settled
17200	3	2	xxs	2620	100.00	0.00
17200	3	2	160	2508	100.00	0.00
17200	3	2	80	2256	100.00	0.00
17200	3	2	40	2220	100.00	0.00
17200	3	3	xxs	2098	100.00	0.00
17200	3	3	160	1956	100.00	0.00
17200	3	3	80	1702	100.00	0.00
17200	3	3	40	1588	100.00	0.00
17200	3	4	xxs	1538	100.00	0.00
17200	3	4	160	1313	99.99	0.01
17200	3	4	80	946	98.87	1.13
17200	3	4	40	752	95.02	4.98
17200	3	6	xxs	314	52.34	47.66
17200	3	6	160	256	46.80	53.20
17200	3	6	80	185	37.46	62.54
17200	3	6	40	160	35.44	64.56
17200	3	8	xxs	116	29.27	70.73
17200	3	8	160	119	29.27	70.73
17200	3	8	80	92	21.48	78.52
17200	3	8	40	83	18.71	81.29
17200	3	10	xxs	69	13.76	86.24
17200	3	10	160	73	13.76	86.24
17200	3	10	80	58	10.17	89.83
17200	3	10	40	53	8.89	91.11
17200	3	12	xxs	35	5.82	94.18
17200	3	12	160	52	8.89	91.11
17200	3	12	80	42	7.06	92.94
17200	3	12	40	39	6.39	93.61

Prediction Of Critical Particle Size and Sand Settlement In Piping
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d (microns) = Theoretical maximum size of particle carried in gas stream, microns
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% Settled = Total percent of solids (based on Core Lab analysis) predicted to settle out of gas stream, %

kPag	MMSCFD	NPS	SCH	d (microns)	% Carried	% Settled
17200	3.884	2	xxs	2626	100.00	0.00
17200	3.884	2	160	2525	100.00	0.00
17200	3.884	2	80	2434	100.00	0.00
17200	3.884	2	40	2340	100.00	0.00
17200	3.884	3	xxs	2220	100.00	0.00
17200	3.884	3	160	2050	100.00	0.00
17200	3.884	3	80	1921	100.00	0.00
17200	3.884	3	40	1836	100.00	0.00
17200	3.884	4	xxs	1781	100.00	0.00
17200	3.884	4	160	1616	100.00	0.00
17200	3.884	4	80	1368	99.99	0.01
17200	3.884	4	40	1218	99.99	0.01
17200	3.884	6	xxs	541	77.81	22.19
17200	3.884	6	160	417	63.07	36.93
17200	3.884	6	80	277	49.47	50.53
17200	3.884	6	40	234	44.27	55.73
17200	3.884	8	xxs	162	35.44	64.56
17200	3.884	8	160	166	35.44	64.56
17200	3.884	8	80	123	29.27	70.73
17200	3.884	8	40	111	26.87	73.13
17200	3.884	10	xxs	90	21.48	78.52
17200	3.884	10	160	96	21.48	78.52
17200	3.884	10	80	75	16.09	83.91
17200	3.884	10	40	68	13.76	86.24
17200	3.884	12	xxs	43	7.06	92.94
17200	3.884	12	160	67	13.76	86.24
17200	3.884	12	80	53	8.89	91.11
17200	3.884	12	40	49	7.88	92.12

Prediction Of Critical Particle Size and Sand Settlement In Piping
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d (microns) = Theoretical maximum size of particle carried in gas stream, microns
% Carried = Total percent of solids (based on Core Lab analysis) carried in gas stream, %
% Settled = Total percent of solids (based on Core Lab analysis) predicted to settle out of gas stream, %

kPag	MMSCFD	NPS	SCH	d (microns)	% Carried	% Settled
17200	8	2	xxs	2899	100.00	0.00
17200	8	2	160	2802	100.00	0.00
17200	8	2	80	2754	100.00	0.00
17200	8	2	40	2672	100.00	0.00
17200	8	3	xxs	2558	100.00	0.00
17200	8	3	160	2442	100.00	0.00
17200	8	3	80	2371	100.00	0.00
17200	8	3	40	2294	100.00	0.00
17200	8	4	xxs	2273	100.00	0.00
17200	8	4	160	2192	100.00	0.00
17200	8	4	80	2027	100.00	0.00
17200	8	4	40	1960	100.00	0.00
17200	8	6	xxs	1645	100.00	0.00
17200	8	6	160	1515	100.00	0.00
17200	8	6	80	1226	99.99	0.01
17200	8	6	40	1055	99.65	0.35
17200	8	8	xxs	606	82.95	17.05
17200	8	8	160	631	87.70	12.30
17200	8	8	80	377	59.04	40.96
17200	8	8	40	316	52.34	47.66
17200	8	10	xxs	230	44.27	55.73
17200	8	10	160	254	46.80	53.20
17200	8	10	80	176	37.46	62.54
17200	8	10	40	156	35.44	64.56
17200	8	12	xxs	87	18.71	81.29
17200	8	12	160	151	33.47	66.53
17200	8	12	80	113	26.87	73.13
17200	8	12	40	101	24.25	75.75

