Effect of Drilling Fluid Properties on Rate of Penetration

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The scope of this work is to determine the effect of drilling fluid properties on penetration rate in a field using daily drilling reports. Based on our field studies the following drilling fluid properties affect penetration rate to varying degrees: mud weight, plastic viscosity and solid content. The result of this study shows that the net effect of drilling fluid properties on penetration rate is less than what it thought to be. Penetration rate is decreased by increasing plastic viscosity, solid content and mud weight. Decreasing the penetration rate is more attributed to increase of depth, because by increasing the depth, rock strength increases and porosity decreases.

Key words: Mud weight, plastic viscosity and solid content, penetration rate, regression

1. INTRODUCTION

The factors which affect rate of penetration are exceedingly numerous and perhaps important variables exist which are unrecognized up to this time. A rigorous analysis of drilling rate is complicated by difficulty of completely isolating the variable under study. For example, interpretation of field data may involve uncertainties due to the possibility of undetected changes in rock properties. Studies of drilling fluid effects are always plagued by difficulty of preparing two muds having all properties identical except one which is under observation.

While it is generally desirable to increase penetration rate, such gains must not be made at the expense of overcompensating, detrimental effects. The fastest on-bottom drilling rate does not necessarily result in the lowest cost per foot of drilled hole. Other factors such as accelerated bit wear, equipment failure, etc., may raise cost. These restrictions should be kept in mind during the following discussion.

In any engineering study of rotary drilling it is convenient to divide the factors which affect the rate of penetration into the following list:

1. Personal efficiency
2. Rig efficiency
3. Formation characteristics (e.g. strength, hardness and / or abrasiveness, state of underground formations stress, elasticity, stickiness or balling tendency, fluid content and interstitial pressure, porosity and permeability)
4. Mechanical factors (e.g. weight on bit, bit type and rotary speed)
5. Hydraulic factor (e.g. jet velocity, bottom- hole cleaning)
6. Drilling fluid properties (e.g. mud weight, viscosity, filtrate loss and solid content)

Formation as nearly an independent or uncontrollable variable is influenced to a certain extent by hydrostatic pressure. Laboratory experiments indicate that in some formations increased hydrostatic pressure increases the formation hardness or reduces its drill-ability.[7]

The bit type selected, i.e., whether a drag bit, diamond bit, or roller cutter bit is used and the various tooth structures affect to some extent the drilling rate obtainable in a given formation.

The mechanical factors of weight on the bit and rotary speed are then linearly related to the drilling rate, provided the hydraulic factors are in proper balance to insure proper cleaning of the hole. The hydraulic factors affect drilling rate only when they influence the rate of penetration or the efficiency of the drilling.

It is known that drilling fluid properties can affect drilling rate. This fact was established early in the drilling literature, and confirmed by numerous laboratory studies.[4] Several early studies were focused directly on mud properties, clearly demonstrating the effect of mud properties on drilling rate.[4]

Inasmuch as it is impossible to change one property of drilling fluid without affecting the others, it is difficult to evaluate the true effect of an individual parameter on penetration rate.[6] Therefore in this article it is tried to eliminate effects of other parameters (such as weight on bit-WOB, rotary speed-N, bit hydraulic, and depth) that are affecting the rate of penetration-ROP, for identifying effects of drilling fluid properties. For this purpose field data were collected and by using multiple regression[1,5,2,] Bourgoyne-Yong equation's constant were identified, then by using this equation penetration rate was normalized to identify the effect of drilling fluid properties on penetration rate.[5]

2. PROCEDURE

To accomplish the objectives of this project the data of an oilfield were used.[1] At first stage, data of wells which had been drilled from date of 2002 through 2006 were gathered.[1] At the second stage required information were selected from these data, which data selection was limited

Table 1. Data for Multiple Regression Analysis[1]

