APPLICATION OF ELECTRONIC DATA PROCESSING TO SONIC ANALYSIS (SOUND LOGGING) DATA IMPROVES INTERPRETATION

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INTRODUCTION

SONAN (sonic-analysis) logging resulted primarily from the research and development of a practical logging sonde by McKinley *et. al.* of Esso Production Research Company (EPRC). McKinley primarily confined his research to the use of this system for documenting fluid flow behind cemented casing but also described the potential of this system as a flow meter. Following the publication of his findings in 1973, several service companies, including Dresser Atlas, began field testing equipment varying slightly from the EPRC designs. The variations were the result of efforts to speed up the recording of the log and to improve the ease of operations of the system and its reliability. In the time since, additional applications of this system have been noted, including its use to (1) find zones of lost circulation in drilling wells, (2) locate leak points in casing and tubing, (3) locate the source of fluid entry in uncased well bores, and (4) use this system in calculating perforation productivity profiles. McKinley also demonstrated that the data recorded could be quantitatively evaluated to determine rate of flow as well as the source. Because of the present method of data recording and the potential quantitative nature of the data, Dresser Atlas found that the processing of the field-recorded data is best performed with the aid of digital computers. Automated processing of the sound log data has been found to speed the interpretation, improve the accuracy of the interpretation and provide customers with a permanent record of our analysis for their well files. The equipment, principle of operation, several examples of the applications previously mentioned, and our processing of the data are discussed in the following pages.

EQUIPMENT AND PRINCIPLES OF OPERATION

All sound-logging systems presently employed are designed to record both the sound intensity as well as give an indication as to the frequency structure of the sound being recorded. The Dresser Atlas SONAN system currently in the field consists of a downhole logging sonde 1.7045 inches in diameter with a length of 59 inches and a total weight of approximately 40 pounds. Included in the system is instrumentation to record casing or tubing collars for depth control. The equipment has been designed to operate in environments up to 17,000 psia pressure with temperatures to 350°F. The sound is recorded down hole by means of a ceramic crystal transducer (microphone). Downhole amplifier circuitry with an overall gain of 600 amplifies the sound and transmits it to the surface by means of a 5/16 inch or 7/32 inch single conductor wireline. After reaching the surface, the sound is passed through a surface amplifier with variable gain settings ranging from 1 to 20 depending on the sound intensity. The sound is then filtered by a series of four high-pass frequency filters set at 200, 600, 1000 and 2000 hertz. The sound intensity after passing through the filters is then displayed in millivolts by four digital display units located in the face of the surface panel. The surface panel is also equipped with a speaker so that the sound may be audibly monitored during the survey. A time constant circuit is also employed to reduce the random sound to representative values. The primary purpose for the filtering is to identify the frequency of the sound being recorded. The frequency is useful in determining the type of phase flow taking place, i.e., a single phase flow, a gas or liquid but not both, or a two-phase flow where a gas and liquid are in simultaneous flow. The sound intensity or loudness is used to determine the rate of flow.

The survey is performed by a series of stationary recordings. The noise of the sonde moving in the borehole prevents coninuous recording. Typically, 15 to 30 seconds at each station is adequate. The intervals between stations varies, depending upon the sonde's proximity to the source of the sound being recorded. For example, in a typical analysis to locate the source of behind-casing flow, the operator stops and records the sound levels at 100 feet intervals as the sonde is lowered in the well. After reaching the well's total depth, he then records the casing-collar log, correlates it to any previous collar survey for the well, and resets for any depth discrepancies. Then, the operator will select his stations for subsequent recording based upon the data noted while lowering the sonde to bottom. The operator will make recordings of as close as 1 foot apart in order to locate the precise source of any sound or sounds the well is making. But most stations will be farther apart in order to keep survey time within practical limits.

