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ANALYSIS OF MUD FILTRATION PROPERTIES USING FACTORIAL DESIGN

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ABSTRACT

Determining the filtration properties of a mud system requires that experiments be run for both the standard API and the high Temperature High Pressure (HTHP) tests at intervals throughout the duration of drilling an oil well. However, cost and hazard considerations cause more emphasis to be placed on the standard API test at ambient ;conditions, without taking into account the effects of elevated downhole pressures and temperatures on filtration properties.

In this work, the factorial design concept was applied to the filtration properties of drilling muds. Different samples of water based bentonitic muds were used for the experimental runs at both Low Temperature - Low Pressure (LTLP) and High Temperature - High Pressure (HTHP) conditions. The input variables considered were temperature, pressure, solids content, mud weight and time; while the response variables were fluid loss and cake thickness. The final results are presented in the form of a statistically significant model that enables prediction of filtration properties at both LTLP and HTHP conditions. This method minimizes the inherent risks usually associated with operating filter presses at elevated pressures and temperatures. In addition, it saves time and cost by minimizing the number of experimental runs always required to assess mud quality; and maximizes the information obtained from the few experimental runs.

This experimental design technique can also be applied to the quality assessment and control of other drilling fluid properties.

INTRODUCTION

Fluid losses from drilling muds could cause shale sloughing and flushing of formations. The filtration properties of a mud-fluid loss and cake thickness - are therefore regarded as major factors in assessing the performance of a drilling fluid, and are continually monitored and controlled during

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Tables and Figures at end of paper.

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drilling. There are presently no satisfactory means of measuring dynamic filtration in the field, hence measurements are thus confined to static filtration using the Standard API test.

In the past, the simple, API low pressure and ambient temperature test was mostly undertaken. However, with deeper drilling, the high temperature, high pressure (HTHP) tests have also evolved. This requires regular measurements at elevated temperatures and pressures. Due to the associated risks land costs, the HTHP tests are rarely done, while the filtrate volume measurements at LTLP may not be accurate for the elevated conditions.

By using factorial design, filtration losses can be analyzed for maximum information from LTLP and HTHP measurements by varying several parameters simultaneously with few experimental runs and thereby reduce inherent risks, costs and time. The impact as well as the interactions of various parameters can also be assessed.

The development of the principle of experimental design dates back to the 1920's(1), and has since proved to have wide range of applications, in agricultural engineering, quality control of manufactured products and even in reservoir engineering. Box and Draper(2) have presented a detailed discussion of the principles and their applications to a wide range of problems in different fields. Box and Bisgaard (3), as well as Ojo and Udo(4) have applied the theory to modern techniques of quality improvement and control of manufactured goods. In the petroleum industry Sawyer *et al*;(5) have applied factorial design concepts to the simulation of the wet combustion drive process. Chu(6) demonstrated the application in the design and analysis of steam-flooding of heavy oil reservoirs. Ovreberg *et al*;(7) applied the concepts to the analysis of geological and reservoir uncertainties. Damsleth *et al*(8) have described the application of experimental design in the development study of a North Sea Field.

In this paper, the principle of experimental design has been applied in oil well drilling, in the evaluation of the properties of drilling fluids. The objective of the work was to be able to determine filtration losses at high temperatures and pressures, without significant hazards and costs.

THEORETICAL FRAMEWORK

For any drilling fluid, a property, *y*, can be treated as a response variable that depends on a number of input parameters, p. Mathematically, this can be expressed by assuming a functional relationship between the response and the input variables:

$$y = f(P1, P2, P3, \ldots) \qquad (1)$$

Using a simple transformation:

$$xi = (Pi - P0)/s \qquad (2)$$

Where,

xi = Coded or standardized variables.

Pi = current value of variable.

P_0 = Centre of region of interest.

s = spread of the variable = Pf-$P0$

Equation(1) can be re-written as:

$$Y = f(x_1, x_2, x_3, \ldots) \qquad (3)$$

Where Y = mean value of the response variable.

