PRJ, Vol. 7 (January 1995); P. 1–30, 13 FIGS, 6 TABLES, 14 CHARTS.

A STUDY OF VERTICAL MULTIPHASE FLOW IN SOME LIBYAN OIL WELLS

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دراسة حول أدائية الرفع العمودي في بعض الآبار النفطية الليبيـــة

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تتناول الدراسة أدائية السريان المتعدد الأطوار في ثمانية آبار نفطية يقع خمس منها في حقل بوالطفل وثلاثة في حقل الغاني.

ولتحقيق ذلك تم أولاً وضع برامج حاسوب خاصة لإختبار علاقة بوتيمان وكاربنتر وعلاقة هاجدورن وبراون المعروفتين في الصناعة النفطية، باستخدام القياسات الحقلية المتوفرة لتلك الآبار. بعد ذلك استخدمت العلاقات في دراسة تاثير كل من قطر أنبوب الإنتاج واتجاه الحسابات الخاصة بمسار الضغط على أدائية الرفع العمودي وكذلك مساهمة كل حد في المعادلة العامة للطاقة على التدرج الكلي للضغط داخل أنبوب الإنتاج. كما تم تعديل هذه البرامج بهدف إعداد منحنيات ادائية جديدة خاصة بحقل بوالطفل، بحيث يمكن بواسطتها تنبوء ادائية الرفع العمودي في الآبار النفطية لهذا الحقل بدقة أكبر بالمقارنة مع منحنيات الأدائية المتوفرة في المراجع العلمية.

أشارت نتائج الحسابات إلى إمكانية زيادة معدل إنتاج البئر (A–55) في حقل بوالطفل إلى مستوى 6870 برميل لكل يوم باستخدام أنبوب انتاج بقطر 4 بوصة. كذلك وجد أن تأثير وزن الموائع المنتجة يشكل نسبة تتراوح ما بين 80 و90 بالمائة من الفاقد الكلي بالضغط ولجميع الحالات التي تم دراستها.

ABSTRACT

The purpose of this work is to study the performance of multiphase flow in five wells located in Abu-Attifel field and three oil wells located in El-Ghani field. Two computer programs are developed using the "C" Programming Language in an attempt to test the Hagedorn & Brown correlation and the Poettmann & Carpenter correlation, which are widely used in the petroleum industry, against actual field measurements. The two correlations are then used to investigate the effect of tubing size, direction of pressure traverse calculation, the contribution of each term in the general energy equation on the total pressure gradient.

The programs are then modified in order to produce a new set of working charts for Abu-Attifel oil field. The new charts can predict the vertical-lift performance in Abu-Attifel oil wells more accurately than those available in the literature simply because they exhibit a wider range of pressure, depth and production rate. The programs can further be used to produce working charts for any other oil field provided that some production data is available.

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INTRODUCTION

Vertical multiphase flow is found in practically every tubing string used in the production of oil today (with the exception of off-shore wells). This fact emphasizes the importance of this topic and explains why it has been a matter of interest to many investigators. Although research in this topic started as early as 1914 by Davis and Weidner [1], it was only from 1952 when Poettmann and Carpenter published their paper [2], that most of the progress towards a solution to the problem of vertical multiphase flow has been made. Most of the approaches use some form of the general energy equation. Some of the correlations have contributed significantly to the vertical multiphase problem such as the correlations of Duns and Ros [3], Orkiszewski [4], Hagedorn and Brown [5], Beggs and Brill [6], Govier and Aziz [7] and the correlation of Poettmann and Carpenter. Others, such as Fancher and Brown [8], and Gilbert [9] contributed slightly to the solution of this problem, so as some earlier work by Hagedorn and Brown on viscous effects.

The pressure gradient (rate of change in pressure with respect to unit flow length) for vertical multiphase flow is the sum of three contributing factors: hydrostatic pressure gradient, friction pressure gradient, and acceleration pressure gradient. The effects of chemical reactions between the phases are neglected; however, such factors as viscosity, surface tension and density are included.

In this study, the vertical multiphase flow problem was considered. A two-component production system (tubing head pressure is constant) was assumed. The system consisted of the flow in the porous media, represented by the (I.P.R.) and the flow inside the well, governed by the vertical multiphase flow correlations. All vertical multiphase flow correlations involve lengthy calculations which consist of a series of steps that are repeated many times until the total depth of the well is reached. Hand calculations are very tedious, time consuming, and there is always the possibility of human error, which increases as the calculations are lengthened. Taking into consideration all the facts mentioned previously, it was necessary to develop efficient computer programs which would save time and effort in order to focus the work on the results, comparison, and discussion.

RESULTS AND COMPARISON OF CORRELATIONS

An essential part of this study is to gather a sufficient amount of actual field data in order to check the reliability of our computer programs, and also to compare between both correlations. Production data for eight wells, three wells located in El-Ghani field with the courtesy of Veba Oil Operations, and five wells located in Abu-Attifel field with the courtesy of Agip Oil Company (N.A.M.E.) were obtained. Although the number of wells is not large, the variation in the production data (production rate, depth, crude properties, etc.) compensated the lack of a large number of wells and served the purpose of this study. For instance the production rate ranged from approximately 400 bpd to 7000 bpd and the depth ranged from 6000 feet to 15000 feet.

The production data for all eight wells is listed in Table 1a and Table 1b. The wells in Abu-Attifel are A-1, A-3, A-27, A-52, and A-55, while those of El-Ghani are VVV5, RRR33, and RRR46.

Table 1a. Production Data for Five Wells in Abu-Attifel Field (Concession 100)-(Courtesy of Agip Oil Company (N.A.M.E)

WELL (A-1):

Description	Value
GOR (scf/stb)	1600.000
Oil Gravity (API)	40.000
Water Gravity	1.050
Gas Gravity	0.745
Oil Production Rate (bbl/day)	6905.00
Water Production Rate (bbl/day)	770.00
Tubing Head Pressure (psi)	1817.00
Depth (ft)	14060.00
Pressure Increment Below (1000)	50.00
Pressure Increment Above (1000)	100.00
Tubing Diameter (in)	3.5000
Surface Temperature (f)	220.0000
Bottom Hole Flowing Pressure(psi)	5540.0000
Pseudo critical pressure (psi)	410.0000
Pseudo critical temperature (f)	665.0000

WELL (A-3):

Description	Value
GOR (scf/stb)	1761.000
Oil Gravity (API)	40.000
Water Gravity	1.050
Gas Gravity	0.745
Oil Production Rate (bbl/day)	4899.00
Water Production Rate (bbl/day)	442.00
Tubing Head Pressure (psi)	1224.00
Depth (ft)	14356.00
Pressure Increment Below (1000)	50.00
Pressure Increment Above (1000)	100.00
Tubing Diameter (in)	3.5000
Surface Temperature (f)	212.0000
Bottom Hole Flowing Pressure(psi)	4423.0000
Pseudo critical pressure (psi)	422.0000
Pseudo critical temperature (f)	665.0000

WELL (A-27):

Description	Value
GOR (scf/stb)	2101.000
Oil Gravity (API)	40.000
Water Gravity	0.000
Gas Gravity	0.745
Oil Production Rate (bbl/day)	6782.00
Water Production Rate (bbl/day)	0.00
Tubing Head Pressure (psi)	1692.00
Depth (ft)	14500.00
Pressure Increment Below (1000)	100.00
Pressure Increment Above (1000)	100.00
Tubing Diameter (in)	3.5000
Surface Temperature (f)	220.0000
Bottom Hole Flowing Pressure(psi)	4776.0000
Pseudo critical pressure (psi)	415.0000
Pseudo critical temperature (f)	665.0000

WELL (A-52):

Description	Value
GOR (scf/stb)	1616.000
Oil Gravity (API)	40.000
Water Gravity	0.000
Gas Gravity	0.738
Oil Production Rate (bbl/day)	5430.00
Water Production Rate (bbl/day)	0.00
Tubing Head Pressure (psi)	1509.00
Depth (ft)	15132.00
Pressure Increment Below (1000)	50.00
Pressure Increment Above (1000)	100.00
Tubing Diameter (in)	3.5000
Surface Temperature (f)	220.0000
Bottom Hole Flowing Pressure(psi)	4949.0000
Pseudo critical pressure (psi)	405.0000
Pseudo critical temperature (f)	670.0000

WELL (A-55):

Description	Value
GOR (scf/stb)	1541.000
Oil Gravity (API)	40.000
Water Gravity	0.000
Gas Gravity	0.738
Oil Production Rate (bbl/day)	5441.00
Water Production Rate (bbl/day)	0.00
Tubing Head Pressure (psi)	1630.00
Depth (ft)	14153.00
Pressure Increment Below (1000)	50.00
Pressure Increment Above (1000)	100.00
Tubing Diameter (in)	3.5000
Surface Temperature (f)	212.0000
Bottom Hole Flowing Pressure(psi)	5051.0000
Pseudo critical pressure (psi)	405.0000
Pseudo critical temperature (f)	670.0000

Table 1b. Production Data for Three Wells in El-Ghani Field (Courtesy of Veba Oil Operations)

WELL (VVV5):

Description	Value
GOR (scf/stb)	475.000
Oil Gravity (API)	38.000
Water Gravity	0.000
Gas Gravity	1.055
Oil Production Rate (bbl/day)	1145.00
Water Production Rate (bbl/day)	0.00
Tubing Head Pressure (psi)	440.00
Depth (ft)	6004.00
Pressure Increment Below (1000)	50.00
Pressure Increment Above (1000)	100.00
Tubing Diameter (in)	3.5000
Surface Temperature (f)	1702.0000
Bottom Hole Flowing Pressure(psi)	500.0000
Pseudo critical pressure (psi)	650.0000
Pseudo critical temperature (f)	670.0000

WELL (RRR46):

Description	Value
GOR (scf/stb)	594.000
Oil Gravity (API)	38.000
Water Gravity	0.000
Gas Gravity	1.055
Oil Production Rate (bbl/day)	416.00
Water Production Rate (bbl/day)	0.00
Tubing Head Pressure (psi)	480.00
Depth (ft)	6142.00
Pressure Increment Below (1000)	50.00
Pressure Increment Above (1000)	100.00
Tubing Diameter (in)	3.5000
Surface Temperature (f)	100.0000
Bottom Hole Flowing Pressure(psi)	1681.0000
Pseudo critical pressure (psi)	500.0000
Pseudo critical temperature (f)	650.0000

WELL (RRR33):

Description	Value
GOR (scf/stb)	660.000
Oil Gravity (API)	38.000
Water Gravity	0.000
Gas Gravity	1.055
Oil Production Rate (bbl/day)	707.00
Water Production Rate (bbl/day)	0.00
Tubing Head Pressure (psi)	540.00
Depth (ft)	5916.00
Pressure Increment Below (1000)	50.00
Pressure Increment Above (1000)	100.00
Tubing Diameter (in)	3.5000
Surface Temperature (f)	100.0000
Bottom Hole Flowing Pressure(psi)	1660.0000
Pseudo critical pressure (psi)	500.0000
Pseudo critical temperature (f)	650.0000

In this study a representative well (A-55) is selected to show in detail the calculations involved in each application of the computer programs. The first step after the completion of the computer programs was to calculate the bottom hole flowing pressure (P_{wf}) starting with the tubing head pressure (P_{tf}) and vice versa for all eight wells, to check the reliability of these programs, and compare between the correlations. The results are presented in Table 2 and Table 3.

Table 2 shows the results when the calculations were carried out from top to bottom, starting with the actual tubing head pressure and calculating downwards until reaching the exact depth of the well to obtain a calculated value for (P_{wf}). The error percentage was calculated using the following relation:

$$\text{Error}(\%) = [(P_{wf}|_{cal} - P_{wf}|_{act})/P_{wf}|_{act}] * 100$$

Table 3 shows the result when the calculations were carried out from bottom to top, starting with the actual value of (P_{wf}) and calculating upward until reaching the surface to obtain a calculated value for (P_{tf}). The error percentage was calculated in the same manner as that of Table 2.

From Table 2 and Table 3, it is clear that the two computer programs function within an error range of 1 to 9 percent, which is considered adequate for this study. The cause of this error could be from number of reasons, error from the correlations themselves or from the available data or other technical problems in the tubing such as scale, paraffin, corrosion, etc. It is clear from the two Tables that the two correlations give close results for most of the wells. The Poettmann & Carpenter correlation yielded good results, especially for the Abu-Attifel wells for which the accuracy was very good (average error 2.38%). This is mainly due to the very high production rates which ensure an entirely turbulent flow that can be considered as one phase, but the results for the El-Ghani field were less accurate (average error 5.43%) probably because the flow rates ranged from 400 to 1000 bbl/day, which is considered low to intermediate. The Hagedorn & Brown correlation gave good results and consistent accuracy, for the Abu-Attifel field the average error was 4.25% and for the El-Ghani field the average was 4.51%. The main reason for this similarity in the error percentage is because the Hagedorn & Brown correlation is a generalized correlation with no specific conditions. An important point should be noted from Table 2, and that is the Hagedorn & Brown correlation always produced calculated values greater than the actual, contrary to the Poettmann & Carpenter correlation which under predicted the pressure in most cases.

EFFECT OF DIRECTION ON PRESSURE TRAVERSE

The first application was to show the effect of the direction of calculations on the pressure traverse for both methods.

The pressure traverse calculated in both directions using the Poettmann & Carpenter correlation, is shown in Fig. 1 while the pressure traverse calculated in both directions by the Hagedorn & Brown correlation, is plotted in Fig.2.

Figures 1 and 2 indicate that the plotted pressure traverse in both direction is different for both methods. The only explanation for this difference is that in each of the two directions, either an actual (P_{tf}) or (P_{wf}) value was chosen and the other was calculated. Since the two correlations do not give the exact pressure traverse (No correlation gives an exact pressure traverse), therefore it is impossible to obtain

Table 2. Results of Calculations when Carried out from Top to Bottom.

	HAGEDORN & BROWN			POETTMANN & CARPENTER		
WELL	CALCULATED Pwf (psi)	ACTUAL Pwf psi	ERROR %	CALCULATED Pwf psi	ACTUAL Pwf psi	ÉRROR %
A-1	5780	5540	4.34	5424	5540	-2.09
A-3	4649	4423	5.12	4517	4423	-2.13
A-27	5046	4776	5.65	4605	4776	-3.58
A-52	5185	4949	4.78	4799	4949	-3.03
A-55	5119	5051	1.36	4880	5051	-3.38
VVV5	1781	1702	4.68	1788	1702	5.05
RRR33	1736	1660	4.57	1759	1660	6.29
RRR46	1753	1681	4.28	1759	1681	4.64

Table 3. Results of Calculations when Carried Out from Bottom to Top.