PRESENTATION OF THE SOUND LOG DATA

Figures 1 and 2 depict the normal presentation of the sound log data. Figure 1 is a plot of the peak millivolt readings recorded at each logging station versus well depth. The depth scale is normally 1 inch per 100 feet of well depth. This scale has been found to clearly present the data for most applications, but occasionally, more detailed scales are necessary. The data is normally plotted on a logarithmic grid to promote comparative analysis between sound logs. By the use of the logarithmic scale for presentation of the data, the same scales can be used for all sound logs giving adequate detail when low sound levels need to be interpreted while keeping the plot on scale in intervals of high sound levels. Four curves are presented. The values plotted were recorded by the SONAN operator from the digital displays at each level. The 200 hertz curve indicates peak millivolts recorded for all sound 200 hertz and above in frequency. The 600 hertz curve is the millivolts recorded for the sound 600 hertz and above, and so on. Examination of the relative position of the curves plotted will indicate the major frequency of the sound recorded. For example, if there is substantial separation between the 200 hertz and the rest of the curves, then the sound recorded would be primarily low frequency, i.e. between 200 and 600 hertz. When the average frequency of the sound being recorded increases, the plotted curves for the 600 hertz and higher frequencies will plot closer to

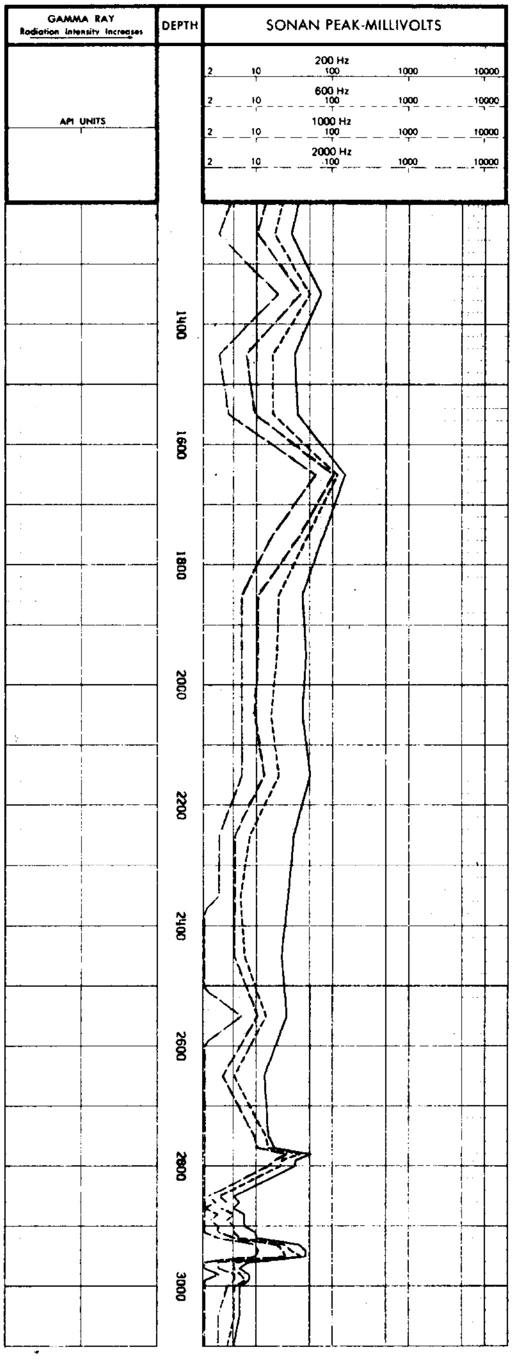

FIGURE 1

the 200 hertz curve.

Figure 2 is a tabulation of the plotted data. Additionally, the difference between the 200 and 600 hertz millivolts readings have been computed and listed in the sixth column. The difference is used to estimate the flow rate when the flow is two-phase. Also the data presented has been normalized for line attenuation. The factors used in normalizing the data are presented on Page 1 of the tabular listing. The line factors have been found to be a function of line length and type and the frequency of the sound recorded. Use of the computer for this time-consuming calculation speeds up the interpretation

