THE EFFECT OF URBAN PLUMBING ON POWER LINE GROUNDING, GROUND CURRENT, AND MAGNETIC FIELD

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Abstract

Leads developed in earlier work are pursued in this study, which investigated urban plumbing for the effects it has on power line grounding effectiveness, ground current, and ambient magnetic fields. The analysis uses the connection of a residence to an urban water system, as opposed to a residence not on a water line (using a private well), as a variable to test statistically significant differences. Both types of residences are present in a small town, where other variables are thought to be undifferentiated. Preliminary analyses indicate that such statistically significant differences do exist. This finding may have important implications for epidemiological work in EMF, and may constitute valuable engineering information, especially for EMF mitigation.

Introduction

A field investigation of power neutral isolation pointed out that the 60-Hz electrical environment may be substantially different at the power service transformer between rural and urban residences [1], a fact that may be relevant to the magnetic field health effect issue. This notion may not come as a surprise, considering that this difference may be a natural extension into the electrical environment of the differences in infrastructures between rural and metropolitan settings that we already are cognizant of.

What distinguishes rural from urban environments is the housing pattern and the level and density of services. Municipal water is another important distinguishing feature. Because of the electrical interconnections between water supply and electrical systems for grounding purposes, the hypothesis is that the rural settings (with no water system) and urban settings (with a water system) have different magnetic field levels. Plumbing has already been shown to be a source of magnetic fields inside the residence [2,3,4]. The presence of an urban-type water-pipe network could then be an important factor to consider in EMF studies.

The question is explored in this paper with the analysis of data collected in 1993, in the course of special tests conducted in the small town of South Republic, Michigan. The data includes sample measurements of outdoor magnetic fields, ground currents, and grounding impedances. Residences are categorized as being urban if they are connected to a city water system, and as being rural if they are not connected to the city water and use a well instead. The strength of this study is limited by the incidental nature of the data and the preliminary nature of the analysis.

There is already a clear engineering understanding [2,3,4] of the underlying phenomenon. These other studies, however, deal with the magnetic field inside the residence. This paper focuses instead on the magnetic field environment outside the residence, which is what started the interest in magnetic fields [5]. Furthermore, the question of most interest here is whether these differences build up to a level of epidemiological significance.

Background and Setting

Figure 1 shows South Republic, a town of about 150 households, with its major geographical features and the main utility services. The town consists of nine square blocks of houses laid out in a 3-by-3 matrix, and another group of randomly distributed houses to the north and south of these, along the Michigamme River. The power distribution line is an overhead four-wire, three-phase wye, 7.2/12.4 kV, with the neutral grounded at every pole. The main line, Figure 1a, comes from the north, fans out through the town, and proceeds to the south. Various taps extend service east and west of the main line. Cable TV and telephone distribution cables are underbuilt on the power poles; some other telephone cables and services are buried. All electrical utilities are grounded together at the residenceS as well as at various points along the line. The municipal water system, Figure 1b, provides water service to the town and some nearby houses, from a pumping station on the river. All remaining residences use wells.

The triangles in Figure 1 represent power service transformers. In the core of the town, each transformer feeds four residences on average, with a maximum of 12 residences in one instance, a pattern that is typical of densely packed, large urban settings. The primary lines run through an alley behind the houses. The service transformers utilize long mains with the secondary neutral separate and isolated from the primary line neutral, except at the service transformer, where there is an interneutral tie. The residences they feed are all served by public water lines running through the middle of the street. There are 36 such transformers, represented in Figure 1 by filled triangles. The other 46 transformers, represented by empty triangles, feed residences not on the public water lines. These transformers feed two residences on average.

