Prof. James R. Wait and Mining Production Technology—An Appreciation

A. C. Tripp, R. McNearny, and C. Furse

***Abstract*—Prof. James R. Wait examined electromagnetic (EM) wave propagation in many situations of interest to mining production, including propagation in tunnels, propagation along extended conductors such as cables and drill stems, and propagation in coal seams. This work remains relevant, both to the mining engineer interested in the EM environment of an operating mine and to the electrical engineer interested in verifying new computational techniques and in extending the scope of EM technology in mining production. Late work in EM focussing in a geological environment is relevant to "next generation" geophysical monitoring equipment.**

***Index Terms*—Geologic measurements, mining industry.**

I. INTRODUCTION

JAMES Wait began his career considering electromagnetic (EM) applications to mining and his contributions to the field were profound. His publications on induced polarization and the EM response of layered earths have been cited constantly by workers in exploration and resource evaluation. His work in transient exploration was innovative and predated mainstream adoption of transient methods in geophysics.

Wait's work concerning EM applications in mining production is perhaps less well known. A mine, surface or underground, is a hazardous work environment producing a commodity for national and international markets. Safety and production efficiency both must be achieved or the mine closes. In such an environment, several factors relating to electromagnetics are important. These include the following.

1) *Efficient communication between miners at all times*. Efficiency and safety require optimal communications between all production workers. When things go wrong, mine rescue is facilitated by communications being maintained by conventional or unconventional means.
2) *Evaluating and containing stray electrical currents*. Stray electrical signals can degrade communications, interfere with geophysical probing, prematurely fire electrical blasting caps, ignite methane-based mine explosions, and electrocute miners. EM theory is important in reducing these risks, even if it is not used routinely.
3) *Detection and imaging anomalous geology ahead of mining*. One of the main reasons for unexpected increases in the cost of mining strata-bound materials, such as coal, is anomalous geology. Paleochannels, faults, dikes, or sills, cutting through production zones affects product quality and producibility.

In these concerns, it is important to be able to calculate EM field strengths for conductor geometries corresponding to those maintained in a mine. The works of Prof. Wait address these problems.

In the following, we provide a bibliography of some Wait publications relevant to mining production technology. We also briefly present specific historical and potential applications of these theoretical publications. Our hope is that such a work, apart from commemorating the life and contributions of Prof. Wait, will increase the awareness of mining and its technological needs among the electrical engineering community.

II. MINE COMMUNICATION

Communications in the underground mine setting is relatively new compared with the long history of mining, both in the United States as well as elsewhere in the world. Communications equipment did not start appearing in western U.S. underground workings until the early 1900s ([59], [60]). Early telephone sets were comparable to the standard aboveground sets of the day, except that they were contained in cast-iron casings to protect them from the underground environment. In the 1950s, the Chesapeake and Potomac Telephone Company developed an explosion-proof telephone set. Its utility was limited, however, because of the heavy casing around it. Telephone sets also required a conduit, which again limited their usefulness, given the size of many underground coal mines.

Although loudspeakers, bells and whistling signaling systems have been used recently, communication systems currently used in most mines in the U.S. include overhead trolley wire or a fixed pager phone. The trolley wire system is used mainly to schedule haulage. Pager systems, usually voice activated, are often broken down into multiple-part units that are often controlled by the mine dispatcher. Newer paging systems have been improved by the incorporation of computerized control, whereby an operator can type a message into a computer that either routs the specific digital message to one individual or to all miners within a working section. Such a paging system was effective during the mine fire at the Willow Creek Coal Mine in southern Utah on November 25, 1998, where the underground miners were quickly notified of evacuation by the mine's paging system [67].

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Also included under the heading of mine communications are monitoring systems which include sensors for methane, carbon monoxide, temperature, relative humidity, airflow, and differential pressure. The output from these sensors is now controlled by computers and is often incorporated into a display that provides operational monitoring of the mine, including the monitoring of production, materials handling, electrical systems, rockbursts, water levels in sumps, and methane drainage equipment [68].

The curious will find more extensive information concerning the history and practice of mine communications contained in supplemental references [59]–[74].

Establishing good communications underground can be difficult, since the mine environment is only partially amenable to human intervention. For example, many mining operations require metallic mechanical parts such as cables, cutting blades, or machinery. These metallic components can be thin and extended such as cables or can be discrete and massive such as continuous mining equipment. Rock encountered in the mine can range in conductivity over more than 12 orders of magnitude [70] and the conductivity varies over microscopic to mine dimension scales. Design of effective communications equipment in such conditions requires effective modeling, demonstrated in abundance by Wait and his colleagues.

The chronological bibliography of Prof. Wait's relevant publications reveals three major geometries related to mine communications. These are EM propagation in layered earths, EM propagation in tunnels, and EM propagation on cables and drill steel.