Data Entry	Depth (ft)	*ROP* (ft/hr)	*h*	Jet Impact Force (1 000 lb)	*WOB* (klb/in)	*RPM*	*ECD* (lb/gal)	Pore gradient (lb/gal)
1	3 231	31.3	0.25	1.86	1.57	155	9.29	9.0
2	3 592	25.3	0.25	1.82	2.86	160	9.02	9.0
3	3 608	45.0	0.50	2.35	3.29	165	8.78	9.0
4	4 021	16.5	0.50	1.77	1.86	165	9.25	9.0
5	4 156	32.2	0.44	1.85	4.00	190	8.57	9.0
6	4 156	35.6	0.38	2.16	3.14	155	9.11	9.0
7	4 251	15.9	0.50	2.00	2.57	160	8.89	9.0
8	4 267	29.5	0.38	1.96	3.00	180	8.73	9.0
9	4 500	22.0	0.38	2.22	2.86	165	9.53	9.0
10	4 749	17.6	0.63	2.24	2.57	155	8.84	9.0
11	4 789	26.2	0.00	1.88	2.43	145	9.35	9.0
12	4 808	13.9	0.50	2.18	2.57	163	9.72	9.0
13	4 858	17.1	0.38	1.69	2.33	193	9.02	9.0
14	4 979	10.6	0.50	2.15	2.14	163	9.60	9.0
15	4 982	18.2	0.38	2.37	2.86	160	9.42	9.0
16	4 999	21.4	0.63	2.40	3.14	148	9.64	9.0
17	5 005	18.3	0.31	2.16	2.14	160	9.00	9.0
18	5 196	7.3	0.25	1.91	1.07	155	9.66	9.0
19	5 225	21.7	0.63	2.46	2.29	180	9.02	9.0
20	5 241	16.1	0.50	2.36	3.00	150	9.93	9.0
21	5 261	7.1	0.38	1.68	0.97	195	9.09	9.0
22	5 287	13.6	0.25	1.64	2.14	165	10.10	9.0
23	5 405	20.8	0.38	2.24	2.57	155	9.05	9.0
24	5 451	13.4	0.50	2.11	2.71	167	9.75	9.0
25	5 674	14.8	0.50	2.16	2.86	180	9.12	9.0
26	5 911	9.8	0.63	1.71	2.53	160	9.76	9.0
27	6 180	6.9	0.50	1.58	1.86	160	10.70	9.0
28	6 754	8.7	0.75	1.73	2.57	155	10.58	9.0
29	6 760	3.3	0.63	1.65	1.00	145	11.15	9.0
30	7 032	8.0	0.31	1.91	2.29	180	10.25	9.0

to formation in 17.5 inch borehole and rolling cutter bit. Table 1 is a summary of data which consists of bit data, drilling parameter, hydraulic, dull bit grading, and depth out of bit. If rate of penetration is normalized to weight on bit, rotary speed, bit hydraulic, bit tooth wear, and depth, the result is penetration rate that is not affected by the variables that listed above, except by drilling fluid properties. For this purpose a drilling model equation should be selected for predicting the effect of drilling parameters on penetration rate.

In 1974, Bourgoyne and Young proposed a relation using a complex drilling model to compensate mathematically for changes in the various drilling parameters.[4] They proposed it using eight functions to model the effect of most of drilling variables discussed above. The equation form is:

$$\frac{dD}{dt} = \exp\left[\left(a_1 + \sum_{j=2}^{8} a_j x_j\right)\right] \qquad (1)$$

Where exp (x) is used to indicate the exponential function e^x. The terms $a_2 x_2$ and $a_3 x_3$ model the effect of compaction on penetration rate and x_2 and x_3 are respectively:

$$x_2 = 10\,000 - \text{depth} \qquad (2)$$

$$x_3 = D^{0.69} (g_p - \rho_n) \qquad (3)$$

Thus an exponential increase in penetration rate with pore pressure gradient can be assumed. The exponential nature of the effect of compaction on penetration rate was suggested by compaction theory but has not yet been verified experimentally. Therefore an exponential decrease in penetration rate with depth in normally compacted formations may be assumed. The effect of compaction on penetration rate has been normalized to equal 1.0 for normally compacted formation at 10 000 ft and pressure gradient equal nine (g_p =9.0 lb/gal). The term $a_4 x_4$ models the effect of differential pressure across the bottom-hole on penetration rate. Moreover, x_4 is defined by:

$$x_4 = D\,(g_p - \rho_c) \qquad (4)$$

Therefore an exponential decrease in penetration rate with excess bottom-hole pressure may be assumed. The term $a_5 x_5$ models the effect of bit weight and bit diameter on penetration rate. Also x_5 is defined by:

$$x_5 = \ln\left(\frac{w/d - (w/d)_t}{4.0 - (w/d)_t}\right) \qquad (5)$$

Thus it is assumed that penetration rate is directly proportional to $(w/d)^{a_5}$. The term $e^{a_5 x_5}$ is normalized to equal 1.0 for 4 000 lb per inch of bit diameter. The threshold bit weight, $(w/d)_t$ must be estimated with drill-off tests. The term $a_6 x_6$ represents the effect of rotary speed on penetration rate. Also x_6 is defined by:

$$x_6 = \ln\left(\frac{N}{100}\right) \qquad (6)$$

In above relation, it is assumed that penetration rate is directly proportional to N^{a_6}. The term $a_7 x_7$ models the effect of tooth wear on penetration rate. Also x_7 is defined by:

$$x_7 = -h \qquad (7)$$

Where h is the fractional tooth height that has been worn away. The value of a_7 depends primarily on bit type and on formation type. The term $e^{a_7 x_7}$ is equal 1 when either h or a_7 is zero.

The term $a_8 x_8$ models the effect of bit hydraulics on penetration rate. x_8 is defined by:

$$x_8 = \ln\left(\frac{F_j}{1\,000}\right)^{a_8} \qquad (8)$$

Where F_j is the hydraulic jet impact force beneath the bit. Hence, it is suggested that penetration rate is directly proportional to $(F_j)^{a_8}$ based on experimentally microbits studies performed by Eckel.[4]

To calculate the best values of the regression constant a_1 through a_8 using data shown in Table 1, the parameters x_2 through x_8 must be calculated using Equations 2 through 8 for each data entry. Eight

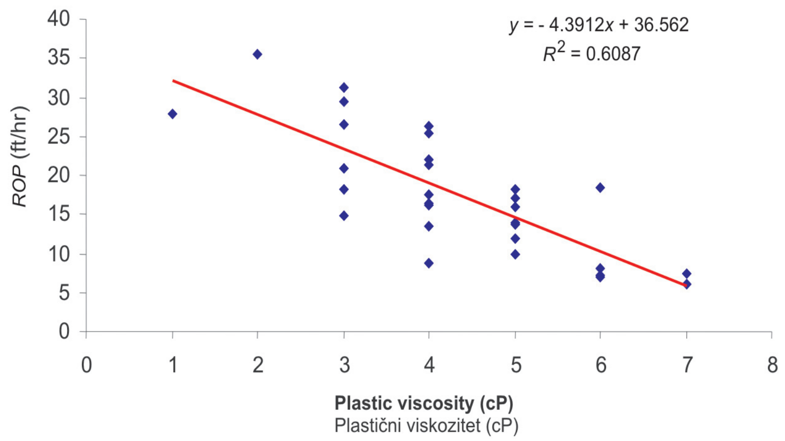

Fig. 1. Observed penetration rate vs. plastic viscosity
Sl. 1. Uočena brzina bušenja u ovisnosti o plastičnom viskozitetu