The fundamental assumption in response surface analysis and in experimental design is that the relationship between the response surface and the input variables can be approximated by a polynomial expression, whose coefficients can be estimated by undertaking a series of experiments. The choice of polynomials depend on the desired design level, as well as whether or not the model should capture only the main effects, include interactions amongst the variables, curvature terms, or more complex scenarios. Thus, for a three-level design, a generalized approximating polynomial has been expressed as:

$$Y = b_0 + b_1 + b_2x_2 + b_3x_3 + b_{12}x_1x_2 + b_{13}x_{13} + b_{23}x_{23} + b_{11}x_{12} + b_{22}x_{22} + b_{33}x_{32} + \ldots + e \qquad (4)$$

Where,

bi = Coefficients to be experimentally estimated

e = error term.

In estimating the unknown coefficients in equation(4), a full or complete factorial design is obtained when all possible combinations of the factors at all levels involved in the experiments are used. In general, the number N of all possible combinations to be performed during the experiments is given by:

$$N = n^{k} \quad (1) \qquad (5a)$$

While a fractional design results when only few combinations are used, such that:
where,

$$N = n^{k-r} \qquad (5b)$$

n = number of levels, and

k = number of input variables

r = number of replicates.

APPLICATION

The above principle has been applied to the prediction of the filtration properties of drilling muds. For consideration for both Low-Temperature-Low-Pressure and High-Temperature-High-Pressure measurements, a two-level factorial design has been chosen. The input variables, which affect the response variable (fluid loss) are temperature, time, solids contents, pressure and mud weight. Thus a full two-level factorial design requires 25 or 32 experimental runs. However, by neglecting the effects of solids content and mud weight, we obtain a fractional factorial design that requires only 8 experimental runs.

EXPERIMENTAL EQUIPMENT AND PROCEDURE

Two standard filter presses were used - a Standard API (LTLP) filter press, and a HTHP filter press. Muds with identical compositions were used in the two filter presses. The LTLP experiments were undertaken at ambient temperature (89.6 °F) and 100 psi, while the HTHP experiments were undertaken at 200 °F and 500 psi. Filtrate volumes were measured at the end of 7 1/2 and 30 minutes.

RESULTS AND ANALYSIS

Table -1 shows the basic composition of two simple bentonitic muds used. Table -2 gives the results obtained from the experimental runs. The results have been analysed for only fluid loss because it is believed that there is a strong indirect relationship between fluid loss and cake thickness. Figures 1-6 show the relationship between fluid loss and the input variables. In this analysis, we have assumed that there are no significant effects of solids content and mud weight on fluid loss in order to simplify the design.

Transforming the input variables (pi) to their coded forms (xi) according to equation (2), we obtain for these cases:

$$X = (T - 144.8)/55.2 \qquad (6)$$
$$x2 = (t - 18.75)/11.25 \qquad (7)$$
$$x3 = (SC - 8.5)/4.5 \qquad (8)$$
$$x4 = (P - 300)/200 \qquad (9)$$
$$x5 = (M - 10.329)/1.33 \qquad (10)$$

The first polynomial approximation that was made was the linear model that accounts for only the main effects:

$$Y = b_0 + b_1x_1 + b_2x_2 + b_4x_4 + e \qquad (11)$$

The coefficients were estimated using Yate's algorithm(1), and it was observed that the model accounts for a rather low 56% of the variation in the experiments, with the standard deviations of the coefficients and the error term at 3.7[illegible]0 and 1.312 respectively. Some interaction terms were therefore added to the model to obtain an expression of the form:

$$Y = b_0 + b_1x_1 + b_2x_2 + b_4x_4 + b12x1x2 + b24x2x4 + e \qquad (12)$$

Using Yates algorithm, the coefficients and variance were obtained as shown in Table -4. This model accounts for about 82% of the variations in the experiment, with standard deviation for the coefficients and the error terms at 1.525 and 0.539 respectively. This is regarded as satisfactory. Further checks on the accuracy of the model undertaken include the F -test, plot of residuals of the response variable versus the predicted mode, and a crossplot of the measured and the predicted response values (figure 7). All the tests confirm the statistical significance of the model.

