Journal of Electromagnetic Waves and Applications
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tewa20

Environmental impact on the magnetic field distribution of a magnetic proximity detection system in an underground coal mine

Jingcheng Li[a], Jacob Carr[a], Joseph Waynert[a] & Peter Kovalchik[a]
[a] National Institute for Occupational Safety and Health, 626 Cochran's Road, Pittsburgh, PA 15236, USA
Published online: 28 Oct 2013.

To cite this article: Jingcheng Li, Jacob Carr, Joseph Waynert & Peter Kovalchik (2013) Environmental impact on the magnetic field distribution of a magnetic proximity detection system in an underground coal mine, Journal of Electromagnetic Waves and Applications, 27:18, 2416-2429, DOI: 10.1080/09205071.2013.852487

To link to this article: http://dx.doi.org/10.1080/09205071.2013.852487

Journal of Electromagnetic Waves and Applications, 2013
Vol. 27, No. 18, 2416–2429, http://dx.doi.org/10.1080/09205071.2013.852487

Taylor & Francis
Taylor & Francis Group

Environmental impact on the magnetic field distribution of a magnetic proximity detection system in an underground coal mine

Jingcheng Li*, Jacob Carr, Joseph Waynert and Peter Kovalchik

National Institute for Occupational Safety and Health, 626 Cochran's Road, Pittsburgh, PA 15236, USA

(*Received 5 August 2013; accepted 3 October 2013*)

A magnetic proximity detection system mounted on an underground mobile mining machine detects whether a worker is hazardously close to the machine. The system generates magnetic fields covering the extended spaces around the machine. A magnetic detector worn by the worker measures the magnetic field flux density and determines the distance from it to the machine. The system is frequently in close proximity to coal as the machine moves, causing the magnetic field flux, in part, to enter massive *in situ* coal. This has the potential to have an adverse effect on the accuracy of the system and on the safety of the worker if the coal were to significantly alter the magnetic flux density distribution. Two experiments were conducted to study the impact of *in situ* coal on these magnetic fields. Measurements in one mine show that coal mass has no significant impact on the magnetic field flux distribution.

Keywords: equivalent circuit; magnetic analysis; magnetic field measurement; magnetic flux density; near-field radiation patterns

1. Introduction

Researchers at the National Institute for Occupational Safety and Health (NIOSH) have developed and used two methods to evaluate the impact of *in situ* coal on the magnetic field distribution of a magnetic proximity detection system, finding that the coal has an insignificant impact on the magnetic flux distribution of the system. The methods, results and the analysis of the results will be presented in this paper. The methods developed here can be used to evaluate the impact of other geological environments on the magnetic fields of proximity detection systems.

Magnetic proximity detection systems are increasingly used in underground coal mines to protect workers from pinning and striking from mobile mining machines.[1–3] Since 1984, there have been 35 fatal accidents in the USA in which a miner was struck or pinned by a 50 ton continuous mining machine.[4] To address this problem, the Mine Safety and Health Administration has published a proposed regulation that would require proximity detection systems on all continuous mining machines except full-face machines.[5]

A magnetic proximity detection system can be mounted on a mobile machine, and generates a magnetic field from its ferrite-cored generators to cover the area around the machine.[6–8] A magnetic field detector worn by a worker detects the magnetic field

*Corresponding author. Email: Jingcheng.li@cdc.hhs.gov

and determines a distance from the worker to the machine by the magnetic flux density detected. The system can generate visual and/or audible alarms to warn the worker if he or she is hazardously close to the machine, or the system can send a signal to the machine control unit to disable machine motion.

As a mobile mining machine moves in the mine, its proximity to the massive *in situ* coal around it changes. As a result, the proportion of the proximity detection system's magnetic flux that passes through the coal is variable. When a magnetic field generator is in contact with the coal face, approximately half of its magnetic flux can pass through the coal body while a smaller fraction of magnetic flux passes through the coal if the system is further from the coal face. Due to this environmental variability, there has been a concern that the coal may change the magnetic flux density distribution (MFDD) of the system, and therefore degrades the accuracy of the separation distance determination.

The impact that *in situ* coal has on a magnetic field can be evaluated using the dielectric properties of coal. Studies have showed that coal generally has low relative permittivity (between 1.6 and 5), permeability (about 1.0), and conductivities (can be lower than 10^{-5} Siemens/m)) at frequencies around 100 kHz, which is close to where a typical proximity system operates.[9–11] These dielectric parameters suggest that coal should have a small impact on the magnetic field. However, there are few actual measurements to confirm this. Further, these dielectric parameters were mostly obtained in laboratories using small specimens of coal. Within geologic strata, impurities, cracks, and voids can result in an inhomogeneous distribution of dielectric properties, and changes in water content, salinity, and temperature can result in a distribution change of dielectric properties.[12] The influence of massive *in situ* coal, therefore, needs to be understood.

2. Measurement methods

To facilitate measurement of magnetic fields in the presence of coal, two measurement methods were developed for two experiments to evaluate the influence of the *in situ* coal. The first was called the single-point magnetic flux density measurement (SPMF) method, and the second was the magnetic flux density distribution measurement (MFDDM) method. The SPMF method was used to measure a magnetic flux density at a fixed location relative to the generator as the distance of the generator relative to the coal was varied. The MFDDM method was used for measurements of multiple points around a generator. The measurements permitted us to obtain a MFDD model and examine the model for any distribution change in the presence of massive coal.