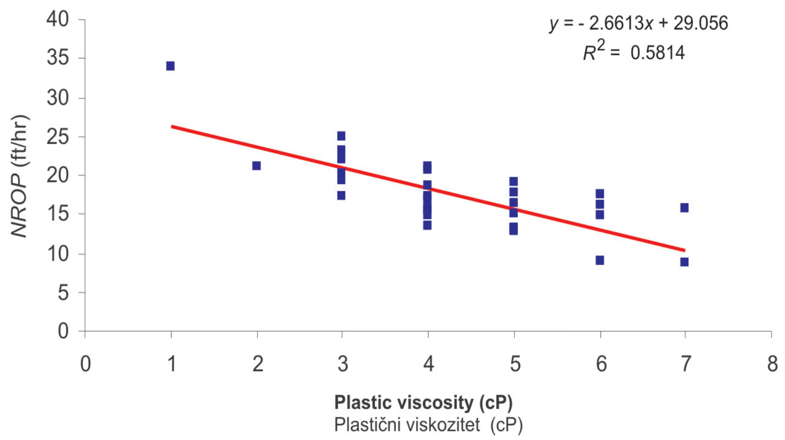

Fig. 2. *NROP* vs. plastic viscosity
Sl. 2. *NROP* u ovisnosti o plastičnom viskozitetu

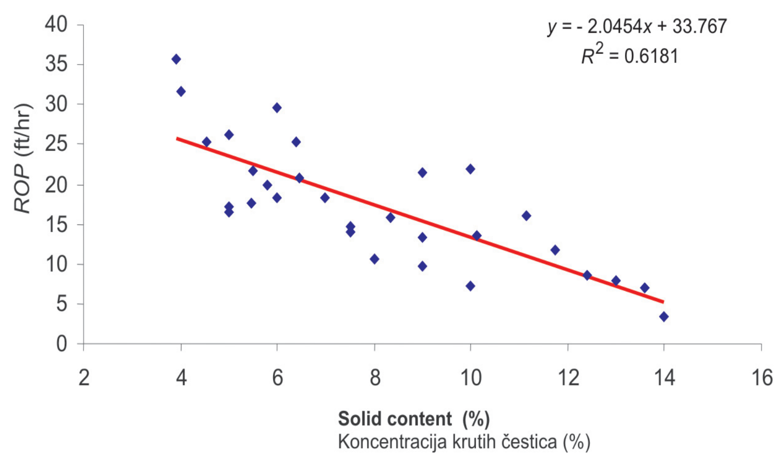

Fig. 3. *ROP* vs. solid content
Sl. 3. *ROP* u ovisnosti od koncentracije krutih čestica

equations with eight unknowns a_1 through a_8 can then be obtained from x_2 through x_8 using procedure described in Appendix. When the resulting system of eight equations is solved for the eight unknowns, the constants a_1 through a_8 for data shown in Table 1 are obtained.

The constants a_1 through a_8 are obtained as:

a_1= 1.522 9, a_2=0.000 34, a_3=0.000 7, a_4=0.000 02, a_5=0.81, a_6=0.64, a_7=0.561, a_8=0.49

3. REGRESSION ANALYSIS AND RESULTS

By normalizing rate of penetration into the weight on bit, rotary speed, bit hydraulic, and depth, result is penetration rate that is not affected by bit weight, rotary speed or hydraulics and depth, which are significant variables in controlling rate of penetration.

$$\frac{dD}{dt} = \exp\left(a_1 + a_2x_2 + a_3x_3 + ...+ a_8x_8\right)$$

$$(dD/dt)_n = (dD/dt) * \exp[a_2(x_{2n} - x_2) + a_3(x_{3n} - x_3) + a_4(x_4 - x_4) + a_5(x_{5n} - x_5) + a_6(x_{6n} - x_6) + a_7(x_{7n} - x_7) + a_8(x_{8n} - x_8)]$$

Effect of plastic viscosity on drilling rate

For investigating effect of plastic viscosity on rate of penetration (*ROP*) two cases would be considered. In case one *ROP* is plotted with respect to plastic viscosity. As it can be seen in Fig.1, penetration rate is decreased by normal slope with increasing plastic viscosity.

In the second case, normalized rate of penetration (*NROP*) plotted against plastic viscosity. As it shown in Fig. 2, by increasing plastic viscosity, *NROP* is decreased. But this reduction is less than the *ROP* reduction.