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DISCUSSION

Equation (12) confirms well-known observations about the significant effects of temperature, time and pressure on filtrate volumes. From the coefficients of the model obtained, it can be deduced that the effects of temperature and time on mud filtrates are more than that of pressure. One obvious advantage of an expression such as equation (12) is that knowing experimental values of mud properties at ambient conditions, those at high temperatures and pressures can be estimated. this reduces the number of HTHP experiments required in the field, and reduces the associated risks and costs.

CONCLUSION

The principles of experimental design have been applied to the prediction of filtrate losses from drilling fluids. This allows the incorporation of the effects of high temperatures and pressures while reducing the number of experiments required. Thus risks associated with HTHP measurements are minimized. The empirical model derived allows for faster land cheaper predictions.

NOMENCLATURE

API	American Petroleum Institute.
bi	Unknown coefficients in the polynomial equation.
e	error term in the polynomial equation.
k	Numbner of factors.
M	Mud weight.
n	Number of factorial levels.
N	Total number of possible combinations.
pi	Uncoded current input variables.
po	centre of region for the input variable.
P	Pressure, psi.
r	Number of fractional replicates
s	Range of values of the input variables.
SC	Solids content.
xi	Coded or transformed input variables.
t	Time, minutes.
T	Temperature, oF.
y	Response variable.
Y	Mean response variable.

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TABLE -2 SUMMARY OF EIGHT EXPERIMENTAL RUNS

RUN NO	1	2	3	4	5	6	7	8
Temp. (°F)	-	+	-	+	-	+	-	+
Time (min.)	-	-	+	+	-	-	+	+
Solids content(%)	-	-	-	-	+	+	+	+
Press. (psi)	-	+	-	+	-	+	-	+
Mud weight (ppg)	-	-	-	-	+	+	+	+
Fluid Loss (cc)	5.0	8.6	14.0	20.8	0	4.0	0	15.0
Cake Thickness (1/32)	2	5	2	5	1	2	1	2

TABLE 3 DEFINITIONS OF THE LEVELS FOR THE INPUT VARIABLES

Input Variables	(LTLP)	+ (HTHP)
Temperature (°F)	89.6	200
Time (minutes)	7 1/2	30
Solids Content (%)	4.0	13.0
Pressure (psi)	100	500
Mud Weight (ppg)	9.0	11.7

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TABLE -4 VALUES AND VARIANCES OF ESTIMATED COEEFICIENTS

Coefficient	Estimate	Variance
bo	8.4250	1.525
b1	1.8375	1.525
b2	2.0125	1.525
b12	0.8875	1.525
b3	1.8375	1.525
b4	0.5425	1.525
b5	0.6375	1.525
b24	0.4875	1,525