2.1. Measurement apparatus for SPMF method

The structure and circuitry of the test apparatus used in the SPFM method is illustrated in Figure 1. An LCR Inductance–Capacitance–Resistance meter acts as an exciting source to the magnetic field generator of a proximity detection system, and provides the measurements of voltage and current supplied to the generator circuit as well as the impedance of the generator circuit. The generator together with capacitor C forms a series LC circuit which is initially adjusted to a near-resonant state at the frequency at which the proximity detection system operates, so that the generator has a good sensitivity to a dielectric characteristic change of objects near the generator. By the coupling effect, a dielectric characteristic change of a nearby object will cause a corresponding

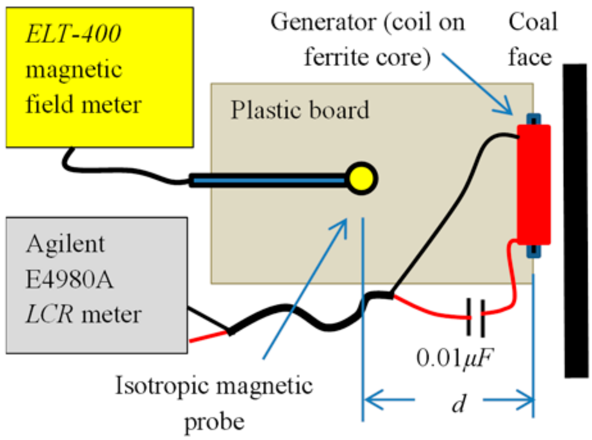


Figure 1. A single point magnetic flux density measurement apparatus in close proximity to a coal face.

change of the electrical parameters on the generator, and therefore, the impedance of the generator, resulting in an impedance change of the generator circuit and a current change in the generator circuit. These changes could be monitored with the LCR meter, and used to identify the dielectric characteristic change of nearby objects.

With an AC current flowing through the generator, a magnetic field is established. The isotropic magnetic probe of Narda ELT-400 magnetic field meter senses the magnetic signal at a fixed location at a distance, *d*, to the generator, and measures the magnetic flux density, *B*, in units of micro-Tesla (μT).When the generator is approaching a magnetic field disturbing object, a redistribution of the magnetic field in the space around the generator can occur, and the change of the magnetic flux density resulting from the field redistribution is sampled by the probe. The magnetic field disturbing object can be thus identified by detecting the magnetic flux density change from the probe.

Any change of the electrical parameters of the generator circuit or a change of the magnetic flux density *B* can be used as an indicator of a magnetic field redistribution resulting from a magnetic field disturbing object approaching to the generator.

The magnetic probe and the generator are rigidly fastened to a plastic board to compose the apparatus. This entire unit is moved toward the coal face from a distance during the experiment. It was hypothesized that as the unit approaches the coal face, the probe would detect a change in the magnetic flux density, indicating that the coal caused a redistribution of the magnetic field. The *in situ* coal can also be considered as a near-field variable load to the generator as the distances between the generator and the coal face vary. If the coal causes the magnetic field to change, it should also cause the voltage, current, and the impedance of the generator to change by the coupling effect. These electrical parameters displayed on the LCR meter can be collected for an analysis of changes in the electrical characteristics of the generator circuit under the influence of the coal.

The measurement unit can, in fact, be in any orientation when moving toward a coal face. Among all possible orientations, the generator shown in Figure 1 can have, at the closest position, its largest surface area touching the coal face resulting in the largest proportion of its magnetic field passing through the coal mass. This configuration is believed to be the most effective to observe the influence of the coal on the magnetic field of the generator and is, therefore, used.

The apparatus is designed to be simple and easy to use in mines to provide a yes or no answer of whether coal or any other geologic formation causes a change in the magnetic fields of a proximity detection system. It, however, cannot provide measurements to quantify the degree or nature of the change in the field distribution over the space around the generator. Therefore, the MFDDM method was developed for that purpose.

2.2. Measurement assembly for MFDDM method

The MFDDM method requires an assembly to take the magnetic flux density measurements of many points distributed in the space around the generator first, and then generates a best fit MFDD model with the measurements. An amplifier is used to supply a current to the generator to establish a stable magnetic field around it. The generator was mounted at the center of a radial coordinate system printed on a 2.44 × 1.1 m sheet of paper as shown in Figure 2. The sheet was laid on a wooden table. An isotropic magnetic probe was used to measure the magnetic flux density at each of the points on the radial grid. The grid paper provided a two-dimensional (2-D) polar coordinate system for the magnetic field, and facilitated the measurement of both location coordinates (ρ, α) and magnetic flux density B at a point on the field, written in (B, ρ, α) as shown in Figure 3. The effect of *in situ* coal on the magnetic field distribution can be evaluated by examining the differences between the field distribution models obtained from the measurements in the absence of coal and the measurements near coal.