Effect of solid contents on penetration rate

For investigating effect of solid contents on penetration rate two cases would be considered. Case one is when plastic viscosity is not constant. In other word, all solid contents are variable. As it shown in Figs. 3 and 4, *ROP* and *NROP* are decreased by increasing solid content.

Case two is when plastic viscosity is constant. As it is shown in Figs. 5 and 6, when plastic viscosity is constant, by increasing solid content, *ROP* and *NROP* are decreased.

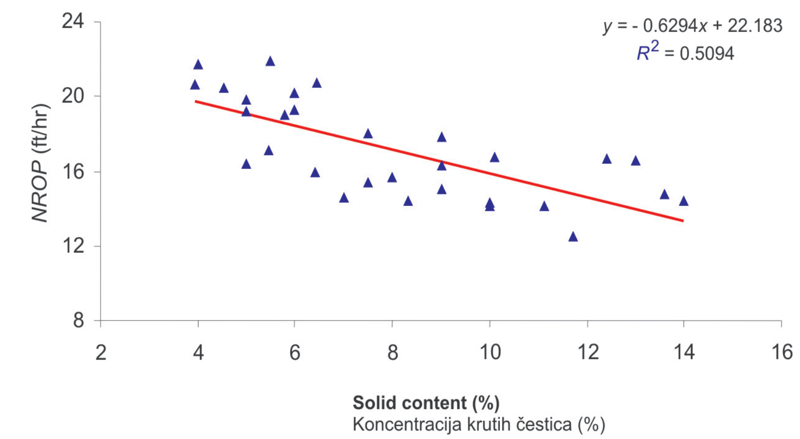

Fig. 4. *NROP* vs. solid content
Sl. 4. *NROP* u ovisnosti od koncentracije krutih čestica

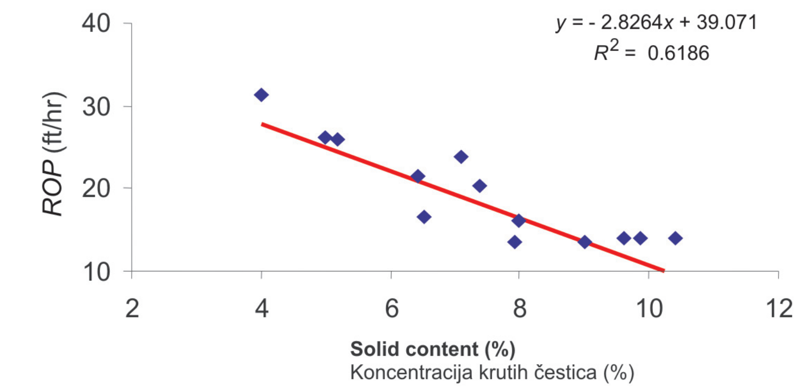

Fig. 5. Effect of solid content on penetration rate at constant plastic viscosity
Sl. 5. Djelovanje koncentracije krutih čestica na brzinu bušenja kod konstantne plastične viskoznosti

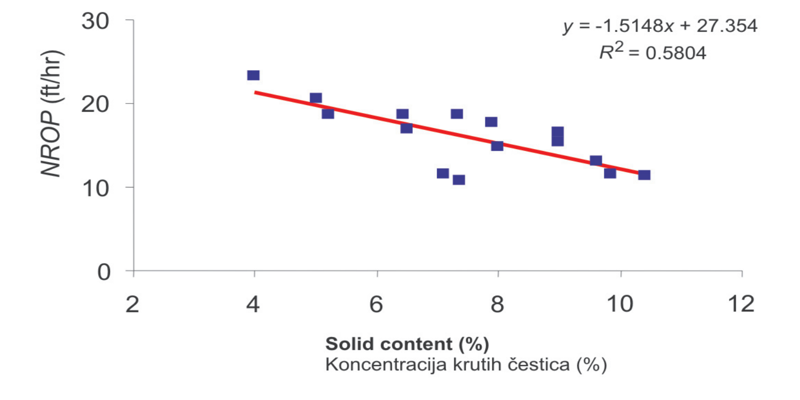

Fig. 6. Effect of solid content on *NROP* at constant plastic viscosity
Sl. 6. Djelovanje koncentracije krutih čestica *NROP* kod konstantne plastične viskoznosti