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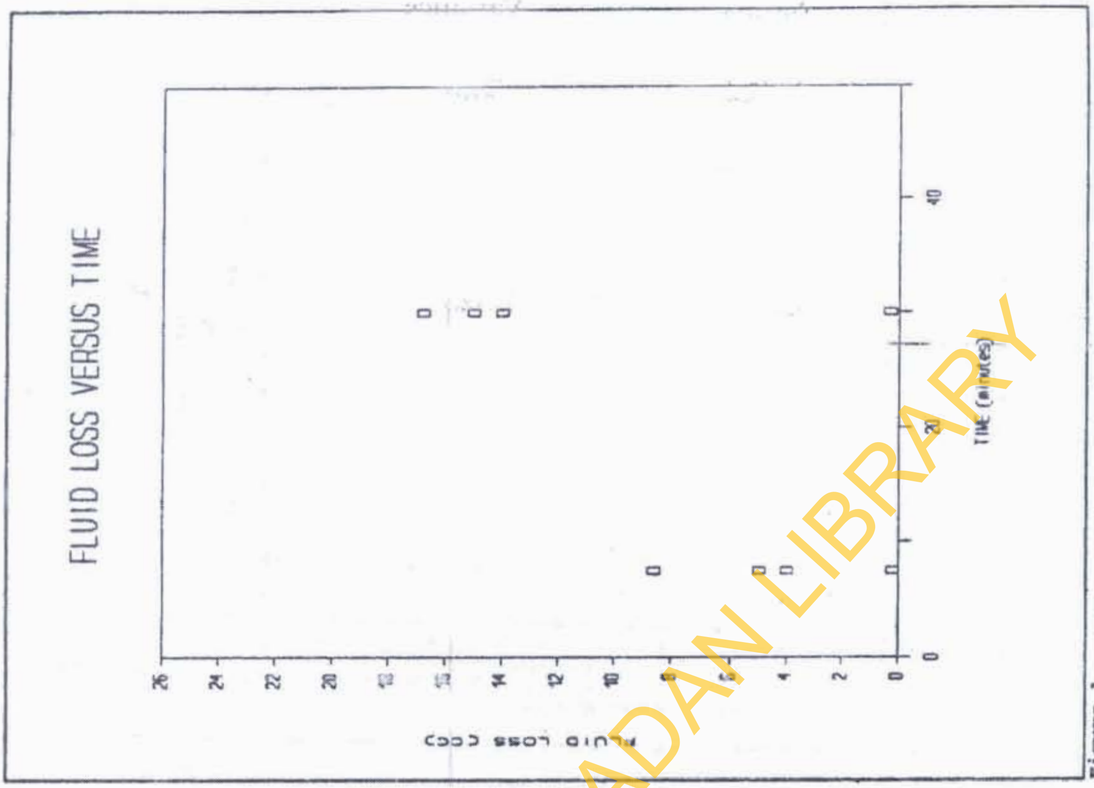