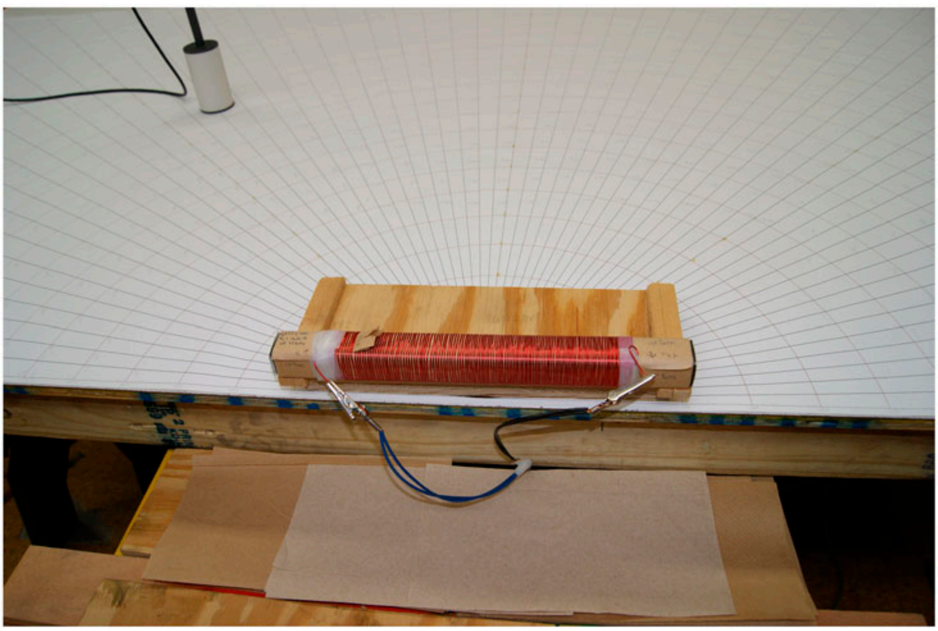


Figure 2. Generator and isotropic probe of the MFDDM measurement assembly with 2-D polar coordinate system.

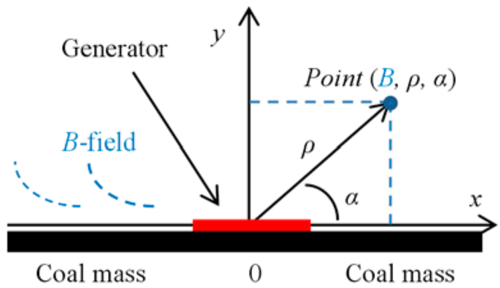


Figure 3. Polar and Cartesian coordinate systems for the magnetic flux density measurement system.

3. Measurement results

The experiments to collect measurement data using both SPMF and MFDDM methods were conducted at the NIOSH research facility just south of Pittsburgh, PA, with experiments involving coal done in our on-site underground mine, the Safety Research Coal Mine (SRCM), in the Pittsburgh coal seam, and other experiment in laboratories on site.

3.1. Measurement results with SPMF method

NIOSH researchers took measurements at two locations in the SRCM using the SPMF method; one location was relatively dry with no visible moisture on the coal face or the nearby areas, and the other was wet with water drops present in the entire face, floor and nearby areas. The set-up at both the locations is illustrated in Figure 4. The generator and the probe were set at a fixed distance on a plastic board before the measurements began. The measurements started with the generator placed about 500 cm from the coal face, powered by a 20 V exciting source from the LCR meter at a frequency of 75 kHz (a typical frequency for proximity detection systems.) The unit was moved toward the coal face in 2.5 cm steps until the generator was in contact with the coal face. The magnetic flux passing through the coal mass increased as the distance between the generator and the coal face decreased. When the generator was in contact

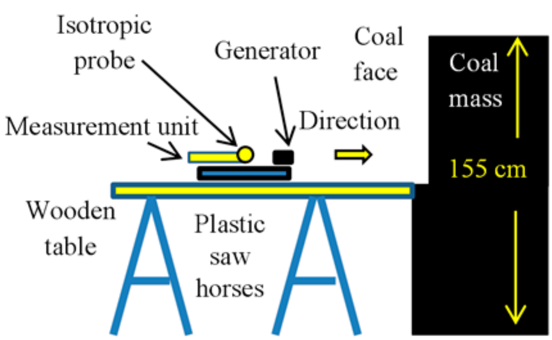


Figure 4. Setup of the single-point measurement system next to an underground coal face.

with the coal face, approximately half of the total magnetic flux could pass through the coal. The magnetic flux density sensed by the probe should show a change with distance between the generator and the coal face if the coal significantly disturbed the distribution of the magnetic field.

The plot in Figure 5 shows the measurement results in the dry coal face in the SRCM. The plot shows magnetic flux density measurements in μT as the distance between the generator and the coal face was varied, and as the distance between the generator and the magnetic probe was held constant. These results show little variation in the magnetic measurements, suggesting no noticeable interference from the coal. Figure 6 gives the average and standard deviation of the magnetic flux density measurements shown in Figure 5. If the average is quantitatively taken to represent the steady portion of the field, and the standard deviation, the portion of the variation of the field, the ratio of the standard deviation to the average can then be taken as a statistical measure of the magnetic field variation, which is 0.107%, indicating that the magnetic field change, caused by a combination of all field-disturbing factors including coal and ambient and measurement apparatus noise, is statistically insignificant.

Similar results were obtained in the location that was wet with water appearing on the coal face.