	POETTMANN & CARPENTER			HAGEDORN & BROWN		
WELL	CALCULATED Ptf (psi)	ACTUAL Ptf psi	ERROR %	CALCULATED Ptf psi	ACTUAL Ptf psi	ERROR %
A-1	1670	1817	-4.09	1729	1817	-4.79
A-3	1130	1224	-7.68	1327	1224	8.41
A-27	1220	1492	-8.2	1624	1492	8.87
A-52	1347	1369	-1.6	1448	1369	5.77
A-55	1588	1630	-2.55	1714	1630	5.17
VVV5	417	440	-5.23	398	440	-9.42
RRR33	503	540	-6.75	506	540	6.29
RRR46	441	480	-8.13	438	480	8.69

the same results when starting with opposite points. Another important point concerning this difference in the plotted pressure traverses is the fact that empirical correlations were used to calculate crude properties such as (R_s) and (β_o), these correlations are functions of temperature and pressure, and give more accurate results when the temperature and pressure are low to intermediate. The pressure and temperature at the surface of the well under study are 1630 Psi and 212°F respectively while at the bottom are 5051 Psi and 288°F respectively. Therefore one would expect that the calculated values of (R_s) and

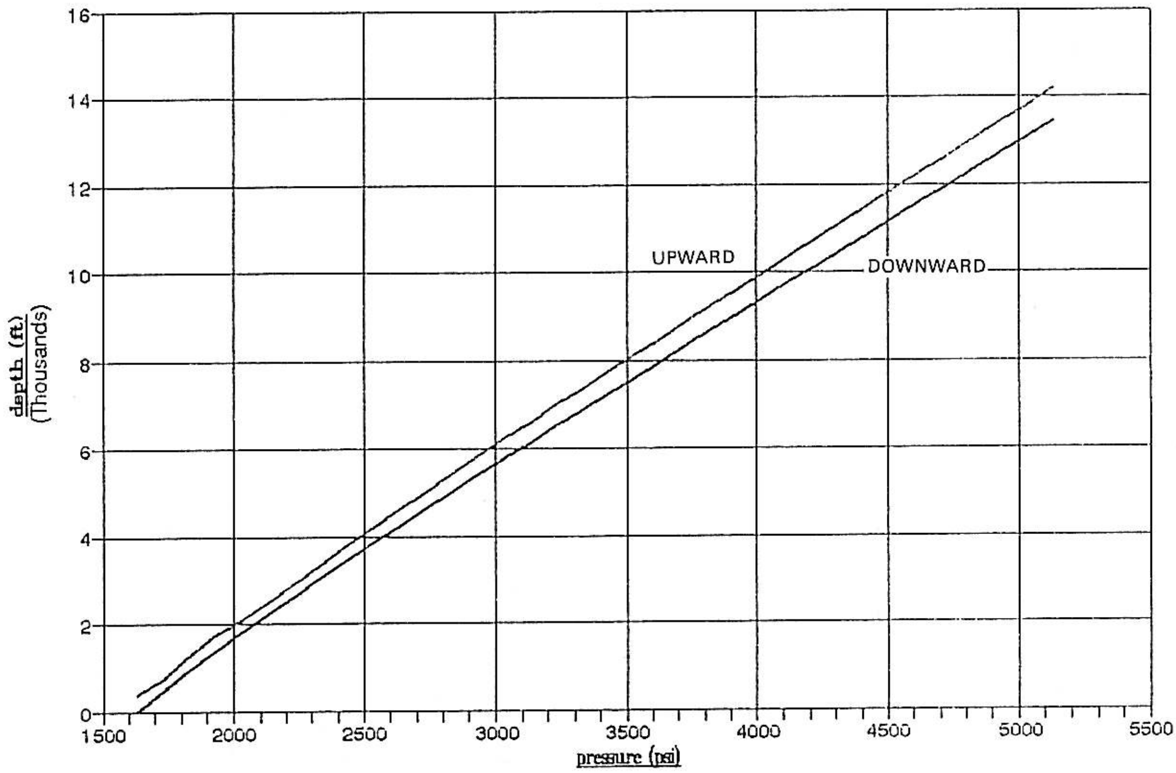

FIG. 1. Pressure traverse in both direction calculated by Poettmann and Carpenter method.

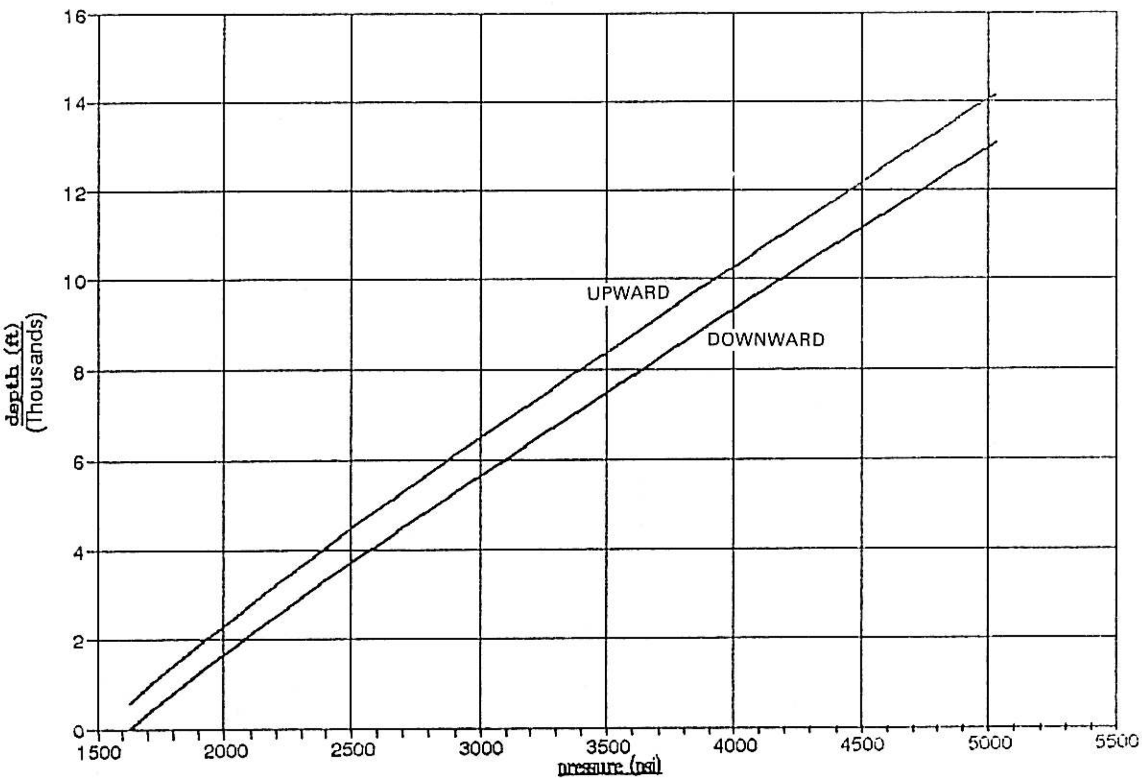

FIG. 2. Pressure traverse in both directions calculated by Hagedorn and Brown method.

(β_o) near the surface to be more accurate which leads to better calculation of the pressure traverse in a downward direction.

EFFECT OF ELEVATION, FRICTION AND ACCELERATION TERMS ON TOTAL PRESSURE LOSS

The second application of the computer programs is to determine the effect of the elevation, friction, and acceleration terms on the total pressure gradient and how much each term contributes to the total pressure loss. In doing so a better understanding of what causes the dissipation of the reservoir energy (pressure), how much is dissipated and where can be achieved. This would be very helpful in the analysis of the vertical multi-phase problem and would be a very useful tool in finding methods that would decrease this loss in vital energy.

The calculations for well (A-55) were carried out for each pressure increment, where the contribution was expressed in (Psi) and added to the actual tubing head pressure (P_{tf}) until the total depth of the well has been reached. At the end of the calculations, the contribution of each term to the total pressure loss is expressed in percentage.

The results from the Hagedorn and Brown correlation are shown in Figures 3a and 3b (Note: For Fig. 3a the contributions are expressed in (Psi) and they are cumulative starting with the actual tubing head pressure (P_{tf}), for Fig. 3b the contributions are represented in percentage of each pressure increment).

The results for the Poettmann & Carpenter correlation are plotted in Fig. 4a and Fig. 4b.

The results show that the predominant factor in the contribution to the total pressure loss is the elevation term. The friction term also has a significant effect, but the acceleration term is quite negligible for most cases. Although this case can be considered somewhat general, the percentages of each term differs from one case to the other depending on other variables such as flow rate, tubing size, and gas liquid ratios. To further express the effect of these variables, Fig. 5 and 6 show the effect of flow rate (for a constant GLR and the same tubing size 3.5 inch) on the total contribution of each term for the specified well (A-55) (Note: The total contribution for each term is expressed in percentage of the total pressure loss).

It is quite clear from Fig. 5 and Fig. 6, that an increase in flow rate means that the friction term becomes more effecting contrary to the elevation term whose influence decreases, but remains dominant. If the calculations were to be done on a smaller tubing size the friction term would have been increased and the elevation term would have been reduced even more. This effect is shown in Figs 7 and 8 where the tubing size is equal to 2.0 inch.

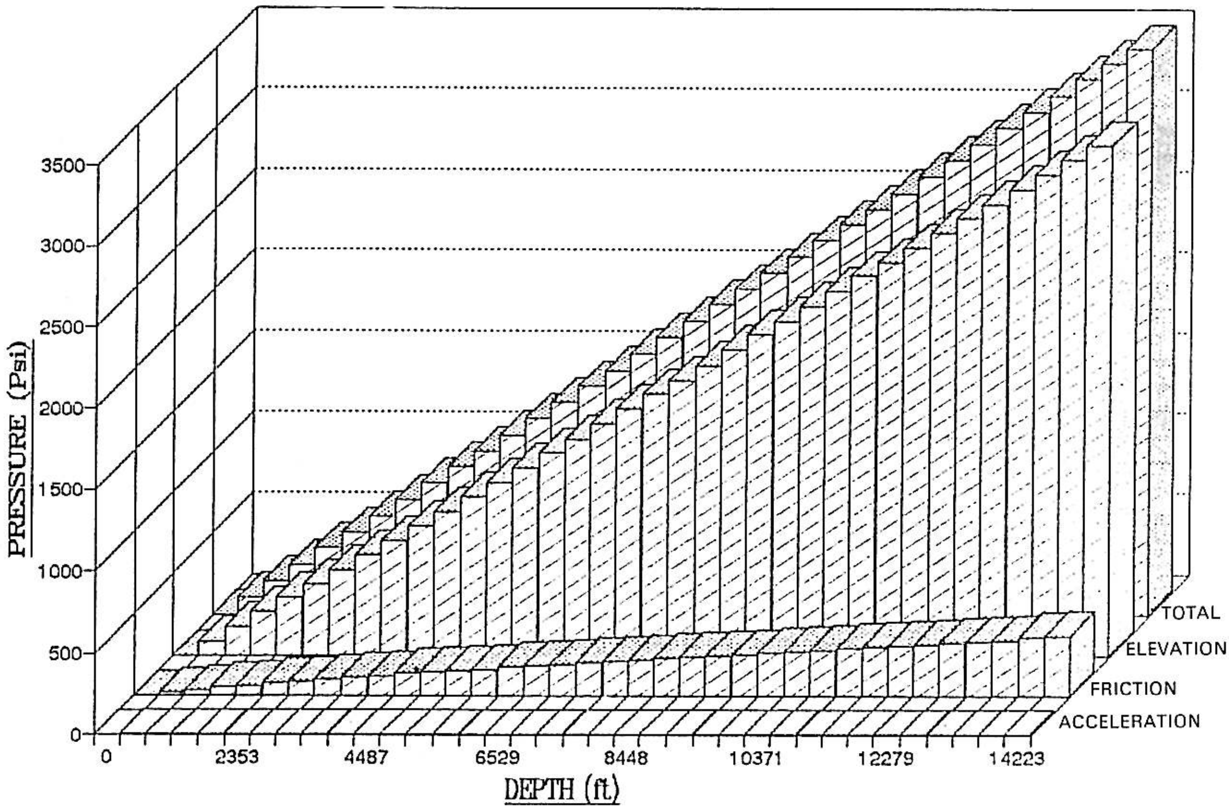

FIG. 3a. Pressure loss contributions by Hagedorn and Brown method.

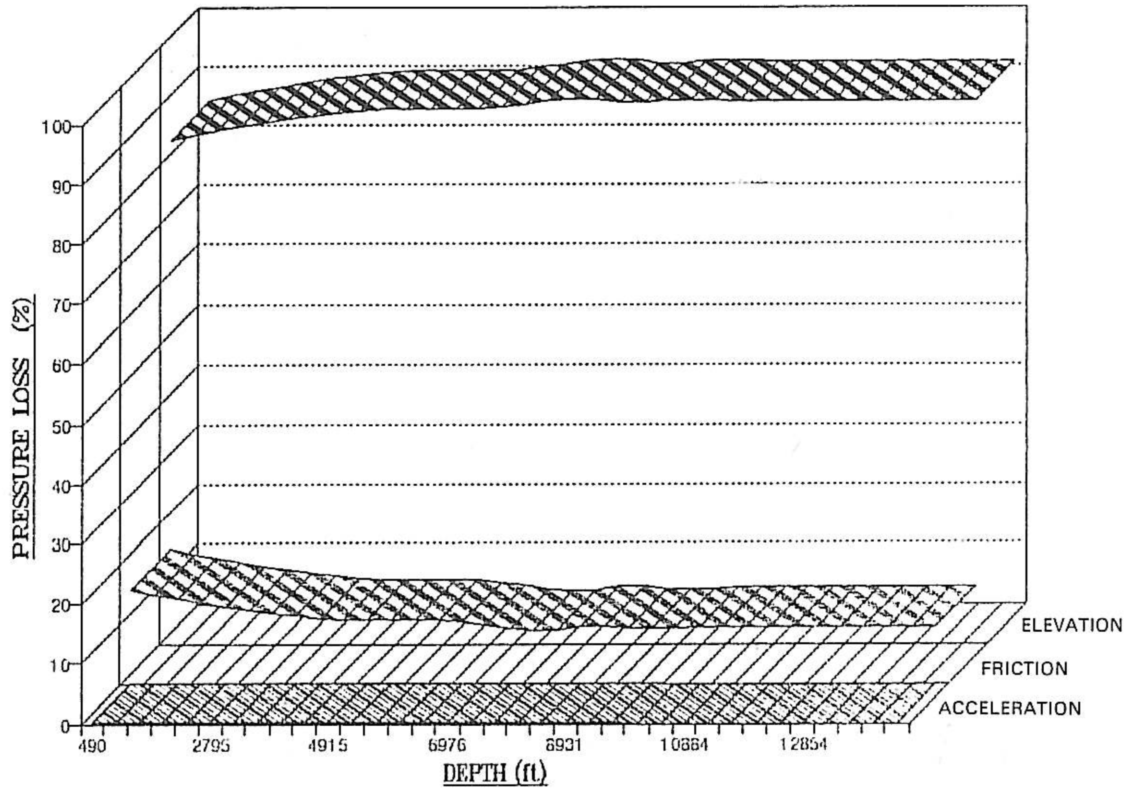

FIG. 3b. Pressure loss contributions as percent of total pressure loss by Hagedorn and Brown method.