Figure 1

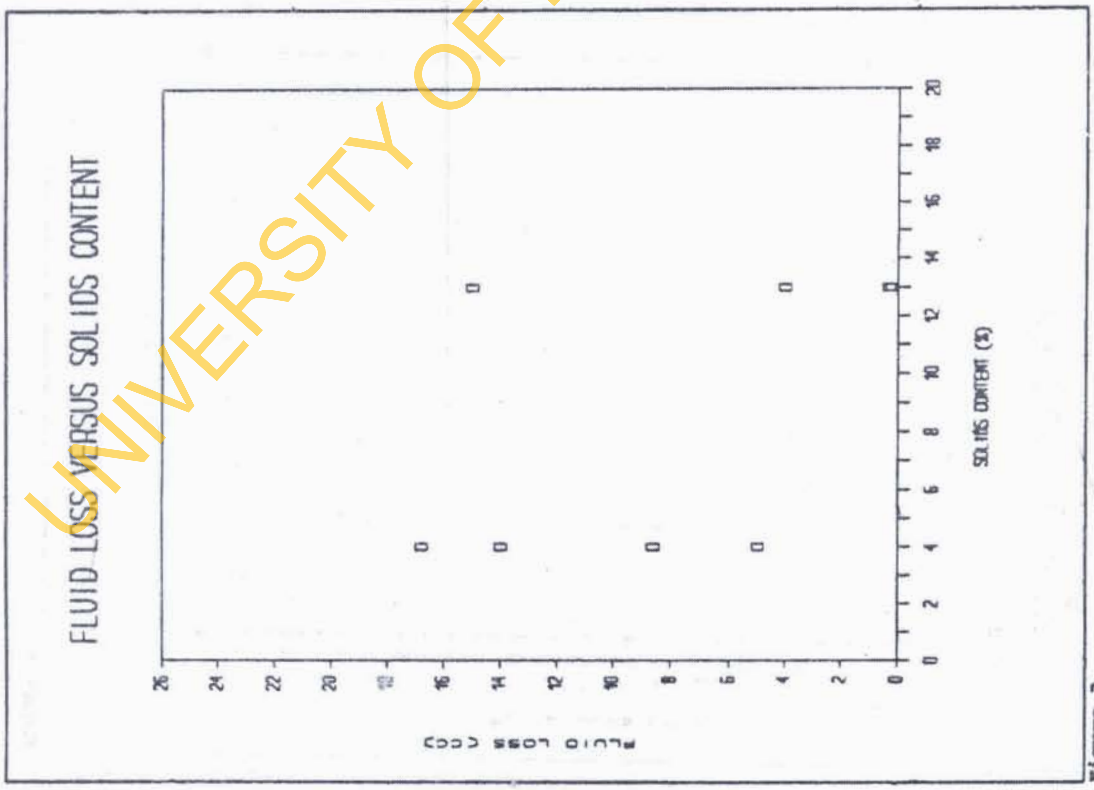

Figure 2

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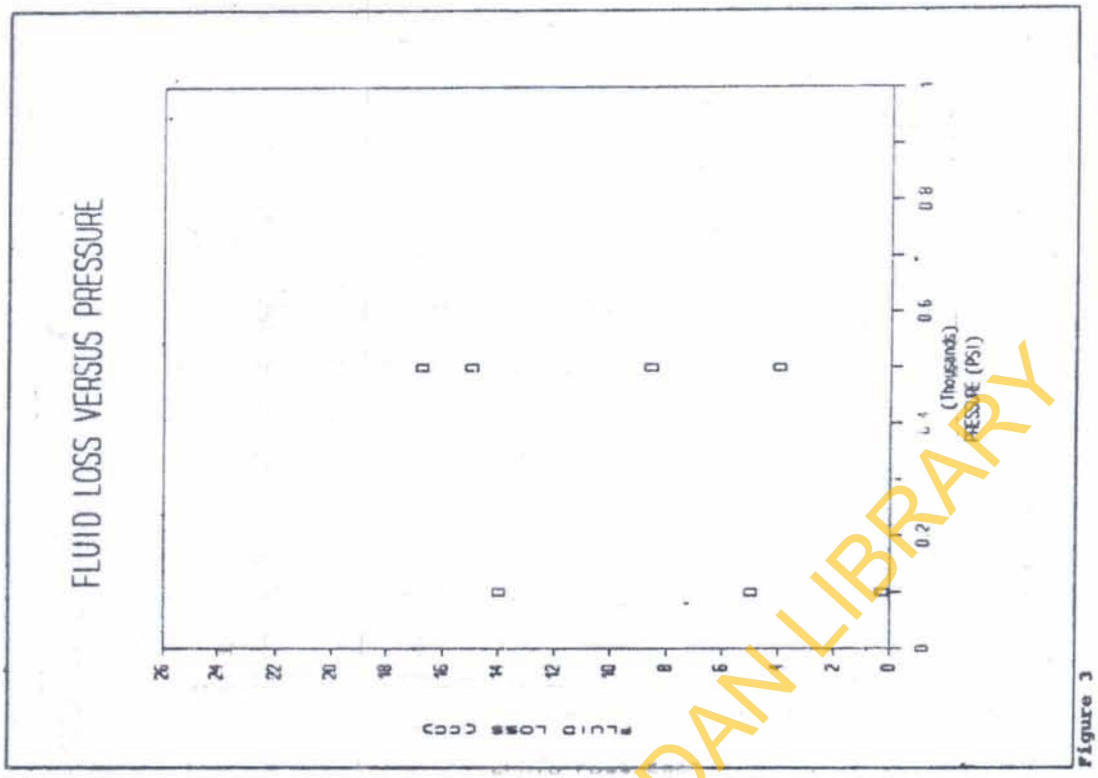