	S O N A N NORMALIZED DATA (PEAK-TO-PEAK MILLIVOLTS)				
DEPTH	200 HZ	600 HZ	1000 HZ	2000 HZ	200-600
			LINE FACTORS		
	0.906	0.933	0.960	1.027	
50	70.3	31.7	23.1	9.2	38.6
150	129.0	97.7	81.6	35.9	31.3
250	61.4	35.6	26.2	10.3	25.7
350	46.9	38.6	29.2	11.3	8.3
450	95.3	78.7	64.5	29.8	16.5
550	125.3	99.5	77.8	39.0	25.7
650	126.4	89.6	72.6	31.8	36.8
750	72.0	54.5	40.3	18.5	17.5
850	72.3	47.5	34.2	14.4	24.8
950	39.3	23.6	16.1	5.1	15.6
1050	42.0	23.7	16.1	6.2	18.4
1150	43.0	26.5	16.1	6.2	16.5
1250	27.7	16.7	10.0	3.1	11.0
1350	68.0	48.7	36.4	18.5	19.3
1450	30.3	15.6	7.1	3.1	14.7
1550	33.2	15.7	9.1	4.1	17.5
1650	138.0	109.5	97.2	57.5	28.5
1750	74.2	45.7	36.3	15.4	28.5
1850	38.9	18.7	10.1	6.2	20.2
1950	43.4	17.7	10.1	6.2	25.7
2050	38.7	14.8	9.1	6.2	23.9
2150	49.1	18.7	12.1	6.2	30.3
2250	30.0	7.9	5.1	3.1	22.1
2350	25.3	6.0	5.1	3.1	19.3
2450	20.7	6.9	5.0	0.5	13.8
2550	24.0	13.0	10.1	6.2	11.0
2650	12.3	4.9	3.5	0.5	7.4
2750	13.7	12.7	9.0	0.5	0.9
2770	16.5	13.7	9.9	0.5	2.8
2780	49.9	36.2	23.9	0.5	13.8
2790	31.7	20.7	16.9	0.5	11.0
2800	30.6	19.6	13.9	0.5	11.0
2850	4.8	3.1	2.2	1.0	1.7
2860	5.8	3.9	2.8	0.5	1.8
2870	4.8	3.3	2.0	0.4	1.5
2880	6.7	4.9	3.0	0.6	1.8
2890	6.7	3.9	2.4	0.4	2.8
2900	6.7	4.9	3.0	0.6	1.8
2910	9.5	4.9	3.0	0.6	4.6
2920	9.7	6.0	5.1	3.1	3.7
2930	34.8	21.9	17.2	9.2	12.9
2940	43.4	27.8	21.2	10.3	15.6
2950	42.9	37.3	23.1	9.2	5.5
2960	7.6	4.9	3.0	0.5	2.8
2970	5.8	4.9	3.0	0.5	0.9
2980	7.9	6.0	5.1	3.1	1.8
2990	7.8	6.9	5.0	0.5	0.9
3000	5.9	4.9	4.0	0.5	0.9
3050	5.8	4.9	3.0	0.5	0.9
3100	4.9	3.9	3.0	0.5	0.9
3150	5.9	5.0	4.0	2.1	0.9
3200	6.9	5.0	4.1	3.1	1.8
3250	5.9	5.0	4.1	3.1	0.9
3300	5.9	5.0	4.1	3.1	0.9
3350	5.9	5.0	4.1	3.1	0.9
3400	9.8	7.0	6.1	4.1	2.8
3450	5.9	5.0	4.1	3.1	0.9
3500	5.9	5.0	4.1	3.1	0.9
3550	6.9	5.0	4.1	3.1	1.8
3600	6.8	5.9	5.0	0.5	0.9
3650	9.8	7.9	7.0	0.5	1.8
3700	9.7	6.9	6.0	0.5	2.8
3750	8.8	7.0	6.0	2.1	1.8
3800	8.8	6.9	6.0	0.5	1.8
3850	8.8	6.9	6.0	0.5	1.8
3900	8.9	8.0	7.1	3.1	0.9
3950	9.8	8.0	7.1	3.1	1.8
4000	9.8	8.0	7.1	3.1	1.8
4050	9.9	9.0	8.1	4.1	0.9
4100	10.9	10.0	8.1	4.1	0.9
4150	9.9	9.1	7.4	5.1	0.8
4200	10.0	9.2	9.1	4.1	0.8
4250	10.9	10.0	9.1	4.1	0.9
4300	10.8	9.9	9.0	0.5	0.9
4350	10.9	10.0	9.1	4.1	0.9
4400	10.8	9.9	9.0	0.5	0.9
4450	11.8	10.9	9.9	0.5	0.9
4500	13.8	12.0	11.1	4.1	1.8
4550	10.9	10.0	9.0	2.1	0.9
4600	11.8	10.0	7.8	5.1	1.8
4650	13.7	12.8	9.9	0.5	0.9
4700	12.8	11.9	11.0	1.0	0.9
4750	13.8	12.9	11.9	0.5	0.9
4800	15.9	14.1	13.1	6.2	1.8
4850	16.8	15.9	13.1	5.1	0.9
4880	16.9	15.0	14.1	5.1	1.8
4900	16.9	15.0	14.1	5.1	1.8
4950	16.0	15.1	14.1	6.2	0.9

FIGURE 2

and reduces computational error to a minimum.