Data were collected at each transformer and at some other points in the vicinity of one of the residences served by the transformer. The data include magnetic fields measured outdoors one meter above ground, 60-Hz neutral voltages

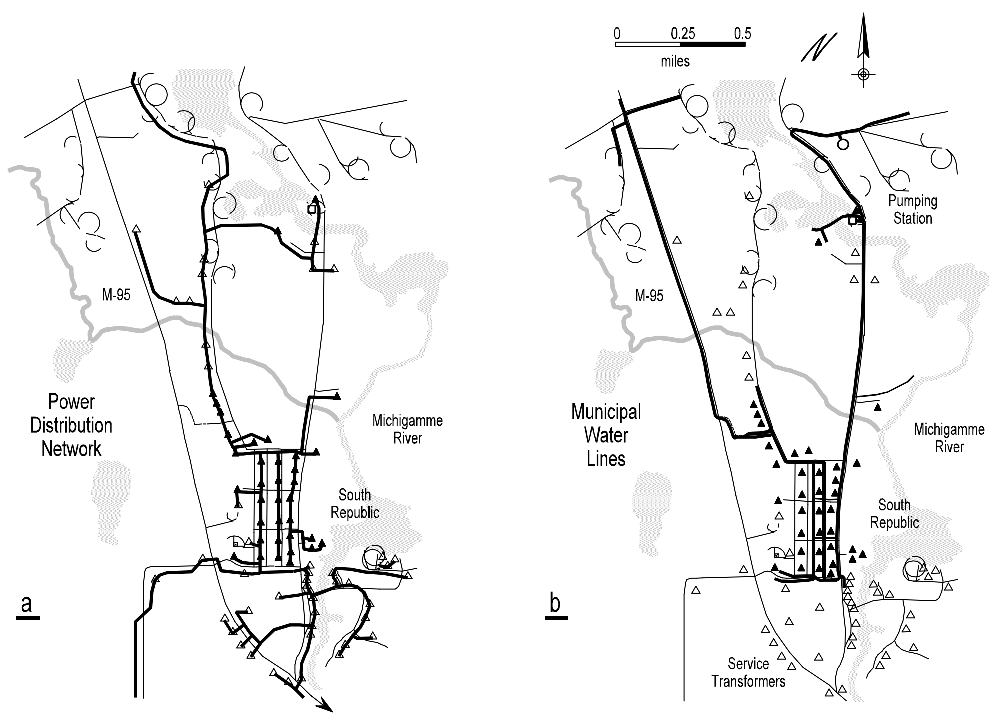

Figure 1. Map of South Republic showing layout of (a) power and (b) water systems.

measured with respect to ground (remote), and the current flowing between the primary and the secondary neutrals at the interneutral tie of each transformer. Magnetic field measurements were made with an EMDEX meter (1) one meter from the transformer pole, (2) one meter from the kilowatt meter of the residence closest to the transformer, (3) midway under the span of the power service drop wires, and (4) above the fire hydrant in the street. (Obviously, this last measurement applies only to urban settings.)

Another variable involved measuring the magnetic fields and other parameters after disconnecting all of the service transformer secondary neutrals from their respective primary neutrals (by removing the interneutral tie at the transformer). In this second pass, the neutral voltage measurements at each transformer became a pair of measurements, one on the primary side and the other on the secondary side. With the interneutral tie removed, the current measurement between these two systems is not applicable, but the impedance measurement between them becomes germane, as does the voltage between them.

Data Analysis

The data were analyzed statistically in a spreadsheet. Figure 2 shows the natural distribution of magnetic field measurements taken under the power service drop wires, divided into rural and urban groups as defined above. The distribution exhibits a characteristic typical of many electrical measurements: that of being not normal (missing a lower tail, and having a long upper tail). Figure 3 shows the same distribution on a log scale; this distribution is an outline that better fits the normal distribution curve. (The tall bar on the lower tail of the rural sample is caused by the bouncing of data around 0.1 mG, which is at the low end of the sensitivity of the EMDEX meter.) Log-normal distribution is used throughout this paper to present data summaries.

This data presentation is further enhanced by displaying the calculated Gaussian curve for the sample distribution instead of the actual sample distribution. This facilitates comparisons and helps to focus on intrasample differences, eliminating the distractions presented by actual sample-distribution features. This is illustrated in Figure 4. The Gaussian curves are calculated using the mean and standard deviations derived from the log-normal distributions. Some of the sharp peaks in the curve shown are the result of discrete linear sampling in a log scale. Figure 4 shows both the log-normal distributions of the data samples and the probability distribution of the sample means.