Similar results and statistics were also obtained in the measured voltage and current and impedances of the generator circuit. The measurements with the SPMF method, thus, all suggest that the *in situ* coal in the SRCM has no significant influence on the magnetic flux density at the given frequency.

3.2. Measurement results with MFDDM method

The assembly for the MFDDM method was used to collect the measurements of 429 points distributed in the space around a stationary generator at a fixed location, first in

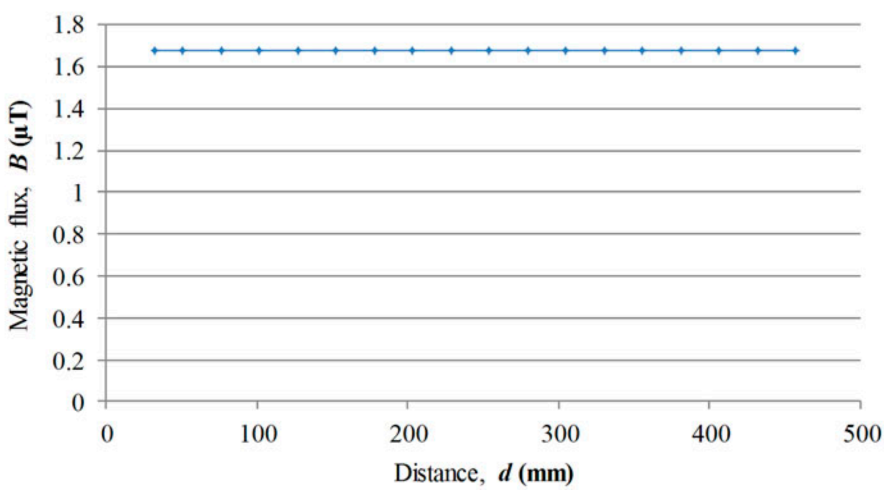
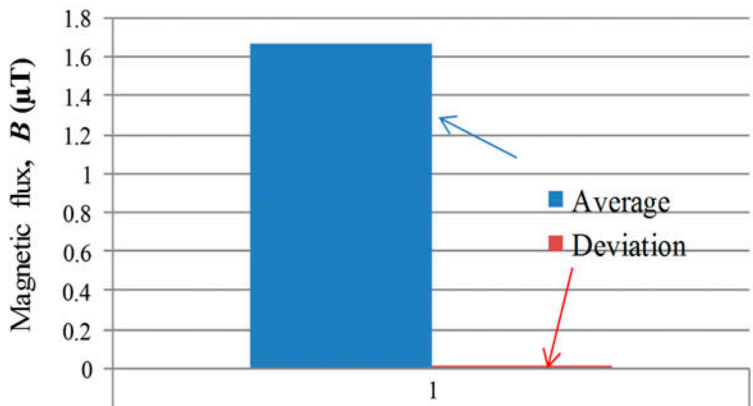


Figure 5. The magnetic flux density measurements as a function of distance between the generator and the coal face.



	1
Average	1.675333
Deviation	0.001795

Figure 6. Average and standard deviation of the magnetic flux density measurements.

the laboratory without coal present and then at a coal face in the SRCM. Two MFDD models were obtained from those two sets of measurements, and compared to find differences between them in order to identify the influence of the coal.

NIOSH researchers previously developed a shell-based distribution model of magnetic flux density to characterize the near-field radiation pattern of a bar-shaped ferrite-cored generator in a constant permeability medium.[6,13] A magnetic shell is defined as the collection of all points around the generator that have an equal magnetic flux density. Using the previously developed procedures, the MFDD was modeled to characterize the fields of the same generator both with and without coal present. With reference to Figure 3 for ρ and α, the generalized 2-D magnetic flux distribution model presented in references [6,13] is again given in Equation (1), where Equation (1a) is a polar shell function which is defined by two parameters, the shell shape parameter a, and the shell size parameter b. The parameters, a and b, can be obtained with Equation (1b) and (1c) for a given flux density B. c_a, d_a, c_b, and d_b are constants for a given steady magnetic field, and completely characterize the field distribution. These constants have to be determined to provide a fit to measured data using the procedures described in [6].

The generator running at a fixed current at a frequency of 75 kHz was first set-up in the laboratory on a 1.22 × 2.44 m wooden table with no coal present, and the measurements, (B, ρ, α), were recorded at all 429 points to create a total of 13 shells around the generator. The same set-up was then moved to the SRCM with the generator nearly touching the coal face as illustrated in Figure 7, with the data acquisition procedures repeated. The measured units of magnetic flux density were μT. For each of the 13 shells on the surface and 13 shells in the presence of coal underground, the shape and size parameters were determined from the measurements using a least-squares fit. Figure 8 shows the plots of a representative sample of measured and modeled half-shells.

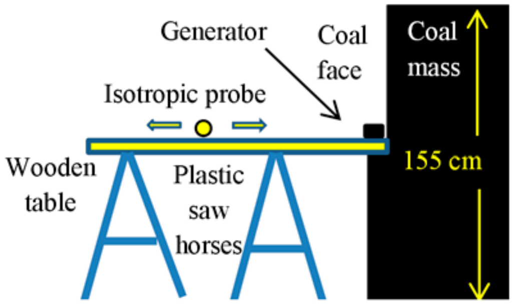


Figure 7. Setup of the magnetic distribution measurement assembly at the coal face.