Figure 3

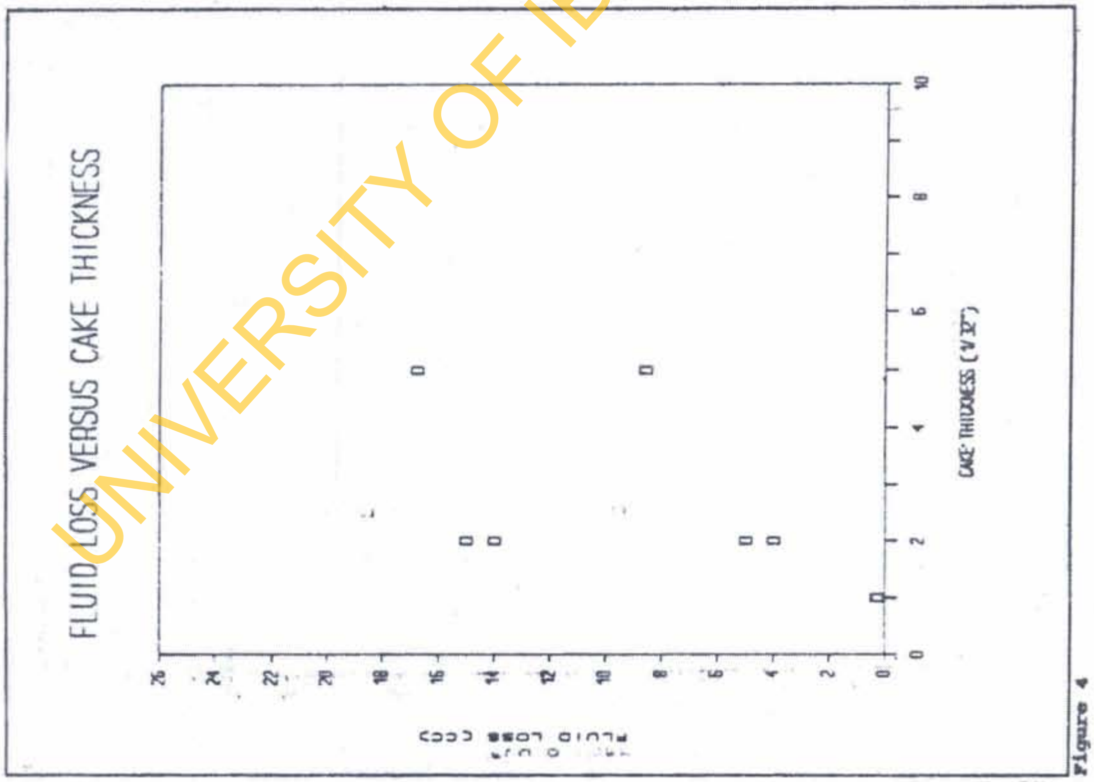

Figure 4

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