Prediction Of Critical Particle Size and Sand Settlement In Piping
Based On Site-Specific Core-Lab Analysis Of Solids Composition

d (microns) = Theoretical maximum size of particle carried in gas stream, microns
% Carried = Total percent of solids (based on Core Lab analysis) carried in gas stream, %
% Settled = Total percent of solids (based on Core Lab analysis) predicted to settle out of gas stream, %

kPag	MMSCFD	NPS	SCH	d (microns)	% Carried	% Settled
6500	3	2	xxs	3930	100.00	0.00
6500	3	2	160	3644	100.00	0.00
6500	3	2	80	3544	100.00	0.00
6500	3	2	40	3386	100.00	0.00
6500	3	3	xxs	3232	100.00	0.00
6500	3	3	160	3030	100.00	0.00
6500	3	3	80	2828	100.00	0.00
6500	3	3	40	2727	100.00	0.00
6500	3	4	xxs	2649	100.00	0.00
6500	3	4	160	2438	100.00	0.00
6500	3	4	80	2122	100.00	0.00
6500	3	4	40	1940	100.00	0.00
6500	3	6	xxs	981	98.87	1.13
6500	3	6	160	741	91.78	8.22
6500	3	6	80	474	72.60	27.40
6500	3	6	40	393	63.07	36.93
6500	3	8	xxs	265	46.80	53.20
6500	3	8	160	272	49.47	50.53
6500	3	8	80	201	39.59	60.41
6500	3	8	40	178	37.46	62.54
6500	3	10	xxs	144	33.47	66.53
6500	3	10	160	154	33.47	66.53
6500	3	10	80	118	29.27	70.73
6500	3	10	40	107	26.87	73.13
6500	3	12	xxs	68	13.76	86.24
6500	3	12	160	105	24.25	75.75
6500	3	12	80	83	18.71	81.29
6500	3	12	40	76	16.09	83.91

Prediction Of Critical Particle Size and Sand Settlement In Piping
Based On Site-Specific Core-Lab Analysis Of Solids Composition

d (microns) = Theoretical maximum size of particle carried in gas stream, microns
% Carried = Total percent of solids (based on Core Lab analysis) carried in gas stream, %
% Settled = Total percent of solids (based on Core Lab analysis) predicted to settle out of gas stream, %

kPag	MMSCFD	NPS	SCH	d (microns)	% Carried	% Settled
6500	3.884	2	xxs	3954	100.00	0.00
6500	3.884	2	160	3793	100.00	0.00
6500	3.884	2	80	3636	100.00	0.00
6500	3.884	2	40	3554	100.00	0.00
6500	3.884	3	xxs	3422	100.00	0.00
6500	3.884	3	160	3232	100.00	0.00
6500	3.884	3	80	3062	100.00	0.00
6500	3.884	3	40	2964	100.00	0.00
6500	3.884	4	xxs	2929	100.00	0.00
6500	3.884	4	160	2740	100.00	0.00
6500	3.884	4	80	2500	100.00	0.00
6500	3.884	4	40	2377	100.00	0.00
6500	3.884	6	xxs	1655	100.00	0.00
6500	3.884	6	160	1362	99.99	0.01
6500	3.884	6	80	833	97.36	2.64
6500	3.884	6	40	654	87.70	12.30
6500	3.884	8	xxs	398	63.07	36.93
6500	3.884	8	160	412	63.07	36.93
6500	3.884	8	80	285	49.47	50.53
6500	3.884	8	40	251	46.80	53.20
6500	3.884	10	xxs	196	39.59	60.41
6500	3.884	10	160	211	41.86	58.14
6500	3.884	10	80	159	35.44	64.56
6500	3.884	10	40	143	33.47	66.53
6500	3.884	12	xxs	86	18.71	81.29
6500	3.884	12	160	138	31.45	68.55
6500	3.884	12	80	108	26.87	73.13
6500	3.884	12	40	98	24.25	75.75