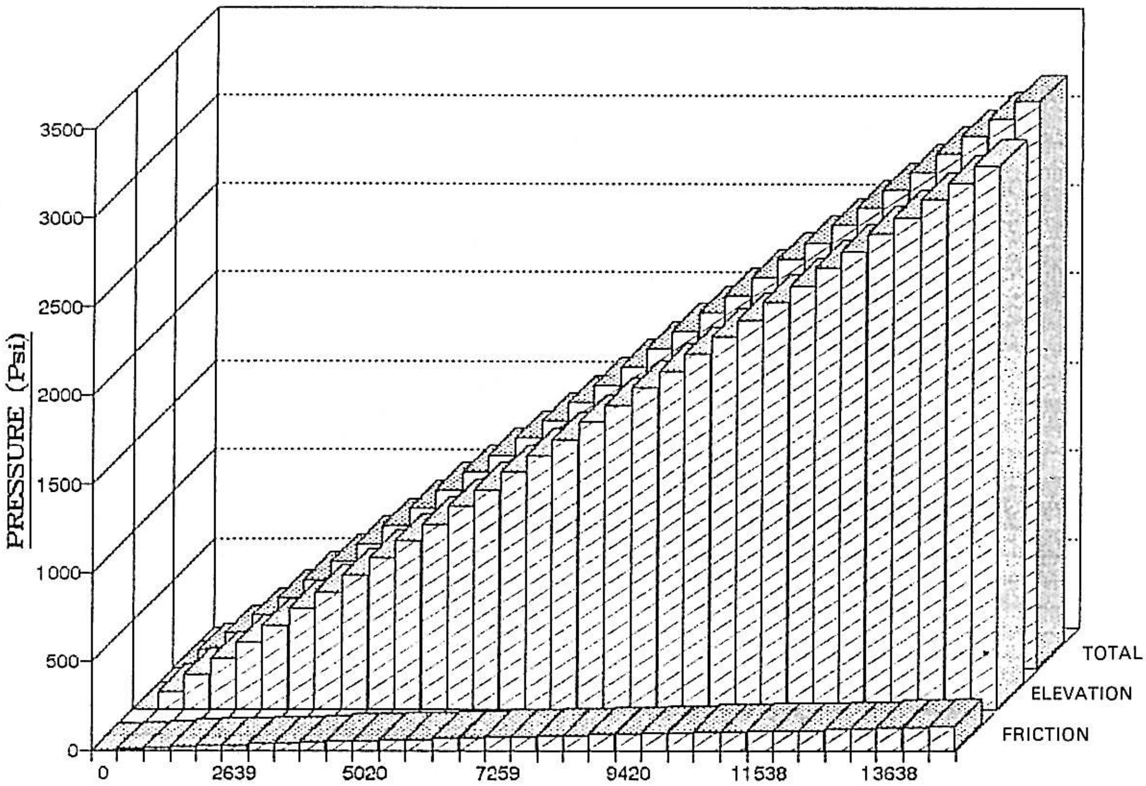

FIG. 4a. Pressure loss contributions by Poettmann and Carpenter method.

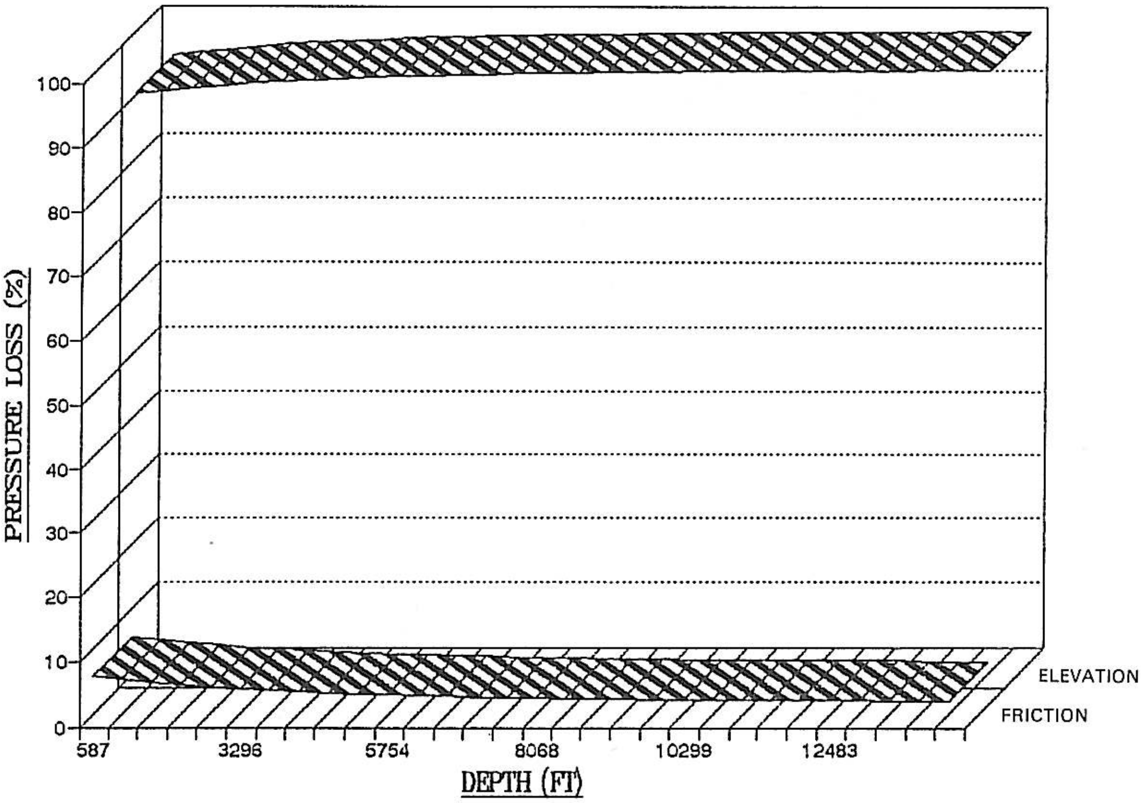

FIG. 4b. Pressure loss contributions as percent of total pressure loss by Poettmann and Carpenter method.

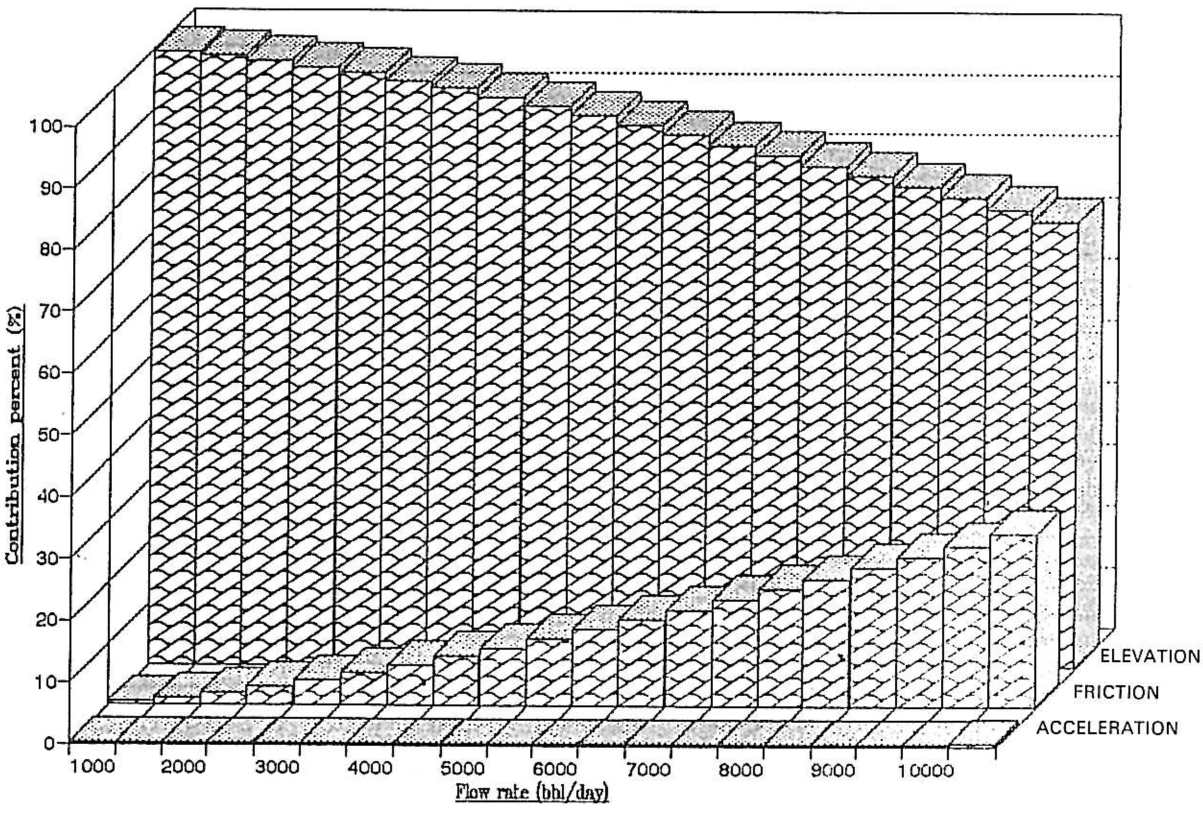

FIG. 5. Effect of flowrate on friction and elevation terms for tubing size of 3.5 inch (Poettmann and Carpenter).

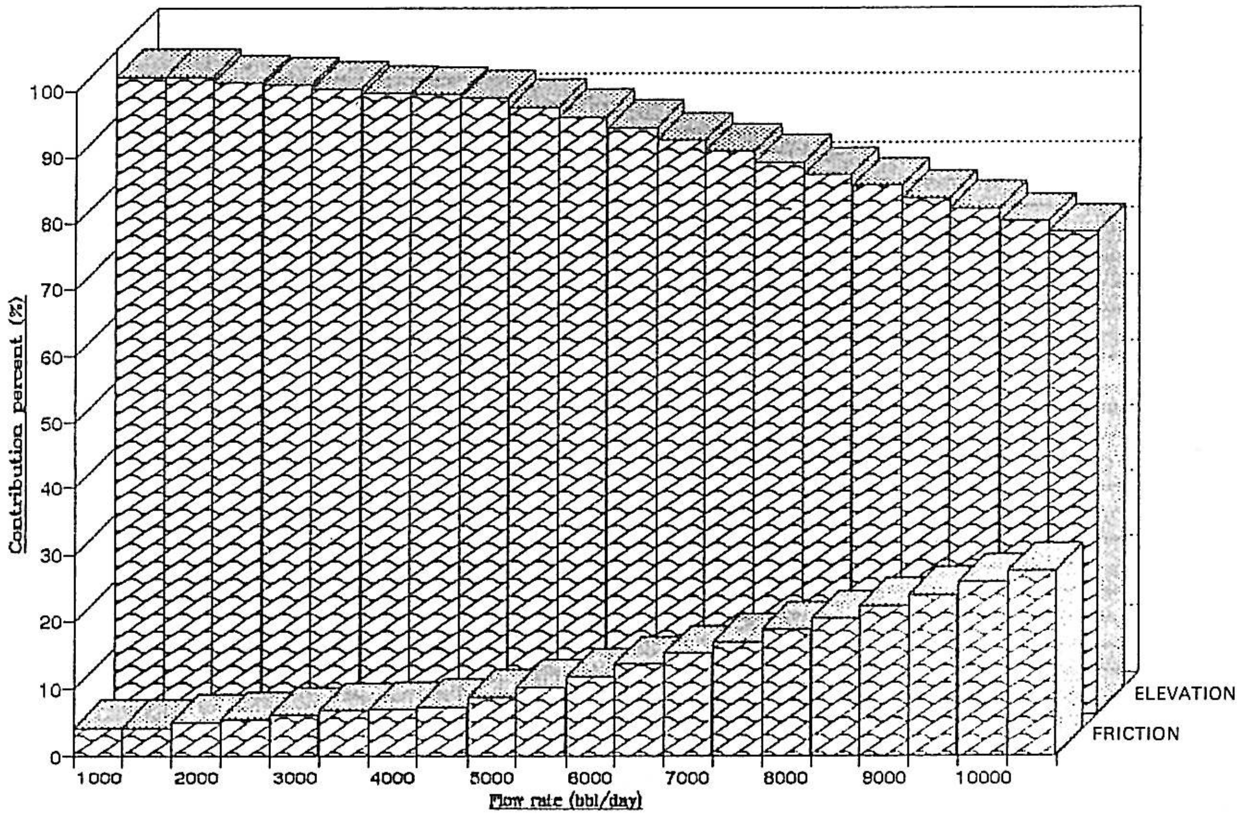

FIG. 6. Effect of flow rate on friction and elevation terms for tubing size of 3.5 inch (Hagedorn and Brown).