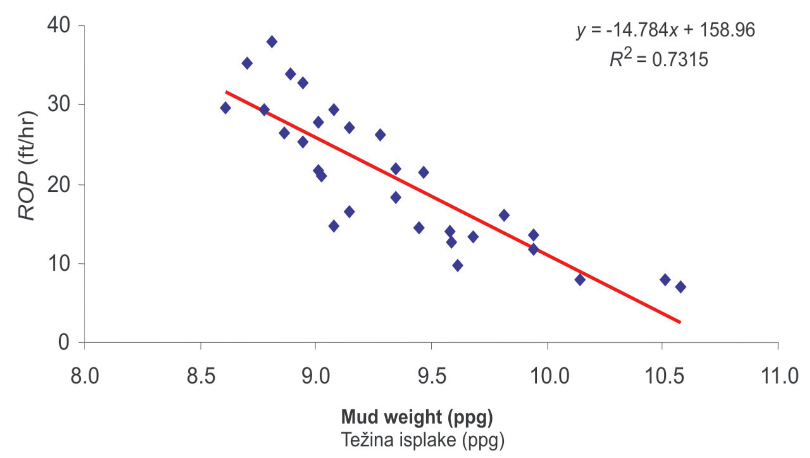

Fig. 7. Effect of mud weight on penetration rate
Sl. 7. Djelovanje težine isplake na brzinu bušenja

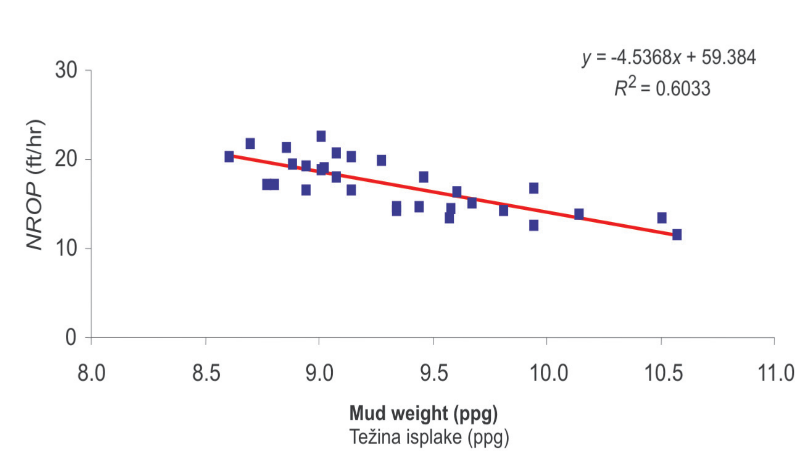

Fig. 8. Effect of mud weight on *NROP*
Sl. 8. Djelovanje težine isplake na *NROP*

Effect of mud weight on penetration rate

Effect of mud weight on penetration rate normalized penetration rate is shown in Figs. 7 and 8.

4. CONCLUSIONS

1. Effect of drilling fluid on penetration rate in Aghajari formation is less than it that is thought should to be.

2. By increasing plastic viscosity, rate of penetration and normalized rate of penetration are decreased, which is confirmed by other authors[3], but decrease in rate of penetration is more than normalized penetration rate.