Based on the best model fits for all 13 shells, the complete magnetic flux distribution model was determined for no coal and coal cases. The models for both cases are given in Equations (2) and (3), respectively. These models apply to the range 1000 mm ≥ $a + b > 152.4$ mm for the generator of length $L = 304.8$ mm for its ferrite core. To facilitate a visualized comparison of Equations (2) and (3), three pairs of the shells are generated from the equations in small, medium, and large sizes to cover most of the defined range for these models and are given in Figure 9. For each of these pairs of shells, one shell came from Equation (2) with no coal present, and the other from Equation (3) with coal present. The average differences between each pair of shells, which could be taken as a statistical indicator of the magnitude of the difference between each pair of these shells, are given in Table 1. The differences are statistically small, suggesting that the influence of the *in situ* coal mass in the SRCM on the magnetic field distribution is insignificant. Similar comparisons were made on all other pairs of shells with similar results.

It is worth mentioning that one of the contributing factors to the small differences between the two magnetic fields shown in Figure 9 and Table 1 was found to be the

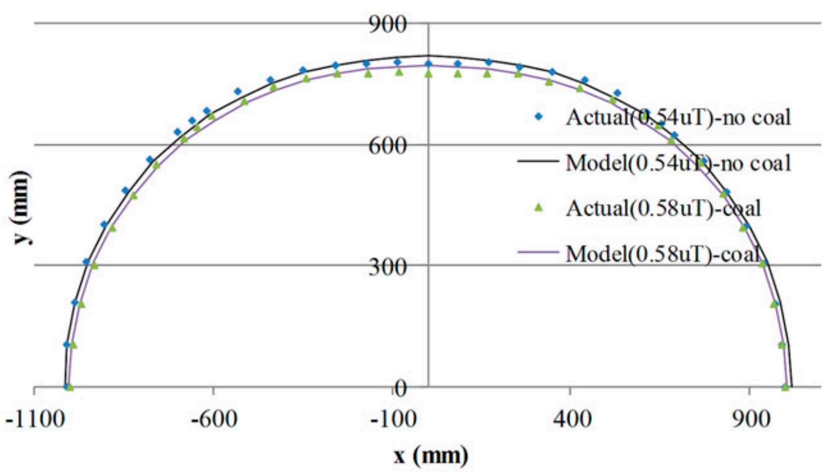


Figure 8. Measurements (in diamonds) for $B = 0.54\,\mu T$ with the modeled shell with no coal present, and measurements (in triangles) for $B = 0.58\,\mu T$ with the modeled shell with coal present.

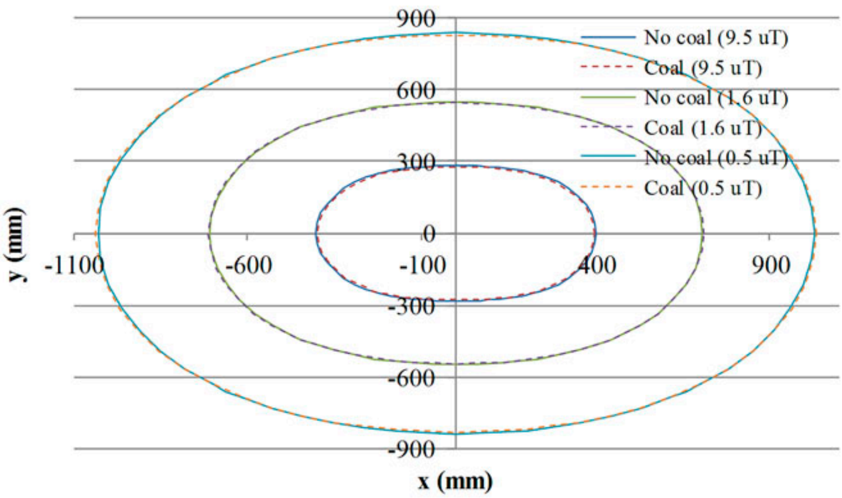


Figure 9. Three pairs of shells with each of the shells in each pair coming from Equation (2) with no coal present and the other from Equation (3) with coal present (Shells are generated with B = 9.5, 1.6, and 0.5 μT, respectively.)

Table 1. Differences between the paired shells generated from the model with no coal present and the model with coal present in terms of calculated magnitudes, ρ.

Magnetic flux density (μT)	Absolute average difference (mm)	Relative average difference (%)
$B = 9.5$	5.37	1.58
$B = 1.6$	0.05	0.02
$B = 0.5$	0.86	0.13

drift in the permeability, μ, of the ferrite core of the generator. The permeability of the core could vary randomly in a small range. A perceptible permeability drift generally occurred when the generator was energized or had a sudden large change in current through the coil causing a corresponding distribution change in the magnetic field. With the laboratory conditions under which the measurements were taken, the effect of the permeability drift was not as apparent as it was in an operating mine, where the power supply to the generator was subject to a frequent on/off cycles, creating more sudden changes in current, and therefore more chances for the permeability drift. In contrast, no single power interruption at the laboratory occurred, and the generator was subject to no such sudden current change. For the in-mine measurements in this experiment, a slightly higher occurrence of permeability drift was observed. Despite the higher permeability drift in the in-mine experiment, the field distribution of the generator with coal present showed little change compared with the one with no coal present.

