Review of Nuclear Magnetic Resonance Magnet for Oil Well Logging

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Abstract--Compared with the magnet of Nuclear Magnetic Resonance (NMR) Spectrometer that of Nuclear Magnetic Resonance Oil Well Logging is faced with some special difficulties. This paper begins with the explanation of these special difficulties, and then analyzes the main known borehole NMR logging apparatuses through strict calculations. Finally, this paper gives some useful clues to solve those problems existing in the designs.

Index terms--NMR, Well logging, Permanent magnet, and Electromagnetic field

I. INTRODUCTION

Brought forward in 1960's, nuclear magnetic resonance well logging has become popular since late 1980's. NMR well logging is by now the only way to get free fluid porosity data directly. The porosity, fluid viscosity, and permeability of the formation can be obtained from an NMR signal. It is viewed as one of the main well logging methods in the next century.

The probe of NMR well logging, containing magnet and antenna is rather different from MRI-CT and NMR spectrometer. Also, there are some environmental limits for the probe due to its working under the earth thousands of meters deep, including high temperature and high pressure. In order to complete this design course, it is necessary to analyze the electromagnetic problems.

II. THE SPECIAL DIFFICULTY IN THE DESIGN OF AN NMR WELL LOGGING PROBE

The typical structure of a normal NMR apparatus is that magnet and RF coil enclose the sample. The size of the magnet is not circumscribed in principle as shown in Fig.1. The magnetic resource can be a super-conducting magnet, electromagnetic coil, or permanent magnet. The feature of the static magnetic field intensity $\mathbf{B}_0$ is its connexity. However, for NMR well logging, the sample is the earth formation. Magnet and RF coil can only be placed in the borehole, the diameter of which is only 6 to 8 inches. There is no way to make the magnet and RF coil enclose sample. The typical structure is that samples enclose magnet and RF coils, while the terms for generating the nuclear magnetic resonance must be satisfied. This is why NMR well logging is faced with some special difficulties. In order to form a sensitive volume around borehole, the first problem is how to arrange the magnet and RF coil in a narrow hole correctly.

Besides this, it is unreasonable to consider a superconductor or electromagnetic coil as the magnetic resource of NMR well logging. It is reasonable to select a permanent magnet as the magnetic resource. The selection of the material of the permanent magnet to resist against the high temperature and pressure under the earth is the other main problem.

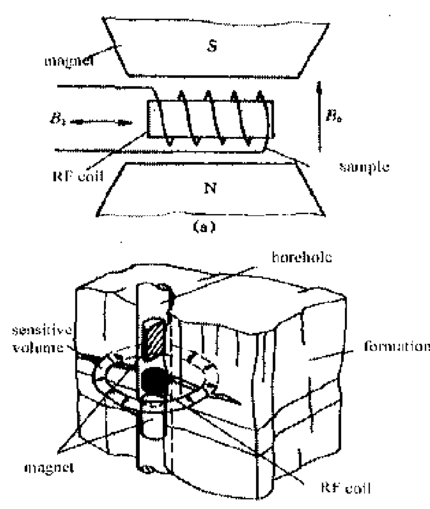

Fig.1. Geometry of conventional NMR spectromemter (up) and NMR well logging system (down)

In many situations, the rock in formation has high magnetic susceptibility, so the static magnetic field intensity $\mathbf{B}_0$ has to be of low value, e.g. 235G or so. The sensitive volume is

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the essential factor in determining Signal-to-Noise ratio because B_0 is hardly changed. So it is another main target to get the sensitive volume as big as possible.

Of course, compared with NMR spectrometer, NMR well logging has its own special advantage. For NMR well logging, the measurement object is just the sensitive volume; it is all right to get integration of signal. That is to say, the uniformity of static magnetic intensity B_0 for NMR well logging is not as stringent as that for NMR spectrometer.

III. REVIEW OF THE MAGNET OF NMR WELL LOGGING

Various projects to arrange the magnet and RF coil have been brought forward since 1960. In the following, several important projects are reviewed.