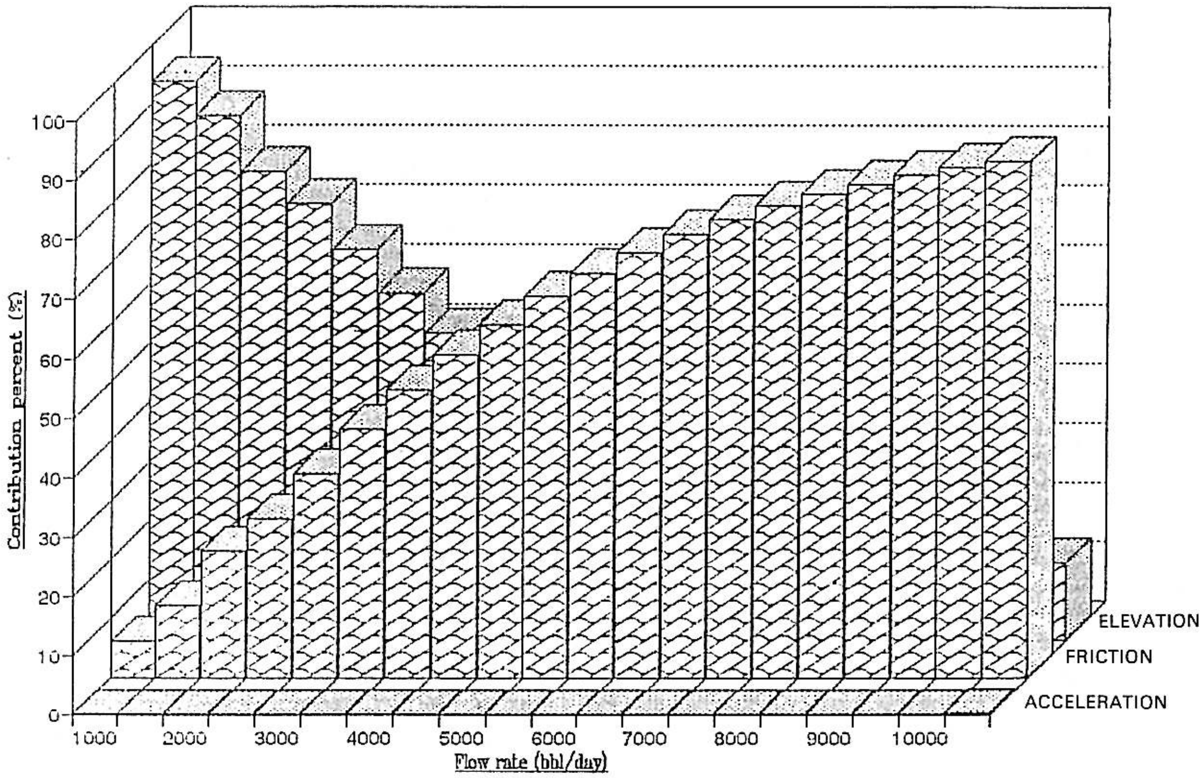

FIG. 7. Effect of flow rate on friction and elevation terms for tubing size of 2.0 inch (Poettmann and Carpenter).

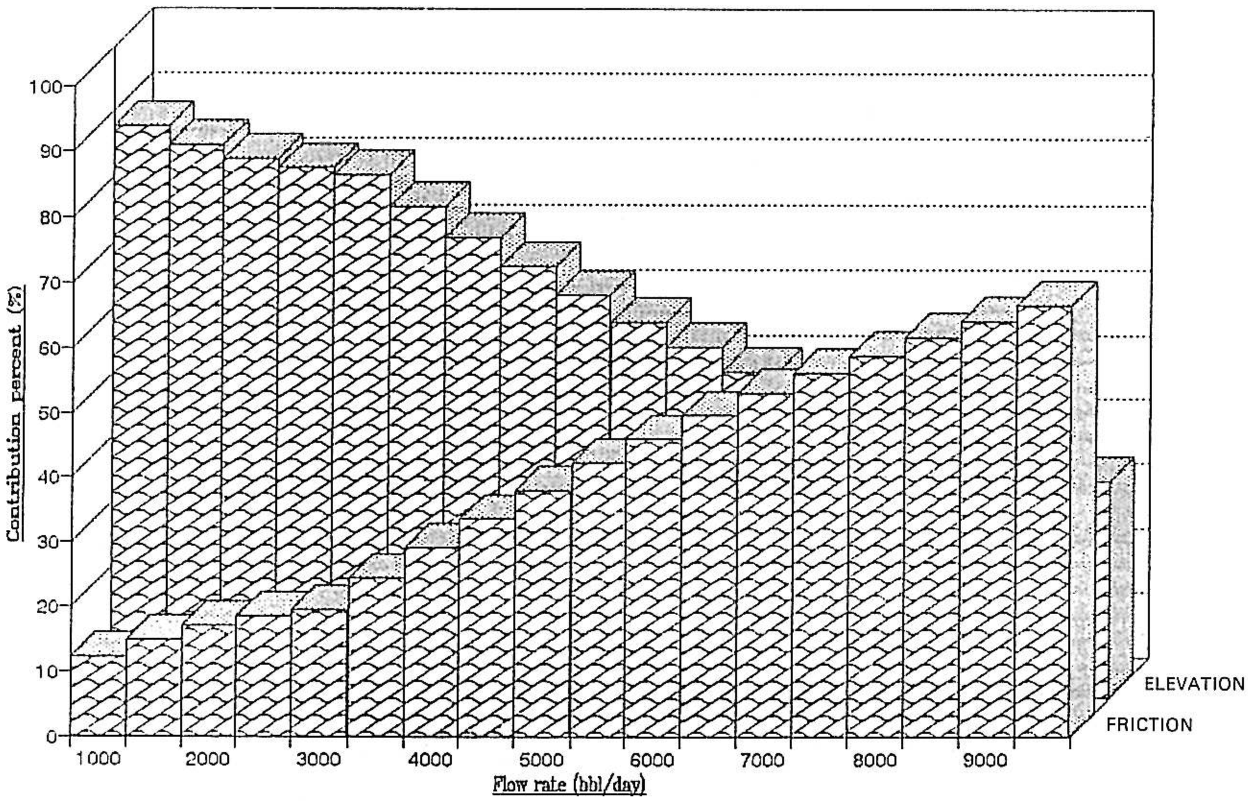

FIG. 8. Effect of flow rate on friction and elevation terms for tubing size of 2.0 inch (Hagedorn and Brown).

The difference in the effect of the terms is very high between the 3.5 and 2.0 inch tubing. In the latter case we notice that the friction contribution reaches 80% of the total pressure loss, this means that most of the energy is consumed (dissipated) in overcoming the friction between the walls of the tubing and the fluids.

EFFECT OF TUBING SIZE ON MAXIMUM PRODUCTION RATE

The third application of the computer programs was to study the effect of tubing size on the maximum production rate possible from a well. The determination of tubing size is extremely important, because the decision about the size should be made prior to drilling. Once the bottom hole flowing pressure is determined for a certain well, calculations are carried out to determine the most suitable tubing size which will achieve the required flow rate and flowing pressure. The maximum fow rate possible from a well is determined from the plot of P_{wf} performance curve and the I.P.R. (Inflow Performance Relationship), the intersection point represents the maximum flow rate possible.

Using the computer programs it was possible to calculate very quickly the P_{wf} performance curves for well (A-55), (the tubing sizes were 2, 2.5, 3, 3.5, and 4 inch, respectively, and the flow rates were from 200 to 10000 bbl/day). The performance curves using both methods were plotted together with the I.P.R in Figs. 9 and 10. For each intersection point on the two plots the contribution of each of the three terms (elevation, friction, and acceleration) is also calculated in order to determine the influences of all the terms and check the possible similarity in their effect for different tubing sizes.

The results for the Hagedorn and Brown, and Poettmann and Carpenter correlations are tabulated in Tables 4 and 5, respectively.

From Tables 4 and 5 and Figs 9 and 10 the followings are noted:

1. The maximum production rate possible from a certain well is proportional to the tubing size used, the greater the tubing size the greater the production rate. It is quite clear that the Poettmann and Carpenter correlation always gave maximum production rates greater than the Hagedorn and Brown correlation. This is mainly because of lower friction losses in the Poettman and Carpenter correlation. There are other factors which play a very important role in determining the tubing size, mainly economical aspects and technical aspects. The economical aspects are concerned with the costs of all possible alterna-

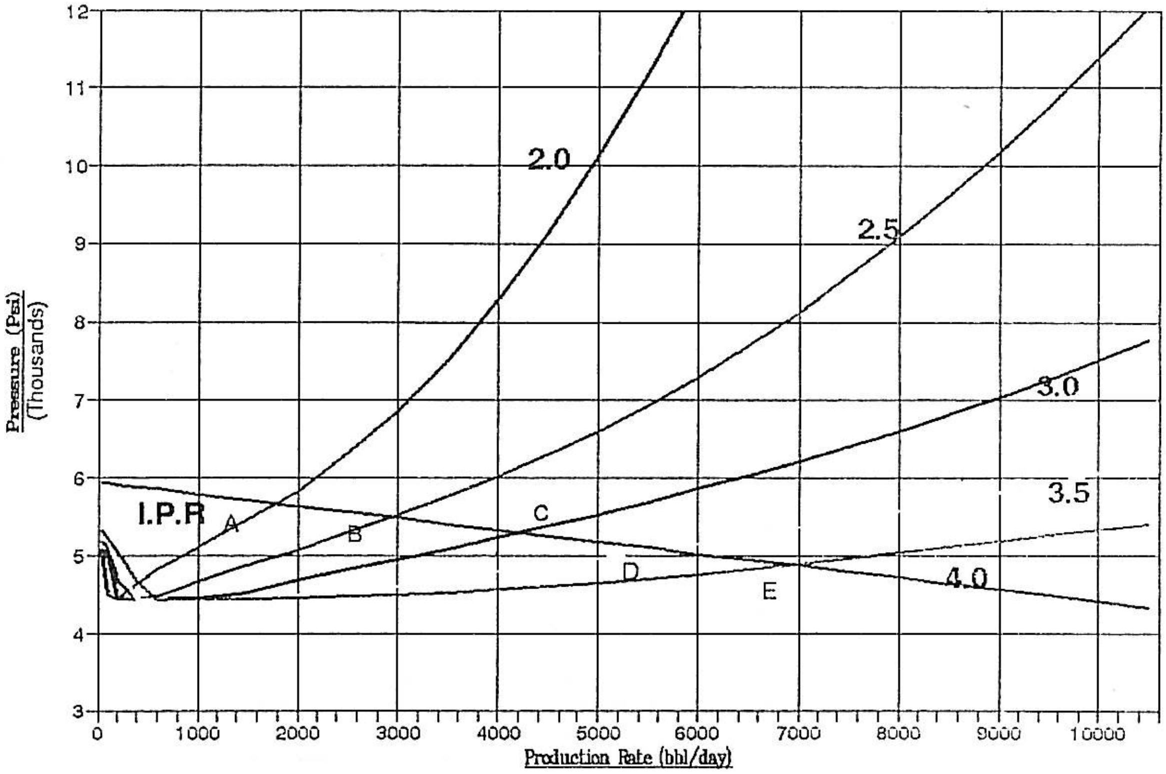

FIG. 9. Well performance curves for different tubing sizes by Hagedorn and Brown; curves A, B, C, D, and E correspond to 2.0, 2.5, 3.0, 3.5, and 4.0 inch tubing sizes, respectively.

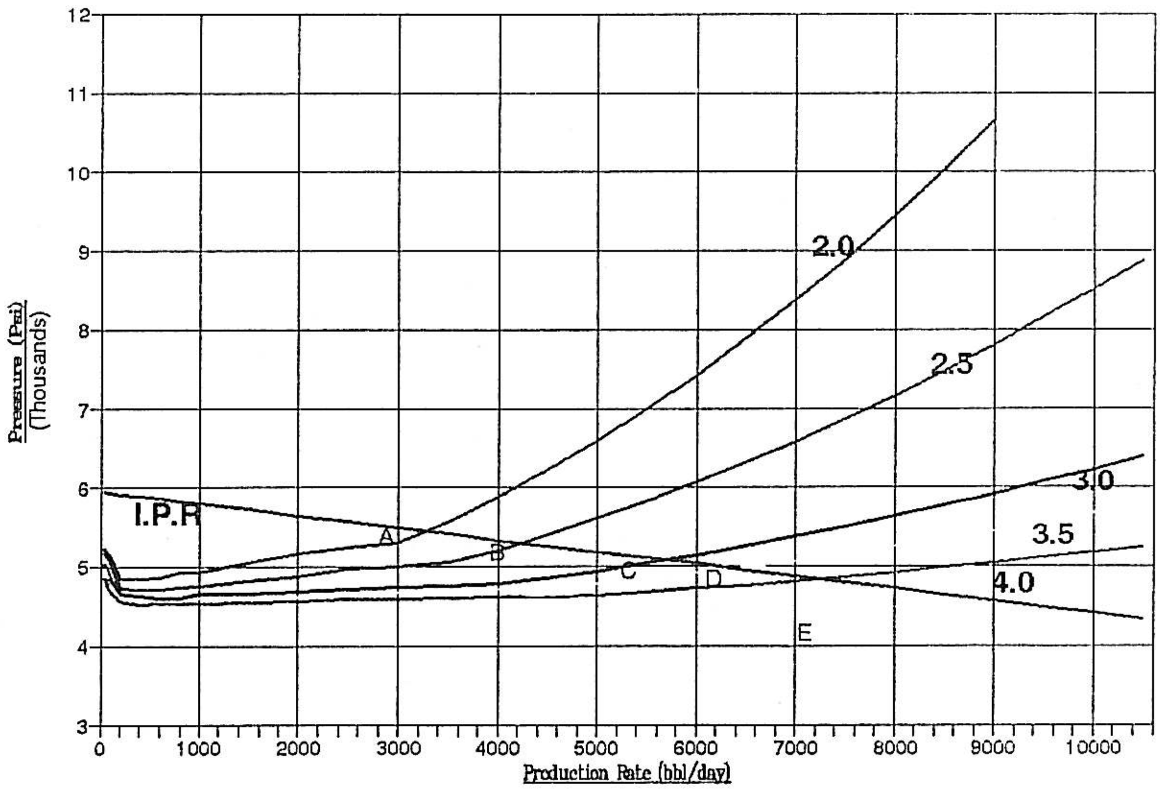

FIG. 10. Well performance curves for different tubing sizes by Poettmann and Carpenter; Curves A, B, C, D, and E correspond to 2.0, 2.5, 3.0, 3.5, and 4.0 inch tubing sizes, respectively.

Table 4. Results of Hagedorn and Brown Correlation

Tubing size Inch	Q_o (bbl/day)	P_{wf} (Psi)	Elevation (%)	Friction (%)
2.0 (a)	1760	5675	83.94	16.03
2.5 (b)	2940	5505	85.76	14.22
3.0 (c)	4200	5310	87.58	12.40
3.5 (d)	5660	5090	89.18	10.80
4.0 (e)	6870	4880	91.25	8.73

Table 5. Results of Poettmann and Carpenter Correlation

Tubing size Inch	Q_o (bbl/day)	P_{wf} (Psi)	Elevation (%)	Friction (%)
2.0 (a)	3250	5720	84.76	15.24
2.5 (b)	4190	5410	86.65	13.35
3.0 (c)	5210	5120	90.12	9.88
3.5 (d)	6250	4950	93.52	6.48
4.0 (e)	7050	4720	95.80	4.20

tives available, for instance, in our case we have a well which has a maximum production rate of 5660 bbl/day using 3.5 inch tubing, this rate can be increased to 6870 bbl/day using 4.0 inch tubing, so the question is, does this increase in production rate justify the extra cost involved in the installation of 4.0 inch tubing? The technical aspects look into the effect of all possible alternatives on the whole producing system (reservoir, tubing, flowlines, etc.), the bottom hole pressure has a profound effect on the reservoir performance and a mutual study between the production engineer and reservoir engineer is inevitable, in order to reach a proper decision concerning the tubing size.