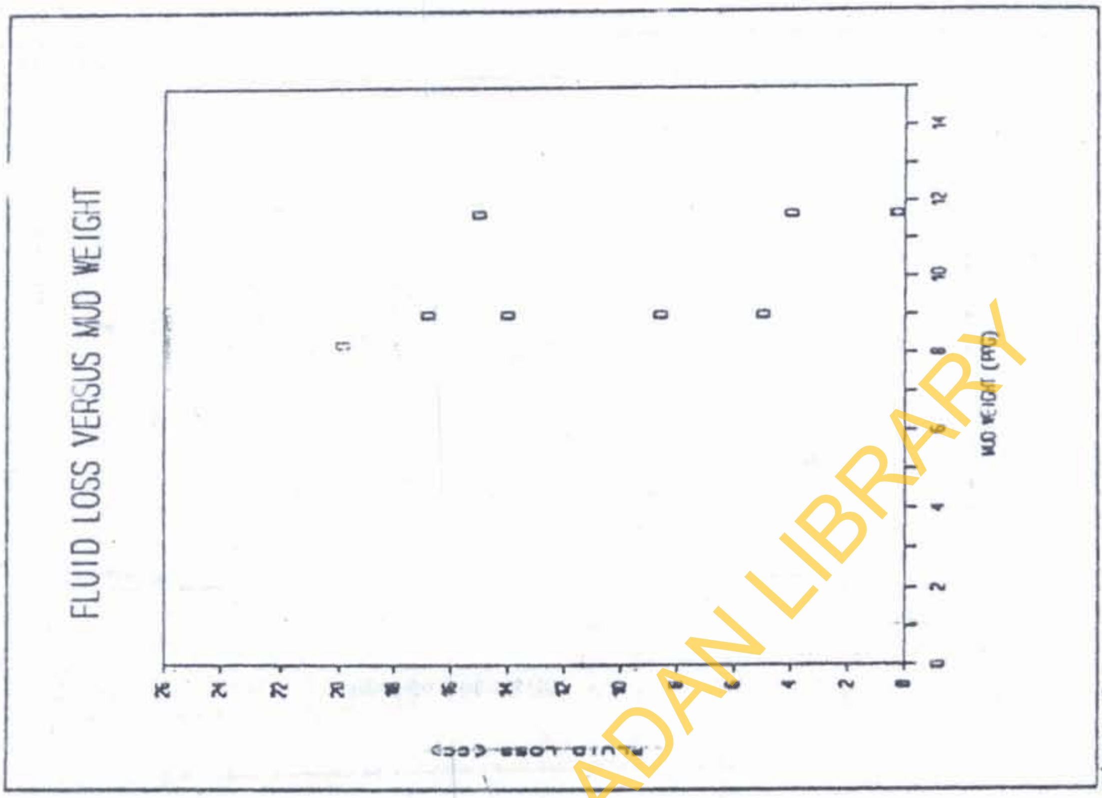

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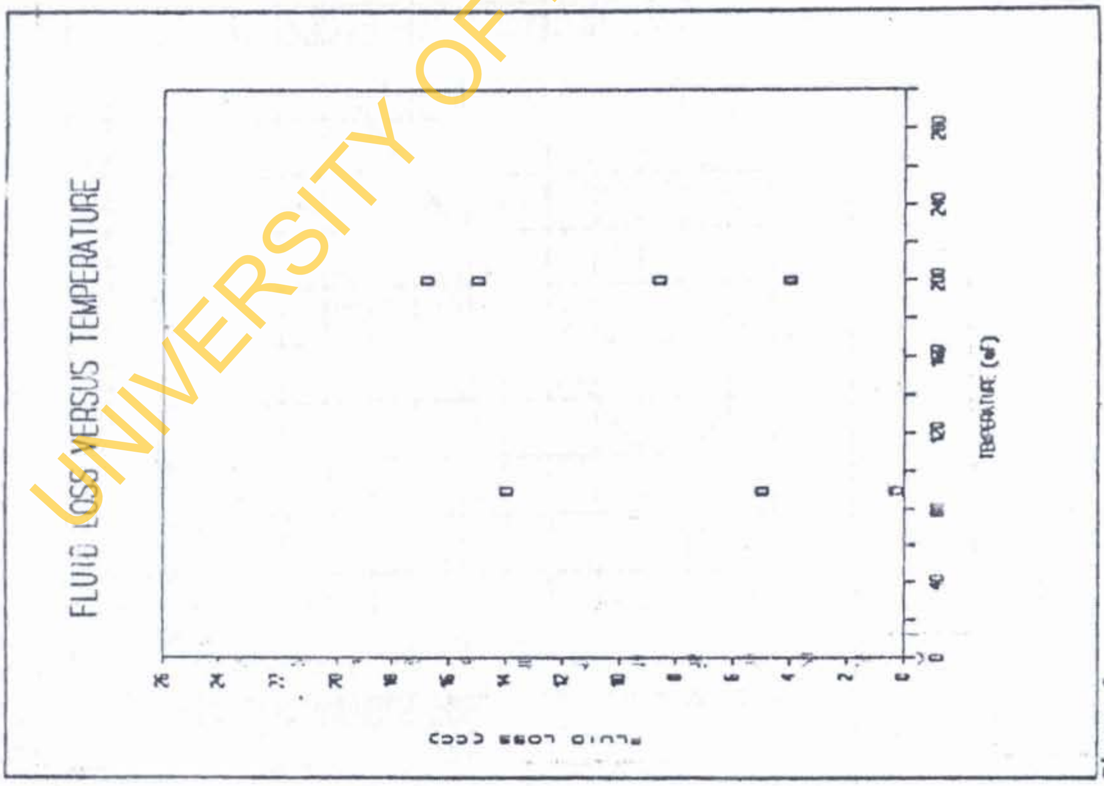