Ideally, mine communications should be able to access every part of the mine and its environs. Such a capacity requires through-the-earth communications, recently contemplated by U.S. mining companies, following the lead of several innovative mines in Australia. Modeling the effect of rock layers on the EM fields is critical in this application. Prof. Wait's work on layered earths was comprehensive in addressing continuous wave (CW) and transient problems over a range of conductivity and dielectric values. References [2], [3], [5], [7]–[15], [20], [26], [29], [38], [43], [51], and [55] are concerned with the problem of EM propagation through an earth—possibly with layers.

If miners are unable to access conventional communications equipment in an emergency, through-the-earth communications becomes critical. References [9], [11], [15], and [20] specifically address emergency communications systems in which trapped or barricaded miners activate a radio transmitter whose fields are detected by rescuers equipped with receivers [71]. The basic concept is similar to the Pieps system for locating avalanche victims. Such systems are not in general use today.

References [29], [43], [51], [55], and [72]–[74] are concerned with EM propagation in coal seams. These works are of interest to anyone interested in coal mine communication or in coal seam monitoring for long-wall operations. They are also important in coal seam tomography.

The reason for applying magnetic dipole antennas instead of electric dipole antennas in a slightly conducting media is explained in [58].

Mine radio communications can use tunnels as lossy waveguides. Wait and colleagues discuss tunnel waveguides in references [4], [17], [21], [27], [33], [42], [50], and [57]. These works, with the exception of [21], use modal expansions with various boundary conditions. Reference [21] uses geometric optics to deal with rectangular tunnels.

A very popular method of mine communication is to use a cable within a tunnel, shaft, or drill hole. References [16], [18], [19], [22], [23], [25], [28], [30]–[32], [34]–[36], [38]–[41], [44]–[47], [49], [52], and [54] all present analyses of various engineering designs of cable-based communication. These references, which are still relevant to mining engineering, have in addition application to well logging in the oil industry and covert-tunnel detection. They also represent a remarkable illustration of the use of analytic methods.

A variation on cable-based communications is communications along a drill rod. This has application to the trapped miner problem and is considered in [48]. This work also has application to drill string telemetry for directional drilling.

III. Ambient Mine Electrical Field Estimation

An underground mine offers a peculiar electrical environment in which highly conductive material such as track or cables are superimposed on resistive access tunnels or shafts. The rock itself may be conductive or resistive—and the transition between the two may be abrupt. Highly conductive water may move through the mine, using small permeability conduits. Mining machinery in this environment may generate a great deal of EM noise. Atmospheric electricity can gain access to workings through external cables or rails.

Deducing the electromagnetic environment in a mine has several potential uses. Among them are:

1) the atmosphere in access areas may have an explosive mixture of methane, which may be detonated through stray sparks;
2) stray currents can interfere with ground conductor monitoring circuits, leading to electrocution hazards;
3) electric blasting caps can be detonated with a sufficiently large ambient electric field;
4) communications can be degraded or disrupted by conductive features or noise sources.

The work on wave propagation in tunnels and along conductors in tunnels is directly applicable to noise field estimation, impacting the safety concerns of electrocution from power distribution faults or accidental methane and electric blasting cap detonation. For example, Wait's publications could be used to estimate the electric field in a quartzite adit due to atmospheric electrical fields carried along tram lines onto ore car rails. As it happens, these fields can be sufficiently large to detonate electric blasting caps.

IV. Historical Retrospective and Future Perspectives

Perusal of the chronological list of references reveals clustering about the 1970s, a period in which technological innovations in mining were encouraged by private and public research funding. The work of Wait and colleagues, driven by the economic climate of the time, provided an archetypal use of analytic methods for modeling a complicated mining environment.

We believe that the importance of Wait's work endures and offers much of value to electrical engineers and mining engineers. Our reasons are the following.

1) The engineering problems addressed by Wait endure. Indeed, remote sensing, communications, and mine safety issues will probably become more important.
2) Many of the analytic models developed by Wait have contemporary application in areas other than mining. For example, Wait's analyses of antennas in lossy media have direct application in designing high-frequency antennas for high-resolution imaging of lossy geological material such as waste dumps. Likewise, his work in EM focusing [56], has application in such potential applications as joule heating for enhanced oil recovery. Propagation along a drill steel is also a viable model for drill-stem telemetry for measurement while drilling (MWD) in well-logging. Wait also examined the possibility of earth material waveguides and resonant loop detection of coal-boundary rock interfaces [43], which both have significance for cutting machine control. Resonant loop detection has also been suggested for plastic antipersonnel landmine detection.
3) While numerical methods continue to improve with improvements in software and hardware, each numeric algorithm is best used on specific types of problems. Analytic solutions such as those of Wait and colleagues, provide verification of these algorithms. It is also true that in certain problems, analytic methods provide the best solution.
4) Given the breadth and depth of Wait's work, it seems reasonable that future investigators will find many of their problems at least partially solved by a Wait paper.

In conclusion, we have found Wait's work to be of perennial interest. It is our hope that future workers, in the spirit of James Wait, will extend the scope and power of EM technology in mining production.

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