Prediction Of Critical Particle Size and Sand Settlement In Piping
Based On Site-Specific Core-Lab Analysis Of Solids Composition

d (microns) = Theoretical maximum size of particle carried in gas stream, microns
% Carried = Total percent of solids (based on Core Lab analysis) carried in gas stream, %
% Settled = Total percent of solids (based on Core Lab analysis) predicted to settle out of gas stream, %

kPag	MMSCFD	NPS	SCH	d (microns)	% Carried	% Settled
6500	8	2	xxs	4260	100.00	0.00
6500	8	2	160	4182	100.00	0.00
6500	8	2	80	4040	100.00	0.00
6500	8	2	40	3961	100.00	0.00
6500	8	3	xxs	3848	100.00	0.00
6500	8	3	160	3737	100.00	0.00
6500	8	3	80	3586	100.00	0.00
6500	8	3	40	3535	100.00	0.00
6500	8	4	xxs	3477	100.00	0.00
6500	8	4	160	3376	100.00	0.00
6500	8	4	80	3231	100.00	0.00
6500	8	4	40	3131	100.00	0.00
6500	8	6	xxs	2757	100.00	0.00
6500	8	6	160	2630	100.00	0.00
6500	8	6	80	2370	100.00	0.00
6500	8	6	40	2222	100.00	0.00
6500	8	8	xxs	1766	100.00	0.00
6500	8	8	160	1798	100.00	0.00
6500	8	8	80	1232	99.99	0.01
6500	8	8	40	993	98.87	1.13
6500	8	10	xxs	639	87.70	12.30
6500	8	10	160	730	91.78	8.22
6500	8	10	80	447	67.62	32.38
6500	8	10	40	379	59.04	40.96
6500	8	12	xxs	188	39.59	60.41
6500	8	12	160	366	59.04	40.96
6500	8	12	80	255	46.80	53.20
6500	8	12	40	223	41.86	58.14

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% Carried = Total percent of solids (based on Core Lab analysis) carried in gas stream, %
% Settled = Total percent of solids (based on Core Lab analysis) predicted to settle out of gas stream, %

kPag	MMSCFD	NPS	SCH	d (microns)	% Carried	% Settled
5200	3	2	xxs	4141	100.00	0.00
5200	3	2	160	4002	100.00	0.00
5200	3	2	80	3838	100.00	0.00
5200	3	2	40	3737	100.00	0.00
5200	3	3	xxs	3558	100.00	0.00
5200	3	3	160	3345	100.00	0.00
5200	3	3	80	3154	100.00	0.00
5200	3	3	40	3027	100.00	0.00
5200	3	4	xxs	2962	100.00	0.00
5200	3	4	160	2749	100.00	0.00
5200	3	4	80	2435	100.00	0.00
5200	3	4	40	2262	100.00	0.00
5200	3	6	xxs	1287	99.99	0.01
5200	3	6	160	974	98.87	1.13
5200	3	6	80	601	82.95	17.05
5200	3	6	40	491	72.60	27.40
5200	3	8	xxs	322	52.34	47.66
5200	3	8	160	331	55.49	44.51
5200	3	8	80	240	44.27	55.73
5200	3	8	40	213	41.86	58.14
5200	3	10	xxs	170	37.46	62.54
5200	3	10	160	183	37.46	62.54
5200	3	10	80	139	31.45	68.55
5200	3	10	40	126	29.27	70.73
5200	3	12	xxs	78	16.09	83.91
5200	3	12	160	123	29.27	70.73
5200	3	12	80	98	24.25	75.75
5200	3	12	40	89	21.48	78.52

Prediction Of Critical Particle Size and Sand Settlement In Piping Based On Site-Specific Core-Lab Analysis Of Solids Composition

d (microns) = Theoretical maximum size of particle carried in gas stream, microns
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% Settled = Total percent of solids (based on Core Lab analysis) predicted to settle out of gas stream, %