EXAMPLE NO. 1 - BEHIND CASING FLOW

Figures 1 and 2 represent typical SONAN log responses when flow is occurring in the annular space behind the casing. The well represented in the figures had 8-5/8-inch surface casing set at 550 feet and a 5-1/2-inch production string set at 5050 feet. Top of cement for the production string was below 3000 feet. After setting the production string, the operator noticed water and gas leaking from the annulus at the surface. Before perforating, a sound log was run to determine the sources of the leak. In the survey, the interval below 3000 feet was found to be in a dead well state (no sound indicated). Above 3000 feet, several noise anomalies were recorded. Our interpretation was that the source beds of the gas was most likely opposite the sound peaks at 2780 feet and 2950 feet. The frequency of the sound is mainly 1000 hertz or above. This indicates a single-phase flow. If two-phase flow were taking place, more low-frequency sound similar to the peak at 2550 feet would be expected. The sound peaks at 1350 feet and 1650 feet probably indicate the source of the water flow (especially the bed at 1650 feet). The sound at this peak is also high frequency and, therefore, indicative of single-phase flow. Also, the spreading of the curves between 1650 feet and 2780 feet indicates mainly low frequency sound. This is usually associated with gas bubbling through a liquid. The water is apparently entering at 1650 feet and has been lifted to the surface with assistance from the gas expanding from below.

The fluid in the annular space down to 2780 feet is either remnants of the brine used to drill or the result of the flow from 1650 feet (or more likely some combination of both). Finally, local knowledge of the area tells us we should expect to find the Yates aquifer very near 1650 feet, which supports the interpretation given. Actually, the bed at 1350 feet could be a sink rather than an additional source. This depends upon the pressure differential between the formation and that of the annulus opposite. As the flow at the surface was very small, it is quite likely to be the case here.

EXAMPLE NO. 2 - GAS WELL PRODUCTIVITY PROFILE

Figure 3 is a plot of the data from a gas well that was producing significant amounts of water. The operator believed that the water production may have been the result of flow behind the production casing from a zone below the lowest perforated interval. The survey was conducted primarily to see if this was the case. This well was a tubingless completion and had a 2-7/8-inch J-55 set at 6535 feet. Perforations were 5885 - 69 feet, 6184 - 92 feet, and 6253 - 55 feet, one shot per foot. All sets of perforations appear to be producing. The perforations 6253 - 55 feet are somewhat masked by the indicated fluid level just below the lowest perforations. This indicates that the lower zone is