2. The contributions of both the elevation and friction (the acceleration term is considered negligible less than 0.2%) terms are also shown for both methods. It is quite clear that the elevation term is dominant in all cases, but the interesting point is that for the intersection points of the 2.0, 2.5 and 3.0 inch tubing curves from Tables 4 and 5, the percentage of the contributions is quite similar, this is because Poettmann & Carpenter studied these tubing sizes only and the extension of their work to greater tubing sizes should be carried out with caution. For the 3.5 and 4.0 inch tubing the Poettmann & Carpenter correlation gave considerably lower friction contributions than that calculated by the Hagedorn & Brown correlation. This is due to the exclusion of liquid hold-up in the Poettmann & Carpenter correlation.

In general it is safe to state that for all intersection points (maximum production rates), the elevation term constitutes approximately 80% to 90% of the pressure loss while the rest is due to friction, and the acceleration term is considered negligible. The influence of elevation tends to increase with increase of tubing size.

PREPARATION OF WORKING CHARTS

The fourth application of the programs is to prepare working charts and for this application in particular the computer programs are very helpful and beneficial, mainly because the calculations involved are extremely lengthy and tedious and hand calculations are totally out of the question. The basic idea behind the working charts is the immediate access to the multiphase flow correlations, when computer services are not readily on hand. Although the results are not as exact as computer results, they do provide a very helpful and adequate alternative when problems needing immediate attention arise. One of the main setbacks of the working charts is that they consider certain fluid properties (gas gravity, oil API, WPOR, etc.) and also certain production data (tubing size, flow rates, WOR, GLR), this usually implies some approximation, because one cannot always find working charts that exactly satisfy the actual conditions, contrary to computer calculations where one can input exactly what is needed.

To prepare working charts it is necessary to calculate pressure traverses many times as a function of gas liquid ratio and production rate while the other parameters are held constant. It was possible to achieve this by adding two nested loops to the original computer programs, with the flow rate being the external loop and the gas liquid ratio the internal loop, so that for each flow rate several pressure traverses were obtained, each one representing a gas liquid ratio. This modification in the computer programs produced a massive amount of output which was converted into graphs by means of graphical software. A whole family of working charts has been produced for flow rates ranging from 400 to 8000 bbl/day (See Appendix A and Appendix B).

The working charts were used to calculate Pwf performance curve for well A-55 (representative well) in order to determine the maximum production rate and compare the results with the computer calculations to check their efficiency. Fig. 11 shows the plot of Pwf performance curves for both correlations and the I.P.R. The maximum production rate and the corresponding pressure for the Poettmann & Carpenter correlation are 6350 bbl/day at a pressure of 4925 Psi and for the Hagedorn & Brown correlation the flow rate was 5700 at a pressure of 5175 Psi.

The results obtained by the working charts for the 3.5 inch tubing are slightly greater than those calculated by the computer programs, this difference in the values of the maximum production rate may be attributed to the following reasons:

1. Human error in reading any chart is a known fact.
2. The approximation involved in using working charts. In this case, the actual GLR for well A-55 was 1541 scf/stb and there is no curve for this GLR, therefore an approximate value of 1500 scf/stb was taken.
3. The accuracy of reading values from a chart depends on the scale, since the depth ranged from zero to 33,000 feet and the pressure ranged from zero to 9000 Psi, it was difficult to produce a scale with clear and adequate divisions.

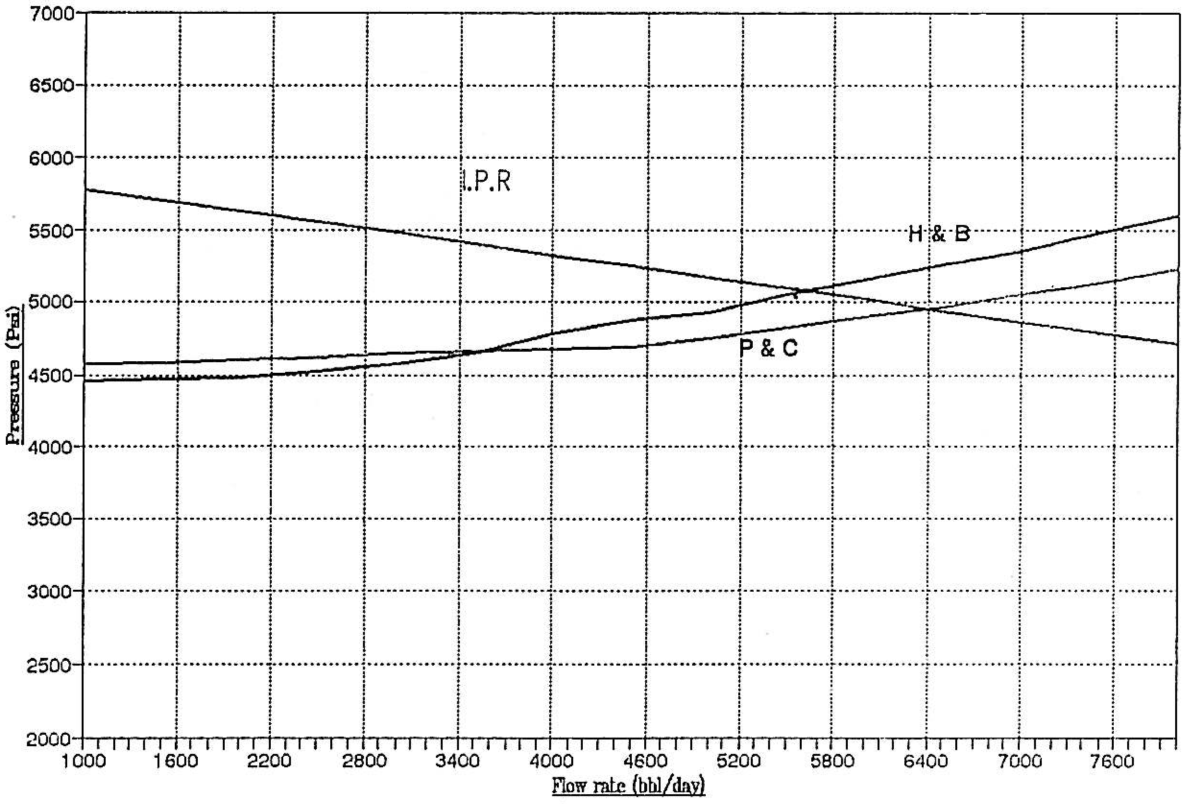

FIG. 11. Well performance curves as predicted by the new working curves for tubing size of 3.5 inch; H & B stands for Hagedorn and Brown whereas P & C stands for Poettmann and Carpenter.

CONCLUSIONS

Although the number of wells in this study is eight, the variation in the production data allows to conclude the following:

- This study and the final results obtained depend greatly on the quality and range of the available field data.
- The fact that empirical correlations were used to calculate fluid physical properties means additional inaccuracies in the results. This also means that the pressure loss prediction method is a combination of a pressure loss correlation and a fluid physical property correlation which should be considered as a unit.
- Both correlations give good results for all wells. The extension of the Poettmann & Carpenter correlation to 3.5 in tubing produces very good results provided that the flow rate is very high (above 2000 bbl/day) and the GLR does not exceed 2500 scf/stb. The Hagedorn & Brown correlation showed ability to predict pressure loss with consistency for all wells.
- The direction of calculations (whether it is upward or downward) has a profound effect on the calculated pressure traverse and a downward direction is recommended.
- For practically all maximum production rates regardless of other variables, the elevation term always constitutes approximately 80% to 90% of the total pressure loss while the rest is due to friction. The acceleration term can be neglected for most cases.
- The accuracy of the working charts depends mainly on their quality, readers accuracy and the approximation involved. The working charts for the Abu-Attifel field are more practical and efficient than those provided by Hagedorn & Brown because the latter charts have depth limitations. By using the computer programs, working charts can be prepared for any field using both correlations.
- The production rate for the representative well (A-55) can be increased to 6870 bbl/day if 4.0 inch tubing were to be installed, but first an economical study must be made to ensure an overall profit due to greater tubing size.

RECOMMENDATIONS

1. For wells producing with very high flow rates and intermediate GLR the Poettmann & Carpenter correlation is suggested, for 3.5 inch tubing the flow rate should exceed 2000 bbl/day. However if there is a wide range of flow rates, GLR and tubing sizes the Hagedorn & Brown correlation gives more consistent accuracy in its results.
2. The direction of calculations should be chosen downwards for greater accuracy and the use of actual fluid physical property data will eliminate the inaccuracies caused by the fluid property correlations.
3. A similar study should be carried out for other vertical multiphase flow correlations, the study should be supported by computer programs and a larger number of wells should be available
4. A two component system was considered in this study consisting of the I.P.R. and P_{wf} performance curves calculated by vertical correlations. The extension of this work to three component systems with the inclusion of horizontal multiphase flow correlations is a must.

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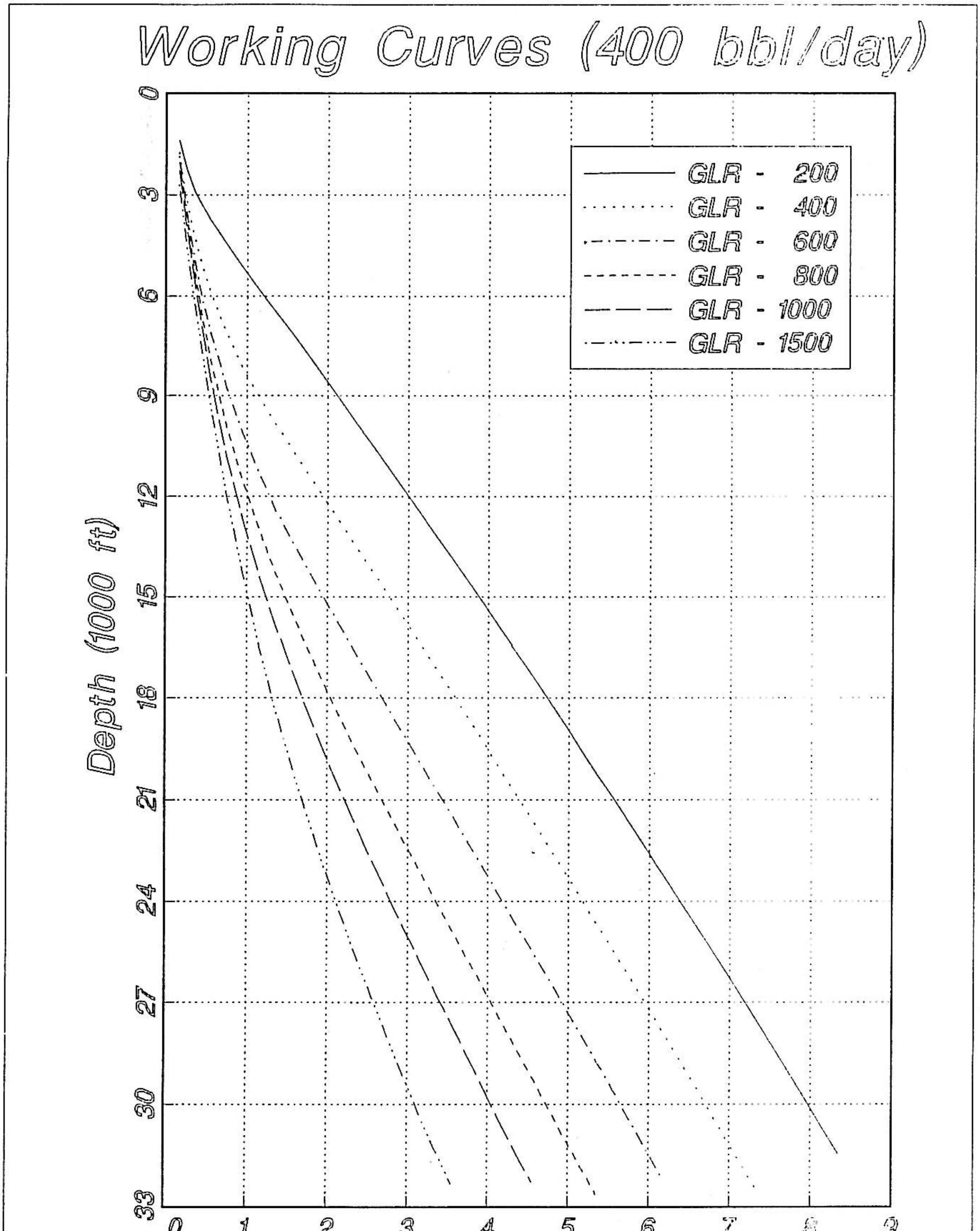
APPENDIX A

The following working charts were calculated using the Hagedorn & Brown Correlation for flow rates of 400 to 8000 bbl/day:

Production Data:

1.	Tubing size	3.5 inch
2.	Oil API gravity	40 API
3.	Gas specific gravity	0.75
4.	Average flowing temp.	245°F

Hagedorn & Brown



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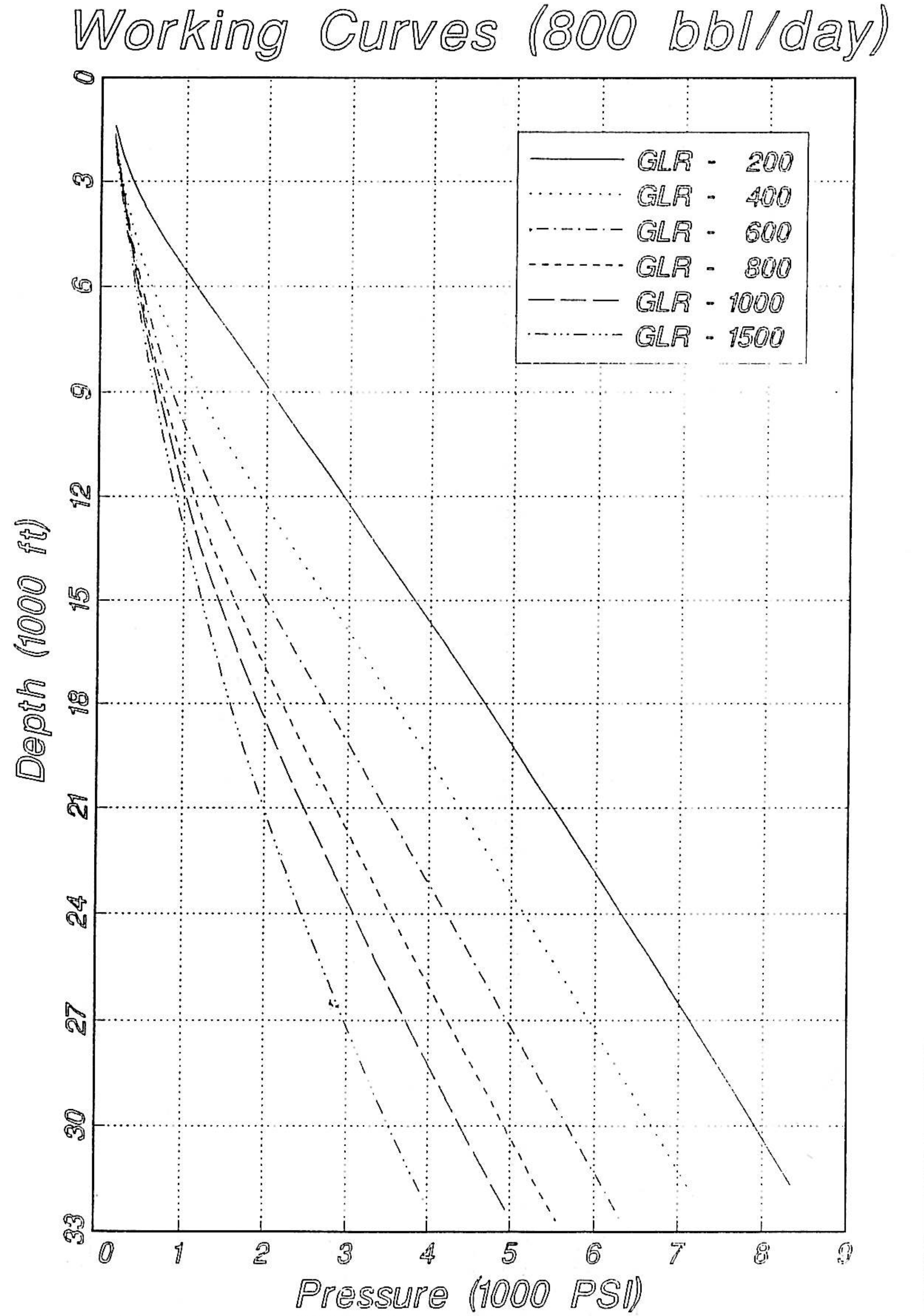