In order to compare with each project conveniently, identical terms should be stipulated: diameter of borehole: 20.32cm; diameter and length of permanent magnetic pillar: 15cm and 150cm(for Schlumberger, maximum length=60cm); B_0=235G; tolerance of B_0: ±1.409G; NdFeB material for *Los Alamos* and Schlumberger: 26MG·Oe; for Numar project: 9MG·Oe.

A. The project of Los Alamos

Dr. Jasper A. Jackson had brought forward the design principle of the 'Inside-out' in *Los Alamos* scientific laboratory and given the first project based on this principle. The Inside-outside principle is that magnet and RF coil are placed inside well while sensitive volume is outside of well, shown as in Fig. 2.

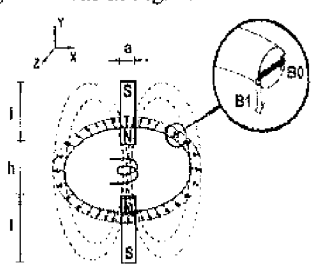

Fig. 2. *Los Alamos* geometry

In Fig.2, two magnet pillars are arranged coaxially with anti-magnetization direction. There exists a sensitive volume perpendicular to axes around the middle point of the air-gap. The position and size of this sensitive volume are depended on the magnetic material, magnet diameter **a**, length **l**, and gap **h** between the two magnets. The RF coil is placed in the gap. Inserting a ferroxcube inside the RF coil can enhance the sensitivity of the RF coil.

Fig. 3 shows the influence of magnet interval on the investigation depth. (d is the distance between two magnets; r is the investigation distance)

There are some difficulties in the use of the *Los Alamos* geometry as follows:

(1) The sensitive volume is in the middle area of the gap, but the static field intensity B_0 decays so rapidly that the investigation distance is not satisfied. (2) The Signal-to-Noise ratio is too low since the background field can be only 120G. The background field is limited by magnetic technology of that time.

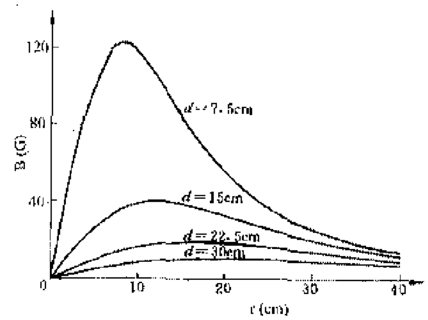

Fig.3. Influence of magnet interval on the investigation depth in *Los Alamos* geometry

B. The Schlumberger project

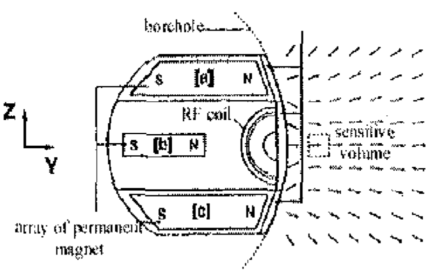

Fig.4. Schlumberger geometry

As shown in Fig. 4, the probe is placed on the edge of the borehole. The array comprised of three parallel magnets, the magnetization direction of that is perpendicular to the axes of the borehole, produces a background field in the front formation of the edge. The RF coil is placed in the half-moon shell between magnet **a** and magnet **c**. The resonance uniformity area can be adjusted by moving magnet **b**.

Compared with the *Los Alamos* project and the Numar project, the Schlumberger project does not require exact RF field configuration because of the uniformity and connexity of its background field. The impact on the RF field by the permanent magnetic materials can be ignored. A permanent magnet with high magnetic energy, such as SmCo and as NdFeB, can be used in this project.

The RF power is lower in this edge-contact project as the mud resistor is not a load component of the RF field. This probe can carry out NMR well logging in any mud situation.

The length of the probe is limited to 30~60cm due to the irregular cliff of borehole. Although it is possible for this kind of probe to log in badly oblique wells, the sensitive volume is too small to get perfect Signal-to-Noise ratio, logging speed, and vertical resolution.

This probe scans the formation with only one frequency. It is necessary to adjust Larmor frequency when the ambient temperature changes.