$$\text{Shell}(\rho, \alpha | B) = \begin{cases} \rho = a \cdot \cos(2\alpha) + b. & \text{(1a)} \\ \quad \text{for } a + b > \frac{L}{2}, |\alpha| < 2\pi & \\ \quad (L: \text{length of ferrite core}) & \\ a = c_a B^{-d_a}. & \text{(1b)} \\ b = c_b B^{-d_b}. & \text{(1c)} \\ \quad \text{for } B > 0 & \end{cases} \quad (1)$$

$$\mathrm{Shell}(\rho,\alpha|B)_{\text{no coal}} = \begin{cases} \rho = a\cdot\cos(2\alpha) + b(\mathrm{mm}). & \text{(2a)} \\ \quad \text{for } a+b > 152.4\,\mathrm{mm},\ |\alpha| < 2\pi & \\ a = 86.56B^{-0.155}. & \text{(2b)} \\ b = 738.41B^{-0.341}. & \text{(2c)} \\ \qquad B > 0, \text{in } \mu\mathrm{T} & \end{cases} \tag{2}$$

$$\mathrm{Shell}(\rho,\alpha|B)_{\text{coal}} = \begin{cases} \rho = a\cdot\cos(2\alpha) + b(\mathrm{mm}). & \text{(3a)} \\ \quad \text{for } a+b > 152.4\,\mathrm{mm},\ |\alpha| < 2\pi & \\ a = 90.92B^{-0.179}. & \text{(3b)} \\ b = 735.10B^{-0.346}. & \text{(3c)} \\ \qquad B > 0, \text{in } \mu\mathrm{T} & \end{cases} \tag{3}$$

4. Influence of coal on generator current

The induced current in coal by the magnetic field can change the current in the generator of a proximity detection system due to near-field coupling effect, resulting in a corresponding change in the MFDD of the generator. To further evaluate the influence of *in situ* coal on the current in a generator, another experiment was designed and executed.

4.1. Transformer effect of generator

When the generator is close to a coal face, it directly couples the energy from its windings to the coal mass through the electromagnetic field. This is similar to the coupling that occurs in a transformer from its primary windings to its secondary windings to a load. A change of the load on the secondary side of the transformer will cause a current change on the secondary windings, which, in turn, brings a proportional change of the current on the primary windings of the transformer. Similarly, a change of the induced current in the *in situ* coal will cause a change of the current on the windings of the generator, resulting in a corresponding change of magnetic field around the generator. This transformer effect of the generator permits us to establish an equivalent circuit of the generator as shown in Figure 10 to study of the influence of *in situ* coal on the current in the generator. In the equivalent circuit, i_p denotes current on the primary windings, i_{coal} denotes the total equivalent induced current on the secondary windings, and Z_{coal} denotes the equivalent impedance of coal mass.

There are two major differences between an ideal transformer and the generator circuit. The first is that the coal is both the secondary windings and the load for the generator, and is equivalent to a one turn winding. The second is that only about half of the total magnetic flux passes through the coal mass as the generator is in contact with the coal face. This effectively reduces the secondary windings to an equivalent of a half turn.

The current in the coal, i_{coal}, is widely distributed in the coal mass, and can be determined theoretically by an integral of all current components, $i(v)$, in individual coal volumes as shown in Equation (4). In practice however, it is difficult to obtain the individual current components, let alone the total current. One way that could be less difficult to estimate the current is through the equivalent impedance of the coal mass, Z_{coal}, as referred to the primary side of the transformer. Transformer theory indicates that Z_{coal} can be transferred to the primary side and the transferred impedance, $Z_{\text{coal}-p}$,

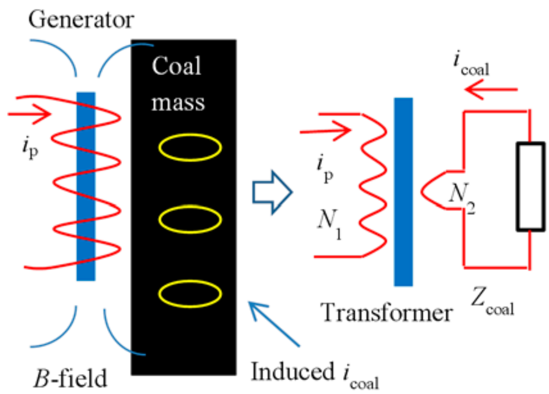


Figure 10. Equivalent circuit of a generator circuit near a coal face.

can be determined using Equation (5), where N_1 is the number of turns in the windings on the generator, which is 130 for the generator used in this experiment, and N_2 is the number of turns of the equivalent secondary windings, which is a half turn. The equivalent generator circuit with the transferred impedance then becomes the one as shown in Figure 11, where v_p denotes the voltage across the generator. The total current i_p, then has the component i_{coal-p} in it as the equivalent current on the generator transferred from the coal mass, or the interfering current from the coal mass to the generator. This complex current component can be determined from Equation (6).