3. Rate of penetration is decreased by increasing mud weight which is confirmed by other authors.[7]

4. At constant plastic viscosity, penetration rate is decreased by increasing solid content.

5. NOMENCLATURE

ROP= Rate of penetration, ft/hr

D= Depth, ft

gp= Formation pressure gradient, lb/gal

ρ_n= Normal fluid pressure gradient, psi/ft

W= Weight on bit, klb/in

d= Bit diameter, in

N= Rotary speed, rpm

h= Fractional tooth height

Fj= Hydraulic jet impact force beneath the bit, lb

NROP= Normalized rate of penetration, ft/hr

r_c = Equivalent circulating density gradient, psi/ft

t= Threshold

w= Bit weight, lb

a= Coefficient

r= Residual error

G= Regression index of correlation

ob= Constant

c= Constant

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APPENDIX

Bourgoyne and Young model is:

$$\frac{dD}{dt} = \exp\left(a_1 + \sum_{j=2}^{8} a_j x_j\right) \quad \text{(A-1)}$$

Taking the logarithm of both side of equation (A-1) yields

$$\left[\ln\frac{dD}{dt} = a_1 + \sum_{j=2}^{8} a_j x_j\right] \quad \text{(A-2)}$$

Equation (A-2) can be checked for validity in given formation at each depth at which data have been collected. If the residual error of the i the data point, r_i is defined by:

$$r_i = a_1 + \sum_{j=2}^{8} a_j x_j - \left[\ln\frac{dD}{dt}\right] \quad \text{(A-3)}$$

Now for n data points, where n is any number greater than 8, the sum of the square of residuals, $\sum_{i=1}^{n} r_i^2$ is minimum when its derivations is zero.

$$\frac{\partial \sum_{i=1}^{n} r_i^2}{\partial a_j} = \sum_{i=1}^{n} 2r_i \frac{\partial r_i}{\partial a_j} = \sum_{i=1}^{n} 2r_i x_j = 0 \quad \text{(A-4)}$$

For j =1, 2, 3… 8. Thus the constant a_1 through a_8 can be obtained by simultaneously solving the system of equations obtained by expanding of $\sum_{i=1}^{n} r_i x_i$

For j =1, 2, 3… 8. Expanding of $\sum_{i=1}^{n} r_i x_i$ yields

$$\left[na_1 + a_2\sum_{i=1}^{n} x_2 + a_3\sum_{i=1}^{n} x_3 + \ldots + a_8\sum_{i=1}^{n} x_8 = \sum_{i=1}^{n} \ln\frac{dD}{dt}\right. \quad \text{(A-5)}$$

$$a_1\sum_{i=1}^{n} x_2 + a_2\sum_{i=1}^{n} x_2^{\,2} + a_3\sum_{i=1}^{n} x_2x_3 + \ldots + a_8\sum_{i=1}^{n} x_2x_8 = \sum_{i=1}^{n} x_2 \ln\frac{dD}{dt} \quad \text{(A-6)}$$

$$a_1\sum_{i=1}^{n} x_3 + a_2\sum_{i=1}^{n} x_3x_2 + a_3\sum_{i=1}^{n} x_3^{\,2} + \ldots + a_8\sum_{i=1}^{n} x_3x_8 = \left.\sum_{i=1}^{n} x_3 \ln\frac{dD}{dt}\right] \quad \text{(A-7)}$$

$$\left[a_1\sum_{i=1}^{n} x_8 + a_2\sum_{i=1}^{n} x_8x_2 + a_3\sum_{i=1}^{n} x_8x_3 + \ldots + a_8\sum_{i=1}^{n} x_8^{\,2} = \sum_{i=1}^{n} x_8 \ln\frac{dD}{dt}\right] \quad \text{(A-8)}$$

The final correlation is checked for accuracy using the regression index of correlation G, given by:

$$G = \sqrt{1.0 - \frac{\sum\left[\left(\ln\frac{dD}{dt}\right)_{ob} - \left(\ln\frac{dD}{dt}\right)_{c}\right]^2}{\sum\left[\left(\ln\frac{dD}{dt}\right)_{ob} - \left(\ln\frac{dD}{dt}\right)\right]^2}} \quad \text{(A-9)}$$

When any of the regression constants are assumed.

To be known, the corresponding terms $a_j x_j$ can be moved to the left side of Eq. A-1 and the previous analysis applied to the remaining terms.