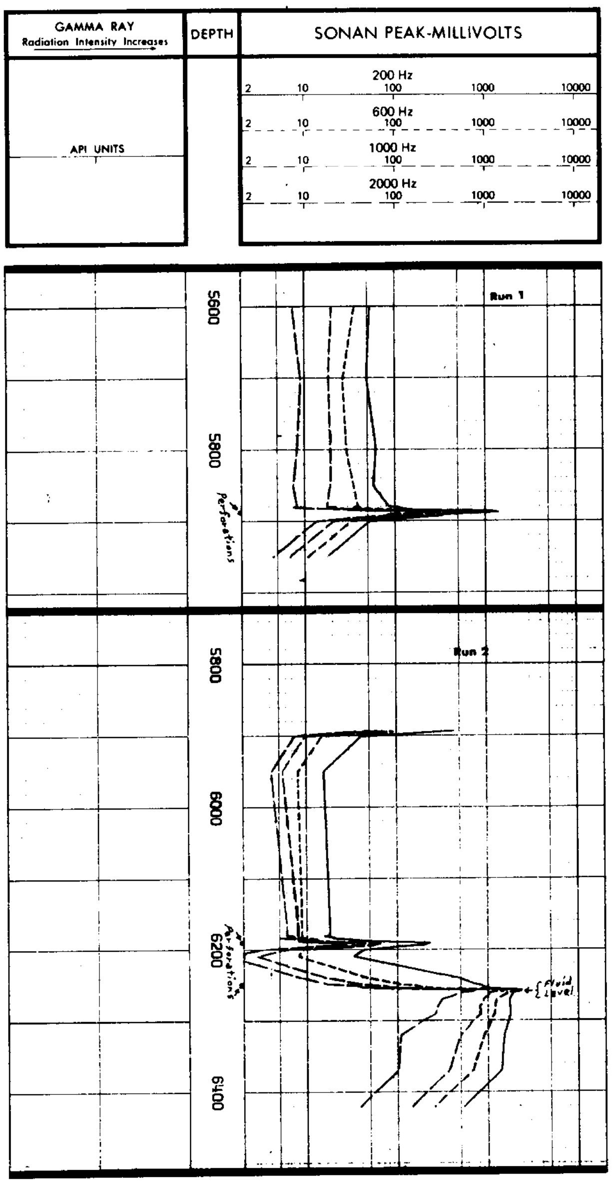

FIGURE 3

still producing sufficient volumes to lift the produced water. Also, the sound levels below the fluid level do not drop off as rapidly with distance from the source as they do when logging in the gas environment above the fluid. This is because the water is superior to gas as a conductor of sound.

The attenuation of the sound below the lowest perforation appears normal for the size casing in this well; the produced water was probably being produced from the perforated zones.

When there is water jetting through a perforation along with the gas, a sound above 2000 hertz in frequency should be heard. Because of the close proximity of the fluid level to the lower perforations, it is difficult to determine if this was the case here. Table 1 is the productivity profile computed for this well. Appendix 1 explains the theory used in making these profiles. Computations indicated that the lowest zone was contributing less than 13 percent of

TABLE 1

Productivity Profile

Depth	N_{1000} hz	N_{1000} hz $^{1/3}$	% of Total Flow
5886	636	8.6	
87	669	8.7	
88	504.5	8.0	
89	252.4	6.3	
90	223.4	6.1	
91	153.2	5.4	
92	171.0	5.6	
93	132	5.1	
94	87.9	4.4	
Total Zone	2829.4	58.2	60.2
6187	10.5	2.2	
88	9.7	2.1	
89	12.1	2.3	
90	25.0	2.9	
91	44.4	3.5	
92	37.1	3.3	
93	41.9	3.5	
94	33.9	3.2	
95	27.4	3.0	
Total Zone	242	26.0	26.9
6251	67.7	4.1	
52	75	4.2	
53	75.8	4.2	
Total Zone	218.5	12.5	12.9
Total	3289.9	96.7	

the total flow. Therefore, because most of the produced water was likely to be from this zone, the operator was advised to squeeze this zone to reduce the water production.

EXAMPLE NO. 3 - CASING LEAK

Figure 4 is a log run on a temporarily abandoned well that had developed pressure at the surface inside the 5-1/2 inch production string. Eight-and-five-eights-inch surface casing was set at 430 feet. The tubing had previously been pulled. When the well was opened up, it would flow approximately 200 barrels of salt water continuously per day. The operator ran the survey to determine the source of the water flow. Before making the survey, a wireline plug was set at 4724 feet. There were no perforated zones above the plug. There was a sound peak at 3400 feet. A casing leak appeared to be at this point. The high frequency sound at this level is indicative of single-phase flow through an orifice. Also, the sound did not decrease much below this point and, actually, higher sound levels are recorded below 4000 feet. The interval between 4000 to 4350 feet was probably the source of the flow. Examination of the open hole logs run on this well indicated this interval to be salt and anhydrite beds and did not contain any beds that could be natural aquifers. In discussing this with the operator, it was learned that there was a salt-water disposal well approximately at 1000 feet from this well that was suspected of having casing and tubing leaks.

It was recommended that the disposal well be shut-in, and this well be monitored for any change. The recommendation was accepted and a pressure drop was immediately noted at this well. This well was then flowed and eventually, died.

CONCLUSION

From sound-logging experience to date, this system has proved most useful in diagnosing a wide variety of common oil-field production problems. Space and time limitation prohibit complete discussion of all the applications for this system that have been mentioned, but experience indicates that we can expect good results. Results to date are extremely satisfactory, and ever-increasing use of this system is expected as more of the industry becomes aware of its capabilities.