$$i_{coal} = \int_{\text{coal volume}} i(v)\mathrm{d}v. \quad (4)$$

$$Z_{coal-p} = Z_{coal}\left(\frac{N_1}{N_2}\right)^2 = Z_{coal}\left(\frac{130}{0.5}\right)^2 = 67{,}600\ Z_{coal}. \quad (5)$$

$$i_{coal-p} = \frac{v_p}{(67{,}600\ Z_{coal})}. \quad (6)$$

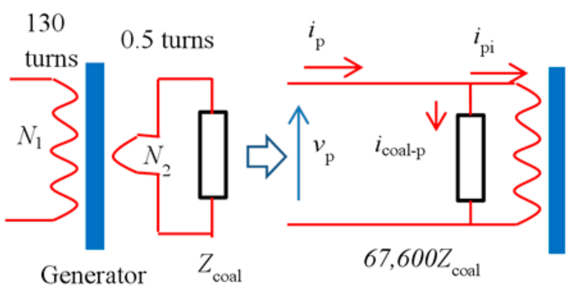


Figure 11. Equivalent generator circuit with the transferred coal impedance to the primary side of the generator.

4.2. Estimate of interfering current from coal

To find the interfering current component, i_{coal-p}, created by the coal mass on the generator windings using Equation (6), we need the coal impedance, which is also a distributed quantity over the entire coal mass. By obtaining the value of the lumped coal impedance, however, it is possible to attain a fair estimate of the magnitude of the impact of the interfering current. In this study, a measured impedance of the coal was used to estimate the interfering current component.

The lumped impedance of the *in situ* coal mass was obtained at the location near the generator in the SRCM at 75 kHz as shown in Figure 12, where two sets of stainless steel bolts were screwed into the coal on both sides of the generator with connecting leads. These bolts served as electrodes to measure the coal impedance. The LCR meter was connected to the leads to obtain the impedance reading of the coal. The current from the LCR meter for the impedance measurement in this set-up had the same flowing direction as the induced current by the magnetic field of the generator in the coal, and saw the same impedance as the induced current did. The measured coal impedance was $57{,}917.62 - j1{,}944.34 = 57{,}950.25e^{-j1.92274^\circ}\Omega$. The impedance took into account of all the impurities, cracks, voids, moisture content, and inhomogeneous dielectric properties of the coal. This measured value was used for Z_{coal} in Equation (6) to obtain an estimated interfering current, i_{coal-p} as shown in Equation (7), where v_p = 562.0 V, the actual voltage across the generator. With the measured current of the generator of $i_{pi} = 31.202027 - j353.64999$ mA $= 355.0375e^{-j84.95819^\circ}$mA without coal present, the total current, i_p, could be obtained from Equation (8). The change in the current magnitude in the generator with coal present can then be calculated from Equation (9), and the relative change can be obtained from Equation (10). As shown in Equation (10), the relative magnitude change of the generator current is 0.000029%, which is too small to have a noticeable impact on the current in the generator, and, therefore, on its magnetic field. In fact, this impact is much less than the amplifier noise. Even with an interfering current assumed to be 10,000 times greater than the calculated current, the relative magnitude change of the current in the generator would be around 0.29%, which could hardly have a significant impact on the magnetic field of the generator.

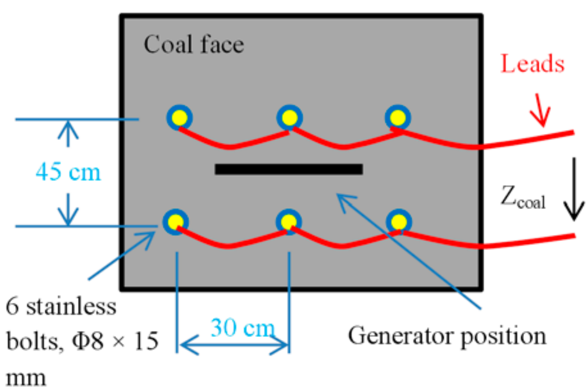


Figure 12. Measuring impedance of a coal mass with leads connected to a set of bolts screwed into coal on both the sides of a magnetic field generator.

$$i_{coal-p} = \frac{v_p}{67{,}600\ Z_{coal}} = \frac{562.0}{[67{,}600 \cdot (57{,}91762 - j1{,}944.34)]} \\ = 0.000143 + j0.00000481\ (\text{mA}). \quad (7)$$

$$i_p = 31.202027 - j353.64999 + i_{\text{coal}-p} = 31.20202 - j353.6638 = 355.0375e^{-j84.9581^\circ}. \quad (8)$$

$$|i_p| - |i_{pi}| = 355.037488 - 355.037496 = -0.000104\ (\text{mA}). \quad (9)$$

$$\frac{(|i_p| - |i_{pi}|)}{|i_{pi}|} = -0.000029\%. \quad (10)$$

5. Discussions

The measurement data from SRCM show that the impact of massive *in situ* coal on the magnetic fields of a magnetic proximity detection system at 75 kHz is small. This indicates that the overall *in situ* coal dielectric properties, considering all geological disturbing factors, has a low influence on the magnetic fields of the proximity detection system. Moreover, both high resistance and reactance of the impedance measurement of the *in situ* coal obtained in the current study also suggest that a low relative conductivity and permittivity of the coal still remain, even taking into account those geological varying factors, resulting in a low-induced current in the coal body.