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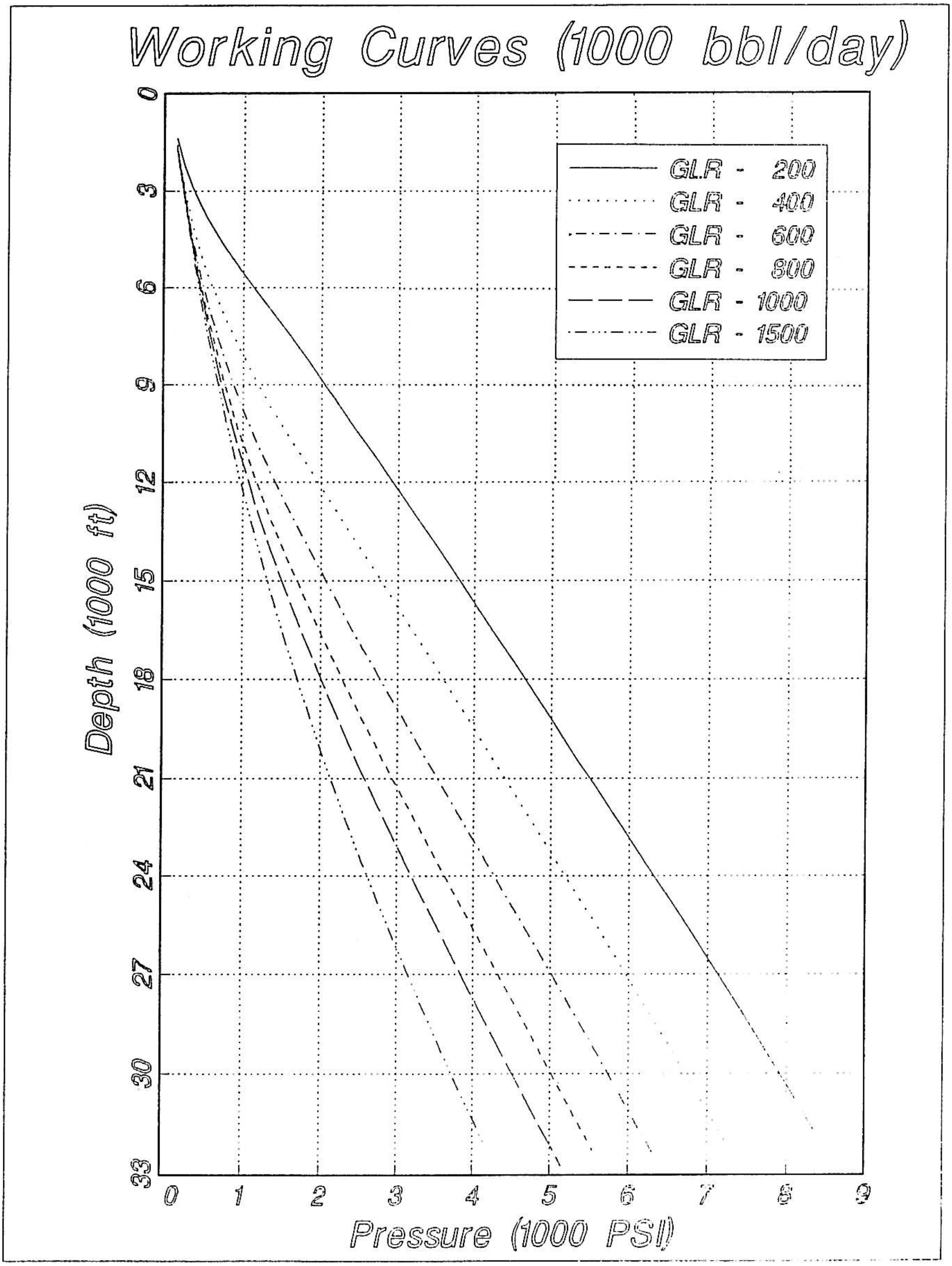

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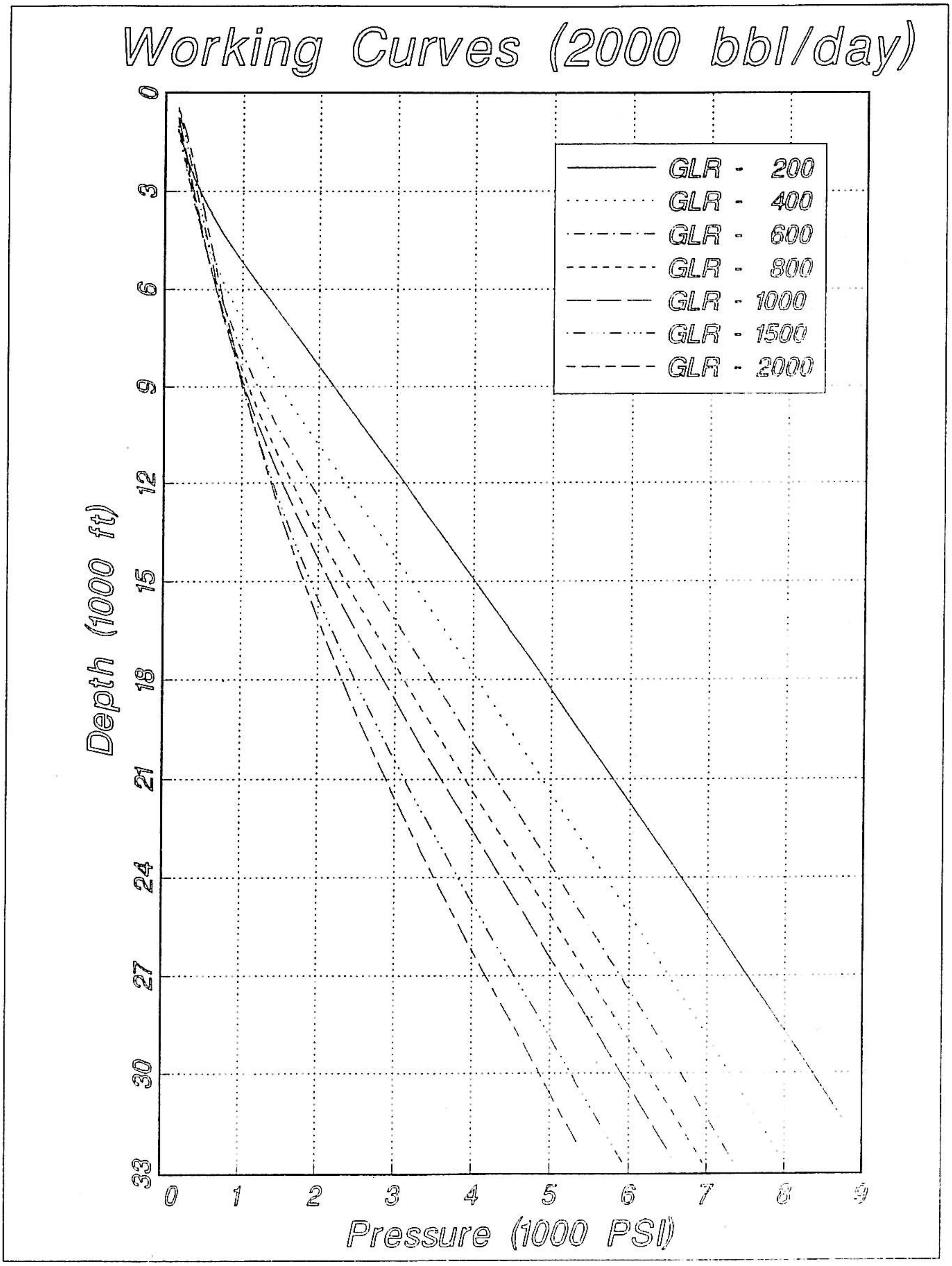

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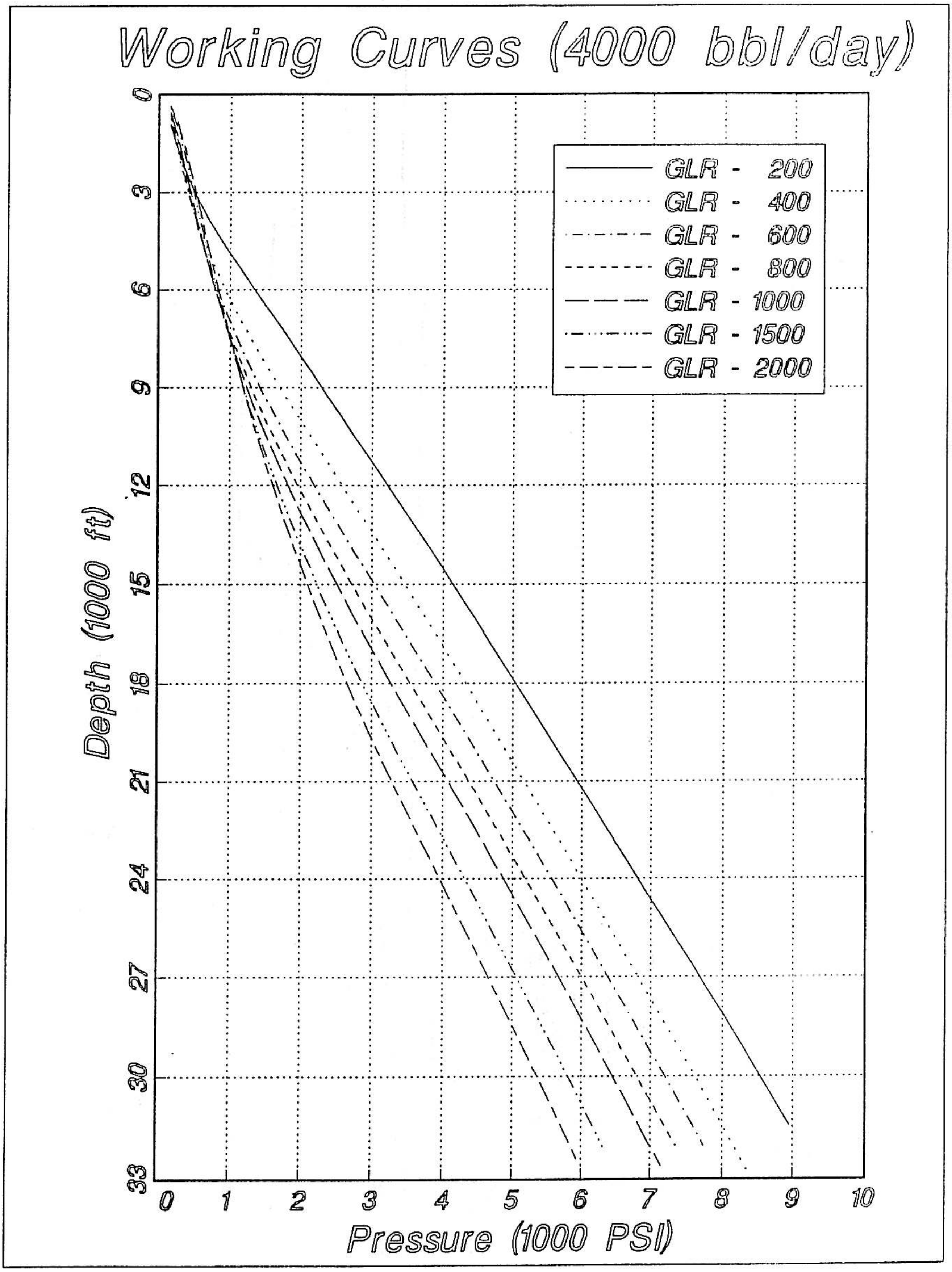