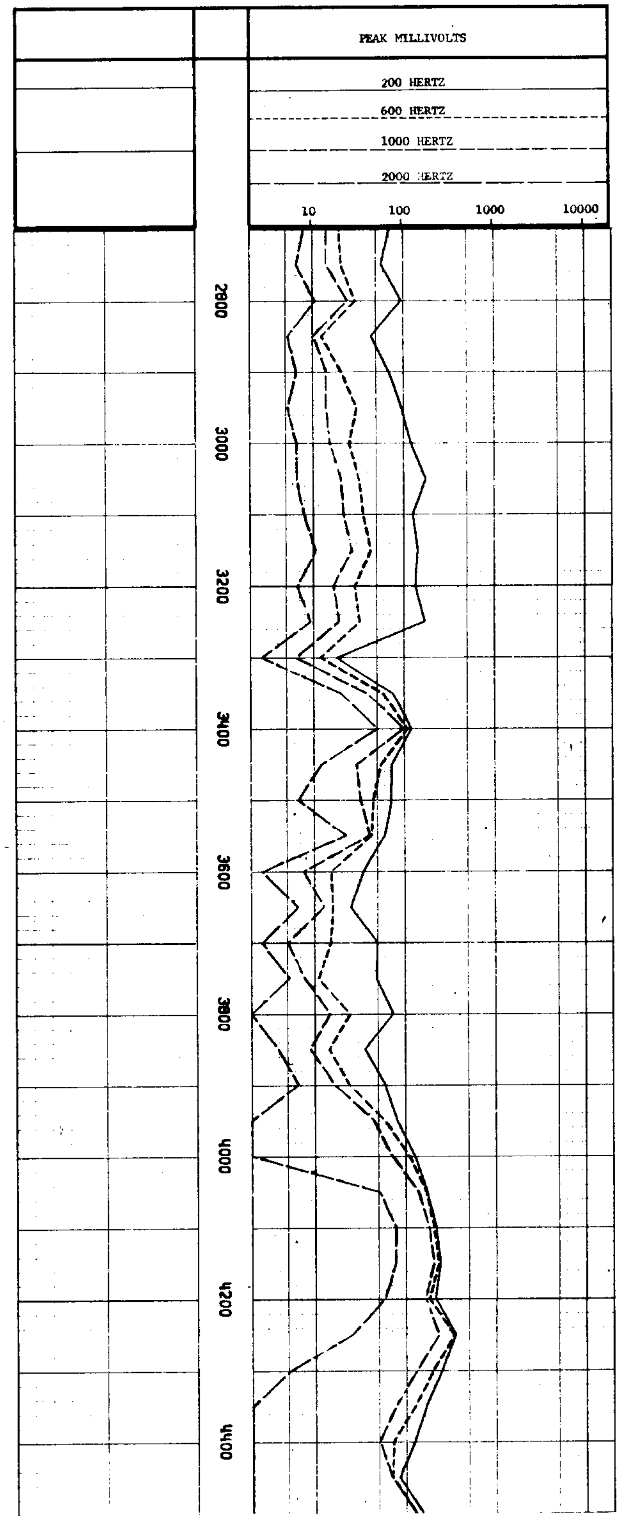

FIGURE 4

APPENDIX 1

Perforation Productivity Profile Using SONAN Data

The noise produced by a single-phase fluid flowing through a deep, unplugged perforation can be described by the following equation.

$$(1) \qquad N_{1000} \approx \left(\frac{Q\Delta p}{D_p^{\;1.3}}\right)^3$$

where: N_{1000} = noise level above 1000 hertz frequency corrrected for line attenuation, in millivolts.

q = flow rate, MCF/day.

Δp = pressure differential across the perforation, psi.

D_p = perforation diameter, in.

In the majority of analyses of SONAN data, it may be assumed that the perforation diameter, D_p, of all the perforations are for calculation purposes, equal. Also, it may generally be assumed that for most analyes, the pressure differential, Δp, at each of the perforations will be essentially equal.

Therefore, in equation (1), we can dispose of the terms Dp and Δp and re-state the equation as a proportionality as in equation 2.

$$(2) \qquad q\% \approx \frac{N_{1000}{}^{1/3}{}_{(i)}}{\Sigma N_{1000}{}^{1/3}{}_{(1...n)}} \,.\, 100$$

where: $q\%$ = percent of total flow.

$N_{1000}{}^{1/3}{}_{(i)}$ = cube root of the 1000 hertz noise level opposite an individual perforation (i).

$\Sigma N_{1000}{}^{1/3}{}_{(1...n)}$ = the sum of the cube roots of all perforations, 1 through n.

If the total flow rate is known, then solving equation (2) will yield the flow from each perforation.

Equation (1) is contained in an unpublished discussion of the subject method by R.M. McKinley of ESSO Production Research Co.

REFERENCE

McKinley, T.M., Bower, F.M., and Rumble, R.C.: The Structure and Interpretation of Noise from Flow Behind Cemented Casing, *Jour. Petr. Tech.*, March 1973.