kPag	MMSCFD	NPS	SCH	d (microns)	% Carried	% Settled
5200	3.884	2	xxs	4288	100.00	0.00
5200	3.884	2	160	4154	100.00	0.00
5200	3.884	2	80	3987	100.00	0.00
5200	3.884	2	40	3907	100.00	0.00
5200	3.884	3	xxs	3753	100.00	0.00
5200	3.884	3	160	3554	100.00	0.00
5200	3.884	3	80	3411	100.00	0.00
5200	3.884	3	40	3330	100.00	0.00
5200	3.884	4	xxs	3243	100.00	0.00
5200	3.884	4	160	3056	100.00	0.00
5200	3.884	4	80	2828	100.00	0.00
5200	3.884	4	40	2672	100.00	0.00
5200	3.884	6	xxs	1985	100.00	0.00
5200	3.884	6	160	1701	100.00	0.00
5200	3.884	6	80	1098	99.94	0.06
5200	3.884	6	40	851	97.36	2.64
5200	3.884	8	xxs	498	72.60	27.40
5200	3.884	8	160	515	72.60	27.40
5200	3.884	8	80	349	55.49	44.51
5200	3.884	8	40	303	52.34	47.66
5200	3.884	10	xxs	235	44.27	55.73
5200	3.884	10	160	254	46.80	53.20
5200	3.884	10	80	188	39.59	60.41
5200	3.884	10	40	168	35.44	64.56
5200	3.884	12	xxs	101	24.25	75.75
5200	3.884	12	160	165	35.44	64.56
5200	3.884	12	80	127	29.27	70.73
5200	3.884	12	40	115	26.87	73.13

Prediction Of Critical Particle Size and Sand Settlement In Piping
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d (microns) = Theoretical maximum size of particle carried in gas stream, microns
% Carried = Total percent of solids (based on Core Lab analysis) carried in gas stream, %
% Settled = Total percent of solids (based on Core Lab analysis) predicted to settle out of gas stream, %

kPag	MMSCFD	NPS	SCH	d (microns)	% Carried	% Settled
5200	8	2	xxs	4649	100.00	0.00
5200	8	2	160	4545	100.00	0.00
5200	8	2	80	4405	100.00	0.00
5200	8	2	40	4343	100.00	0.00
5200	8	3	xxs	4221	100.00	0.00
5200	8	3	160	4057	100.00	0.00
5200	8	3	80	3939	100.00	0.00
5200	8	3	40	3855	100.00	0.00
5200	8	4	xxs	3838	100.00	0.00
5200	8	4	160	3698	100.00	0.00
5200	8	4	80	3535	100.00	0.00
5200	8	4	40	3457	100.00	0.00
5200	8	6	xxs	3073	100.00	0.00
5200	8	6	160	2943	100.00	0.00
5200	8	6	80	2681	100.00	0.00
5200	8	6	40	2528	100.00	0.00
5200	8	8	xxs	2081	100.00	0.00
5200	8	8	160	2131	100.00	0.00
5200	8	8	80	1566	100.00	0.00
5200	8	8	40	1299	99.99	0.01
5200	8	10	xxs	833	97.36	2.64
5200	8	10	160	959	98.87	1.13
5200	8	10	80	563	77.81	22.19
5200	8	10	40	471	67.62	32.38
5200	8	12	xxs	226	44.27	55.73
5200	8	12	160	453	67.62	32.38
5200	8	12	80	310	52.34	47.66
5200	8	12	40	269	46.80	53.20

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% Carried = Total percent of solids (based on Core Lab analysis) carried in gas stream, %
% Settled = Total percent of solids (based on Core Lab analysis) predicted to settle out of gas stream, %

kPag	MMSCFD	SEP. OUTLET MESH PAD		d (microns)	% Carried	% Settled
1034	3	18	40	137	31.45	68.55
1034	3	20	40	113	26.87	73.13
1034	3	24	40	84	18.71	81.29
1034	3	30	40	58	10.17	89.83
1034	3.884	18	40	175	37.46	62.54
1034	3.884	20	40	142	33.47	66.53
1034	3.884	24	40	103	24.25	75.75
1034	3.884	30	40	71	13.76	86.24
1034	8	18	40	393	63.07	36.93
1034	8	20	40	301	52.34	47.66
1034	8	24	40	202	39.59	60.41
1034	8	30	40	129	31.45	68.55
1034	10	18	40	537	77.81	22.19
1034	10	20	40	396	63.07	36.93
1034	10	24	40	255	46.80	53.20
1034	10	30	40	159	35.44	64.56
1034	25	18	40	3257	100.00	0.00
1034	25	20	40	2185	100.00	0.00
1034	25	24	40	938	98.87	1.13
1034	25	30	40	445	67.62	32.38
1034	37.5	18	40	4567	100.00	0.00
1034	37.5	20	40	3955	100.00	0.00
1034	37.5	24	40	2372	100.00	0.00
1034	37.5	30	40	843	97.36	2.64
1034	50	18	40	5222	100.00	0.00
1034	50	20	40	4831	100.00	0.00
1034	50	24	40	3695	100.00	0.00
1034	50	30	40	1561	100.00	0.00