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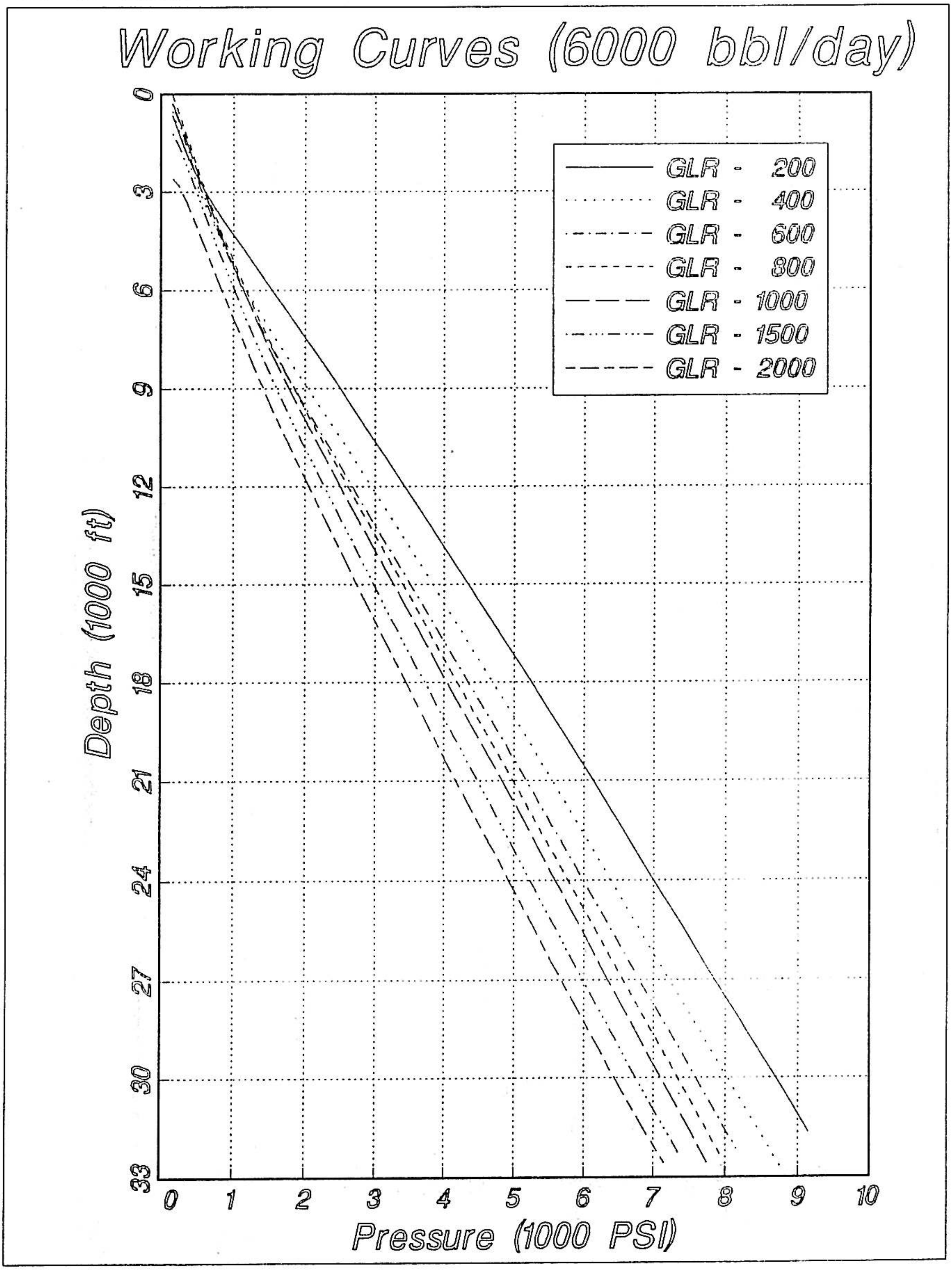

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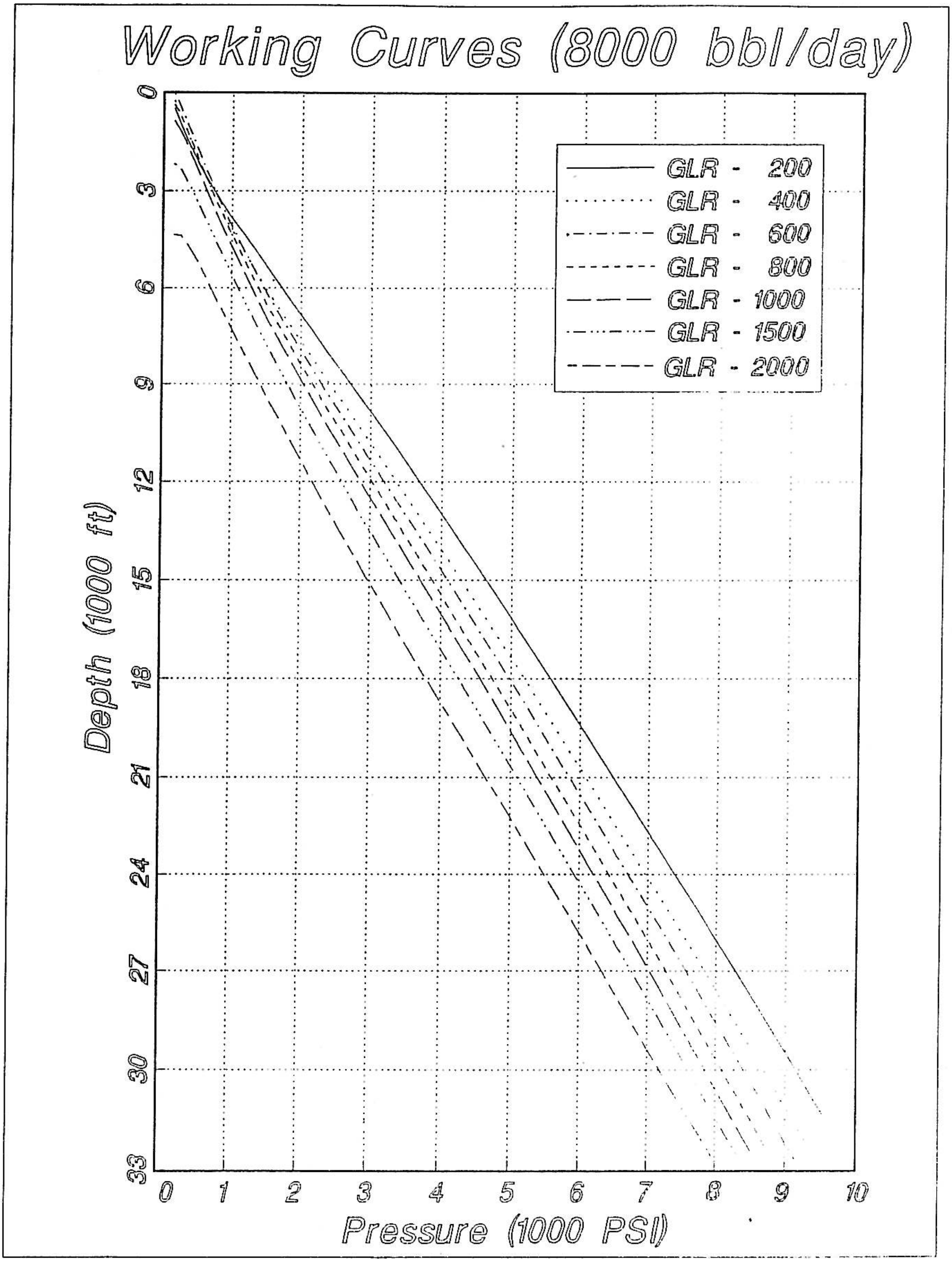


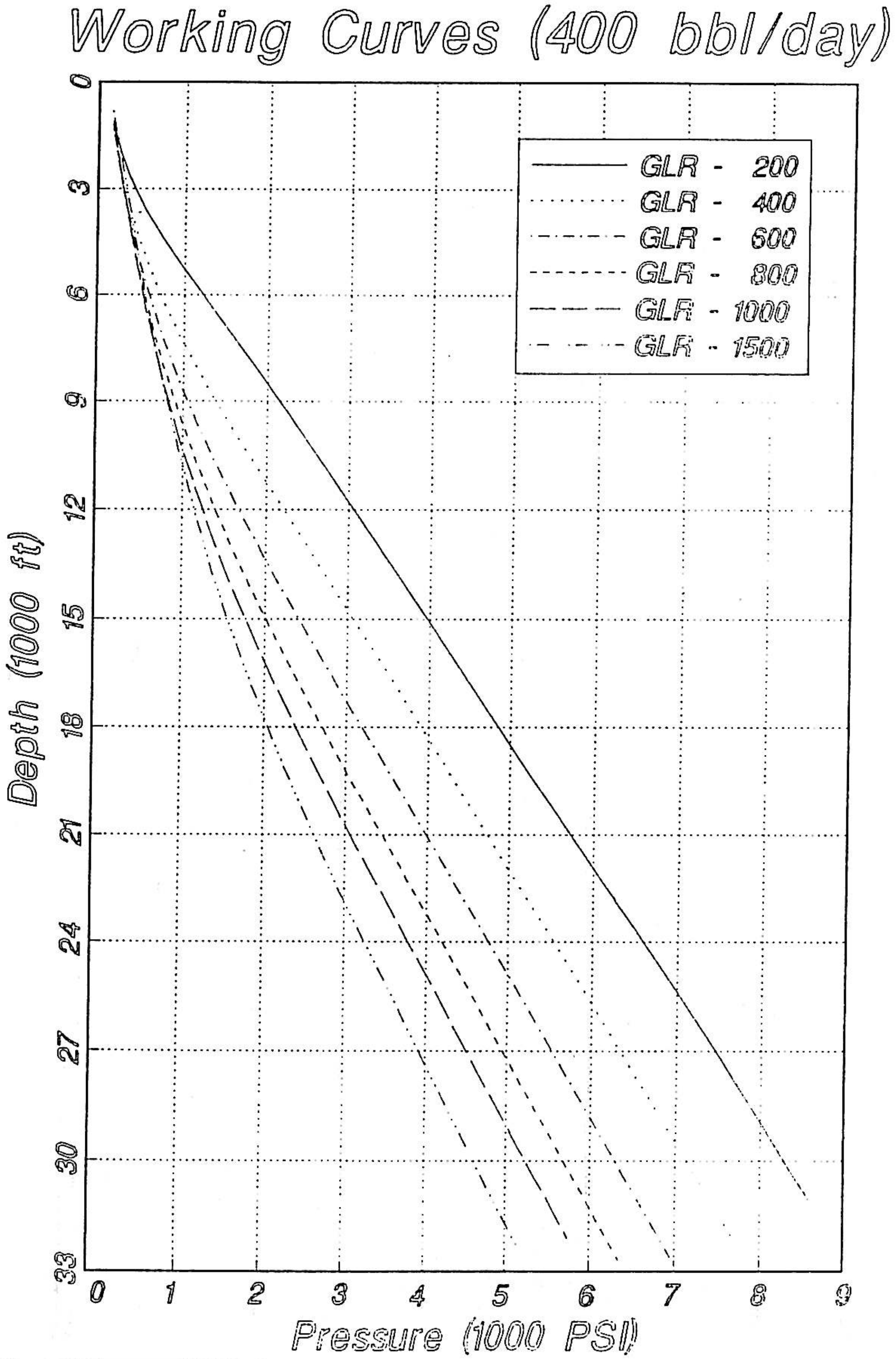
APPENDIX B

The following working charts were calculated using the Poettmann & Carpenter Correlation for flow rates of 400 to 8000 bbl/day:

Production Data:

1.	Tubing size	3.5 inch
2.	Oil API gravity	40 API
3.	Gas specific gravity	0.75
4.	Average flowing temp.	245°F

Poettmann & Carpenter



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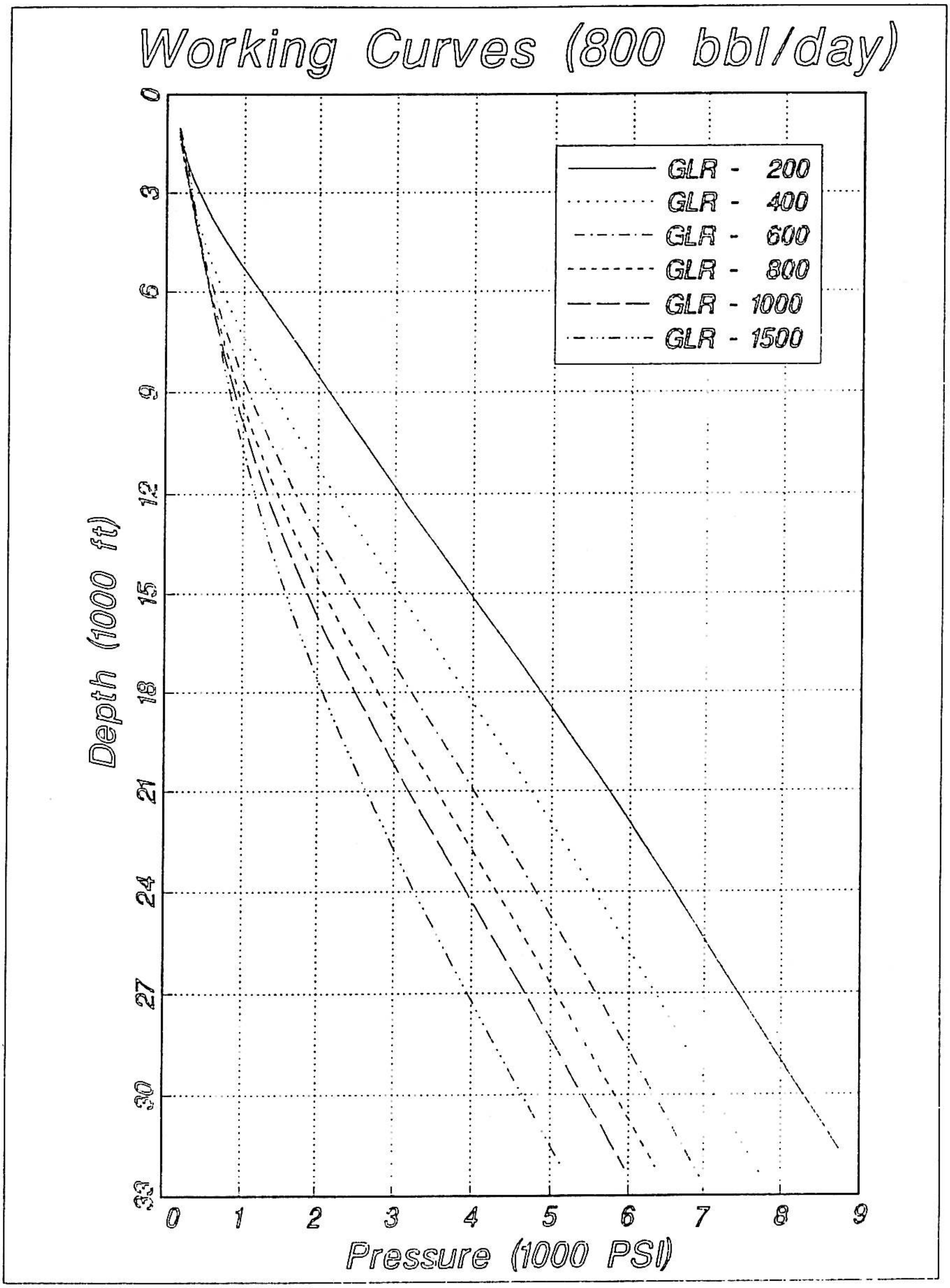