Early research indicates that coal's dielectric properties vary widely between coal mines and even at different locations within the same mine, and change with signal frequency, temperature, water content, and other environmental conditions.[1,14–17] The methods presented in this paper can be used to evaluate the impact of coal having different dielectric properties on the magnetic fields of proximity detection systems, or the impact of coal on the magnetic fields of systems operating at different frequencies.

For proximity systems used in metal/nonmetal mines or in low coal seam mines with significant noncoal geology near the generators, the dielectric properties of those *in situ* rocks could be greatly different from coal. The methods given in this paper could be used to perform similar evaluations of the influence of various geologic conditions on the magnetic field of a proximity detection system.

6. Conclusions

Two methods are introduced in this paper to measure the influence of *in situ* coal mass in an underground coal mine on the magnetic field of a magnetic proximity detection system: a SPMF density measurement method and a MFDD measurement method. The former is used to measure the magnetic flux changes at a fixed point relative to a magnetic generator at varying distances from a coal face, while the latter is used to obtain measurements at multiple points around the generator for determining the MFDD with and without coal present. The data obtained with these two methods in one coal mine showed that the influence of *in situ* coal was insignificant. In addition, the induced interfering current of *in situ* coal mass to the magnetic generator was also evaluated. Analysis of the measurements from that mine showed that the change in the magnitude of the total current of the generator caused by the induced current in the coal was far less than 0.1%. Although the methods were developed for coal, they can be used to study the influence of other geological environments on a magnetic field in general.

Disclaimer

The findings and conclusions in this paper are those of authors and do not necessarily represent the views of NIOSH. Mention of company names or products does not constitute endorsement by the Centers of Disease Control and Prevention.

Acknowledgments

The authors gratefully acknowledge the contributions of Mr Joseph Ducarme, Dr Christopher Jobes, Mr Timothy Lutz, Mr Miguel Reyes, Mr Adam Smith, Mr Bruce Whisner, and Mr Jeffrey Yonkey for their work on the experiment set-up and data collections.

References

[1] Schiffbauer W. Active proximity warning system for surface and underground mining applications. Min. Eng.; 2002 Dec 1;54:40–48.
[2] Chirdon D. MSHA proximity detection; 2009. Available from: http://www.msha.gov/Accident_Prevention/NewTechnologies/ProximityDetection/Proximity%20Detection%Pager.pdf.
[3] Ruff T. Overview of proximity warning and technologies and approaches. Presentation at NIOSH Workshop on Proximity Warning Systems for Mining Equipment; 2010 Sep 15; Charleston, WV. Available from: http://www.cdc.gov/niosh/mining/UserFiles/workshops/proximitywork shop2010/Ruff-NIOSH-PDWorkshop2010-508.pdf.
[4] Huntsley C. Remote controlled continuous mining machine fatal accident analysis report of victim's physical location with respect to the machine; 2011 Dec 23. Available from: http://www.msha.gov/webcasts/Coal2005/Fatal%20Accident%20Summary.pdf on 5/17/2012.
[5] Mine Safety and Health Administration. Proximity detection systems for continuous mining machines in underground coal mines. Notice of proposed rule making. Federal Register. 2011 Aug 31;76:54163–54179.
[6] Li J, Carr J, Jobes C. A shell-based magnetic field model for magnetic proximity detection systems. Saf. Sci. 2012;76:463–471.
[7] Carr J, Jobes C, Li J. Development of a method to detect operator location using electromagnetic proximity detection. Paper presented at: IEEE International Workshop on Robotic and Sensors; 2010 Oct 15–16; Phoenix, AZ, USA.
[8] Li J, Carr J, Jobes. Modeling of the magnetic field around a ferrite-cored generator in a proximity detection system. Paper presented at 14th Conference on Electromagnetic Field Computation; 2010 May 9–12; Chicago, IL, USA.
[9] Marland S, Merchantl A, Rowson N. Dielectric properties of coal. Fuel. 2001;80:1839–1849.
[10] Nelson S, Beck-Montgomery S, Fanslow G, Bluhm D. Frequency dependence of the dielectric properties of coal – part II. J. Microwave Power. 1981;16:319–326.
[11] Iskander M, Dubow J. Time- and frequency-domain techniques for measuring the dielectric properties of rocks: a review. J. Microwave Power. 1983;18:55–74.
[12] Berryman J. In: Ahrens T, editor. Mixture theories for rock properties. America geophysical union handbook of physical constants. New York, NY: AGU; 1995. p. 205–228.
[13] Li J, Jobes C, Carr J. Comparison of magnetic field distribution models for a magnetic proximity detection system. IEEE Trans. Ind. Appl. 2013;49:1171–1176.
[14] Speight J. Hand book of coal analysis. Holbroken (NJ): John Wiley Sons; 2005. p. 124–129.
[15] Speight J. The chemistry and technology of coal. Boca Raton (FL): Taylor & Francis; 2013. p. 277–279.
[16] Chatterjee I, Misra M. Dielectric properties of various ranks of coal. J. Microwave Electromagn. Energy. 1990;25:224–229.
[17] Li J, Whisner B, Waynert J. Measurements of medium frequency propagation characteristics of a transmission line in an underground coal mine. Proceedings of IEEE IAS Annual Meeting; 2012 Oct 7–11; Las Vegas, NV, USA.