Figure 6

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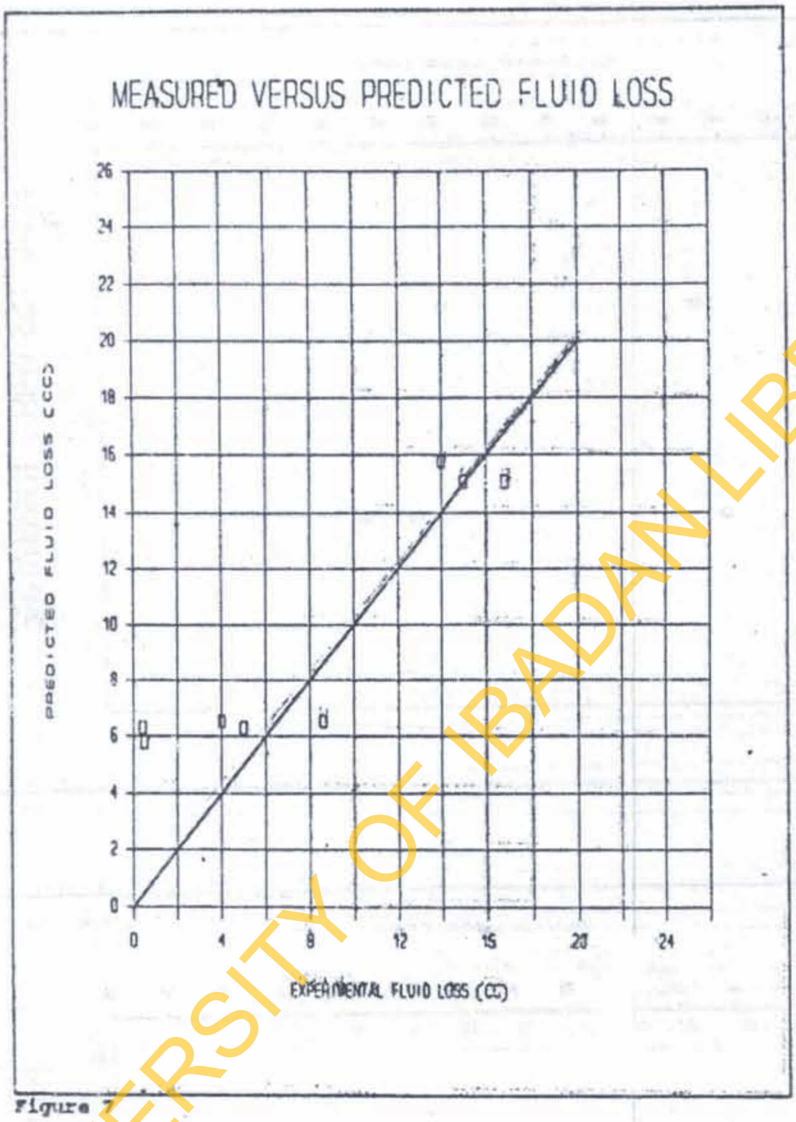

Figure 7

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