Fig. 5 shows the influence of magnetic interval on the investigation distance in Schlumberger project. (d is the distance of two main magnets; Y-axis is the investigation distance.)

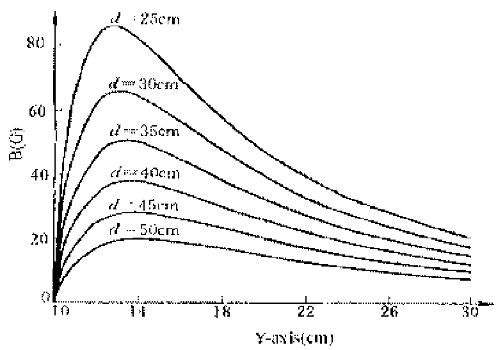

Fig. 5. Influence of magnet interval on the investigation depth and sensitive volume in Schlumberger geometry

C. *The Numar project*

As shown in Fig. 6, a permanent magnet pillar is placed in the borehole. Its magnetization direction is perpendicular to the axis of the borehole. The RF coil is outside the magnet. The sensitive volume is a thin cylinder in the rock. In fact, the contour lines of the static field intensity $\mathbf{B}_0$ and RF $\mathbf{B}_1$ are two ellipses with their long axes vertical with each other. The sensitive volumes become four points.

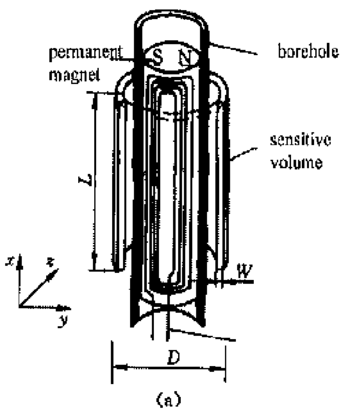

Fig.6 Numar geometry

We suggest another way to get cylinder sensitive volume. The magnet can be made as an ellipse with short axis magnetization direction. The current of RF coil is not uniformly distributed. The objective is to get two approximate circles.

In a former design, the magnetic material was ferrite. Now, cohesive NdFeB can be adopted. Its low conductivity can reduce backset loss and can keep the original contour of the static magnetic field.

The most notable feature of Numar project is that it gives up the connexity of static magnetic field but satisfies the terms of NMR. It scans the formation with several frequencies. It is unaffected by borehole effect, but it needs more RF power.

IV. Conclusion

In the course of designing the probe of NMR well logging, the main difficulty includes (1) the sensitive volume is outside the probe, i.e. magnet and RF coil. (2) The environment can affect the magnet thousands of meters deep below the earth. The high temperature and high pressure will disturb the stabilization of the magnet's working point. (3) The main objective is to get sensitive volume and investigation distance as big as possible.

Among the three projects above, the *Los Alamos* project is the first and it guides other projects. With the development of permanent magnetic material, it may exhibit its potential benefits. The Schlumberger project is similar to NMR spectrometer, but the edge-contact probe has its own advantage. The Numar project is the most practical for NMR well logging. It is rather different from NMR spectrometer. Up to now, it scans formations with the highest Signal-to-Noise ratio of the three projects as it can get the maximum sensitive volume and get the longest investigation distance, but it still has to be improved in many aspects.

Besides the main problems discussed in this paper, there are many other problems to be solved, e.g the loss of RF, and impact on RF field by other pulse sequences, etc.

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REFERENCES

[1] Jackson J A□Burnett L J, Harmon J F. Remote (Inside-Out) NMR. □. Detection of Nuclear Magnetic Resonance in a Remotely Produced Region of Homogeneous Magnetic Field. Journal of Magnetic Resonance, 1980, 41: 411~421

[2] Kleinberg R L et al. Novel NMR Apparatus for Investigating an External Sample. Journal of Magnetic Resonance□1992, 97: 466~485

[3] Kleinberg R L et al. U.S. Patent 5055787.1991

[4] Taicher Z et al. U.S. Patent 4717877. 1988

[5] Abdurrahaman Sezginer et al., U.S. Patent 5487761. 1996

[6] Clow H□Percival W S□Walters P E. U.S. Patent 4629986. 1986