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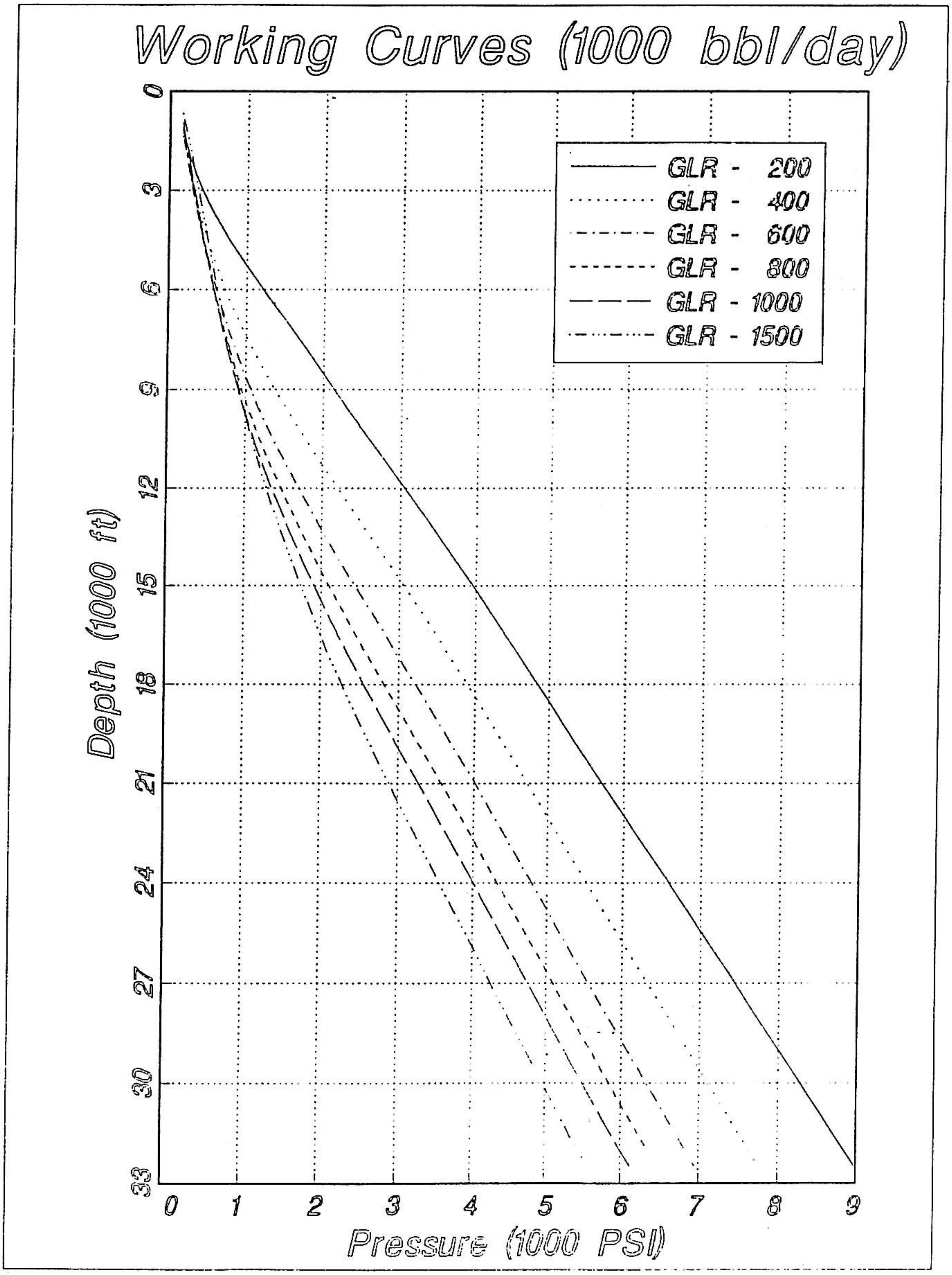

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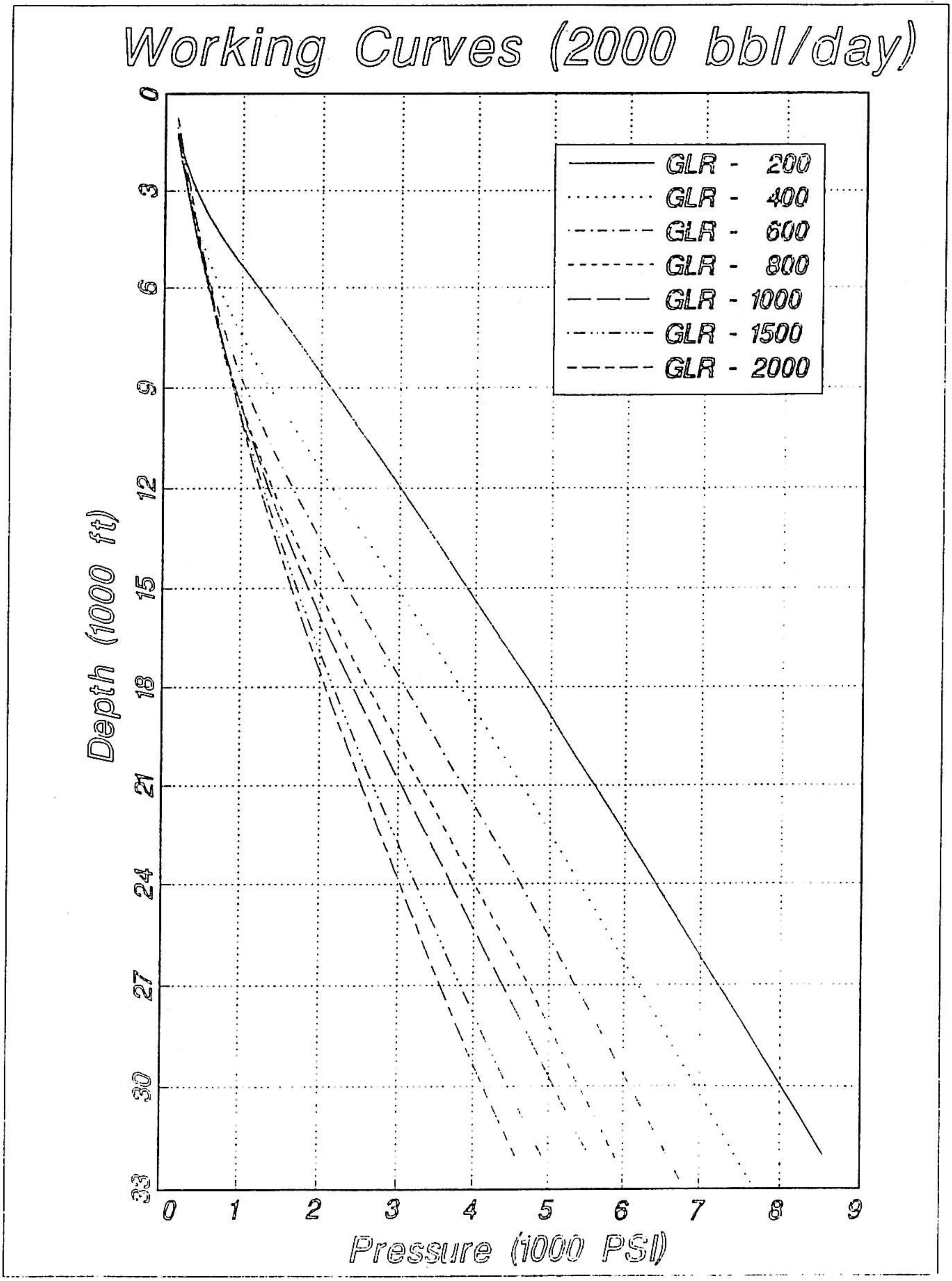

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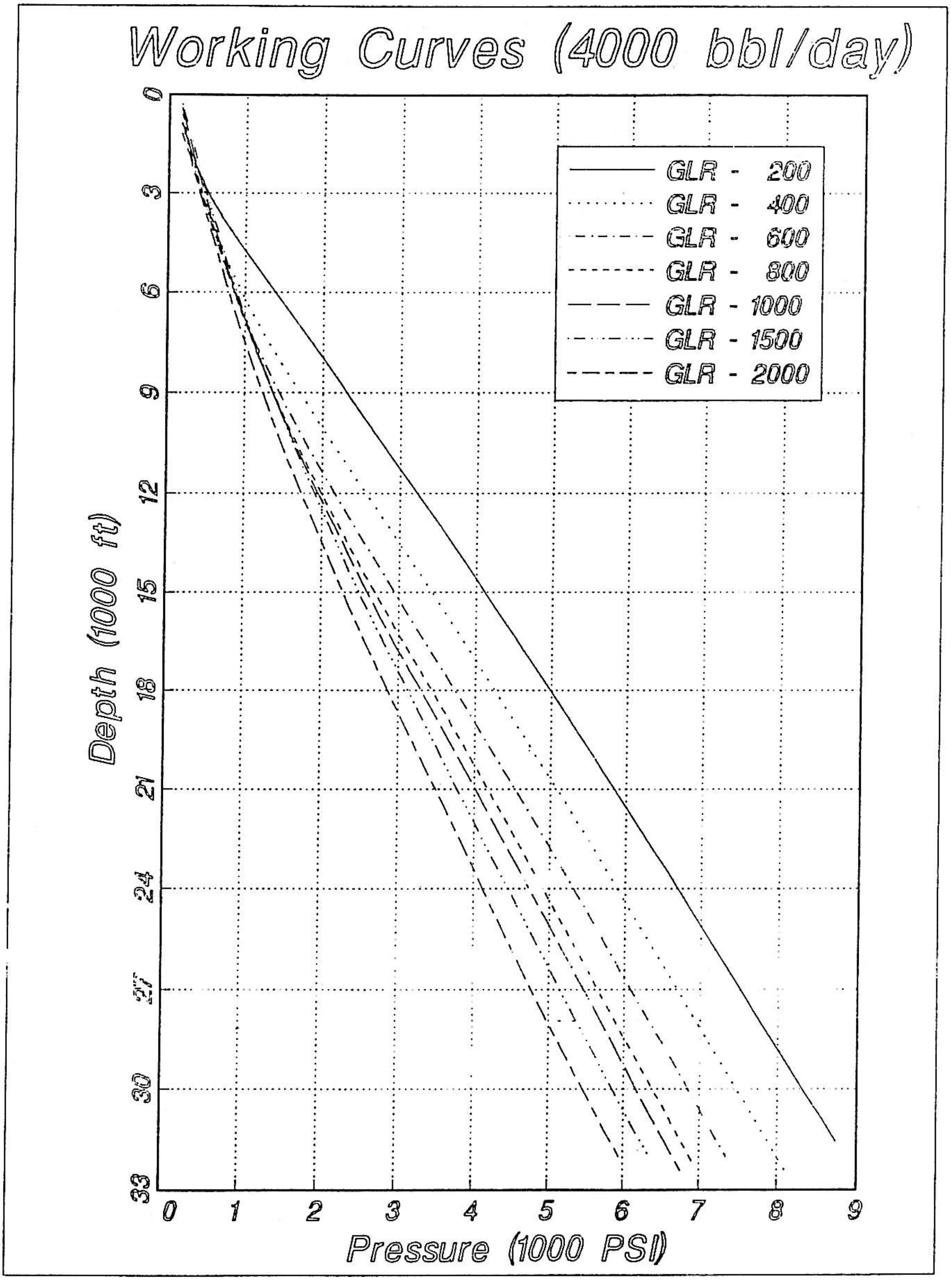

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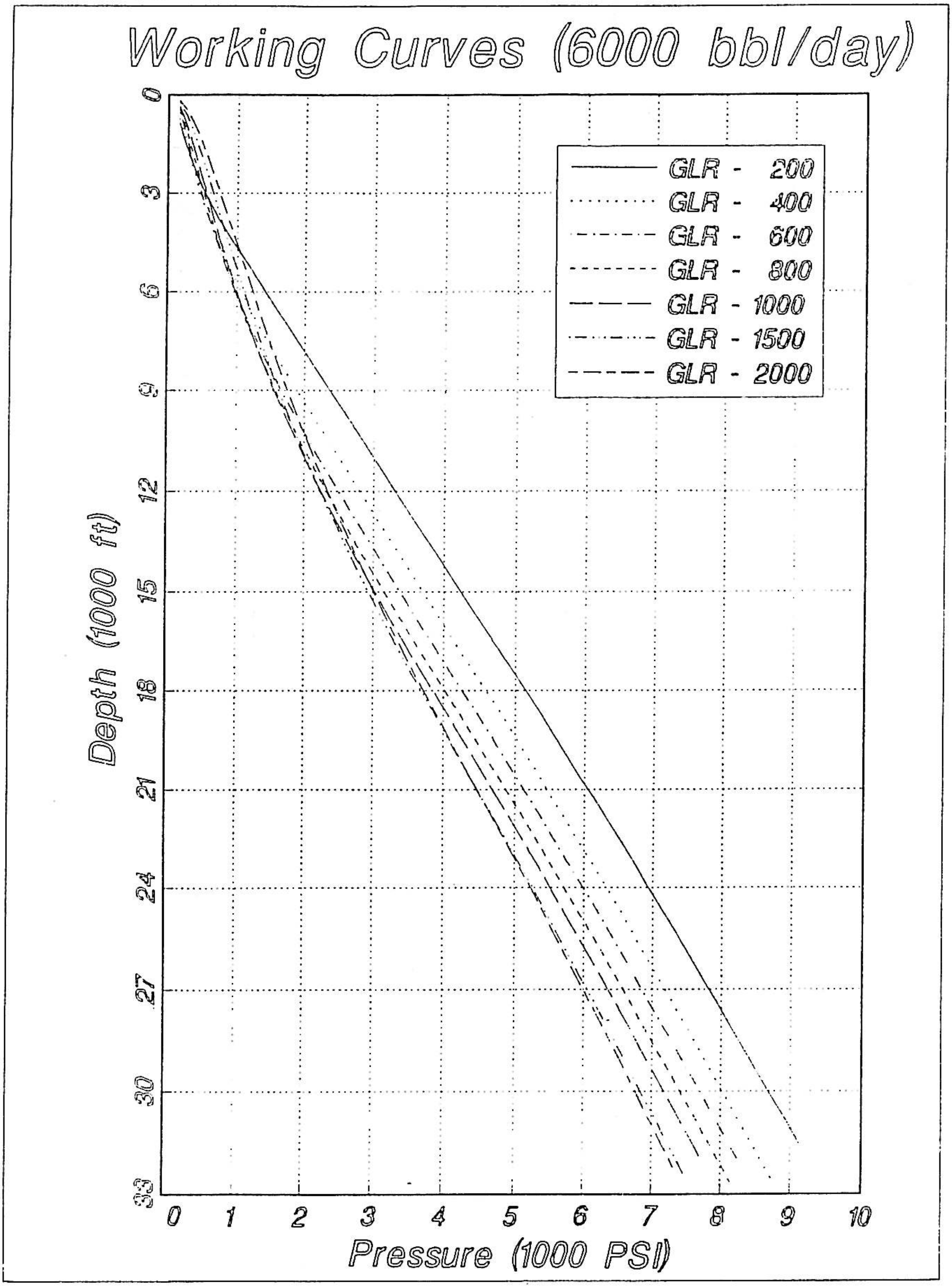

Poettmann & Carpenter