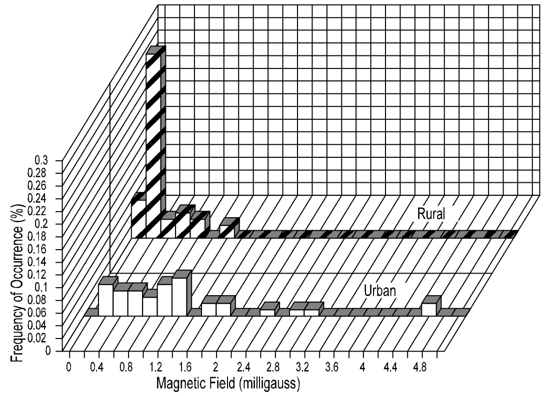

Figure 2. Natural distribution, rural and urban, of magnetic field data under drop wires.

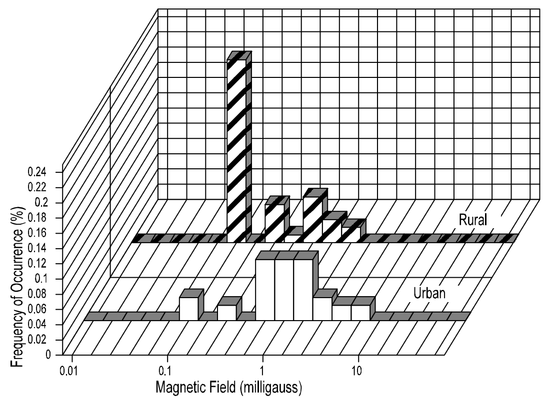

Figure 3. Log-normal distribution, rural and urban, of magnetic field data under drop wires.

Figure 5 presents the probability distribu-tion for the means of all four samples of magnetic field data collected under the power service drop wires. The samples include measurements divided between urban and rural settings, each with and without the interneutral tie at the service transformer. Figures 4 and 5 both show that the means of urban magnetic fields under the drop wires are about three times as large as those of similar fields in rural settings, and that this is a statistically significant difference. Furthermore, these values change very little with the interneutral tie open or closed. The magnetic field tends to drop in an urban setting as the neutral is opened, while it tends to rise in a rural setting. These changes, however, although perceptible, are not statistically significant. The magnetic field mean under power drop wires is 0.74 mG in urban settings and 0.25 mG in rural settings.

Figures 6 and 7 show similar curves of sample group means for two other locations: near a pole with a distribution transformer on top (Figure 6), and near the kilowatt power meter on the side of the house (Figure 7). The patterns among sample groups at these two locations are similar to the pattern just discussed for the data from measurements under the drop wires. Basically there is a statistically significant difference between samples taken in urban settings and those taken in rural settings. The urban sample means near the transformer pole are three times as large as the equivalent rural means. The urban-to-rural ratio for measurements taken near the kilowatt meter is around 5. There is no statistically significant difference whether the interneutral bond is open or closed. However, these small changes could have physical significance, rather than being due to statistical randomness alone. The field means are 1.0 mG-urban and 0.35 mG-rural for the transformer location, and 1.64 mG-urban and 0.33 mG-rural for the kilowatt meter location.

Figure 8 presents the sample mean distributions for the magnetic field over fire hydrants. There is a perceptible but statistically insignificant difference according to whether the interneutral bond is open or closed. It is noteworthy that such a small change is perceptible in the street, far from the transformer pole in the alley; this is an indication that some of the interneutral current is flowing on the municipal water lines. The magnetic field mean at the fire hydrant is 0.75 mG.

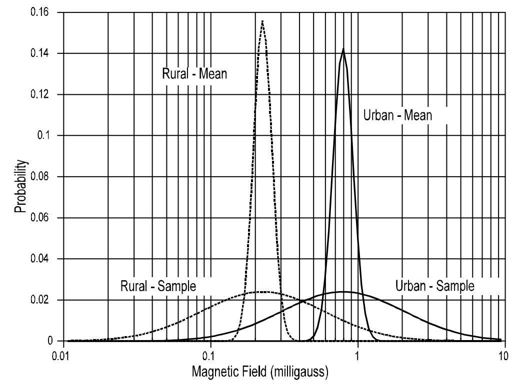

Figure 4. Gaussian distribution, rural and urban, of magnetic field data under drop wires, and probability distribution of data averages by sample group.

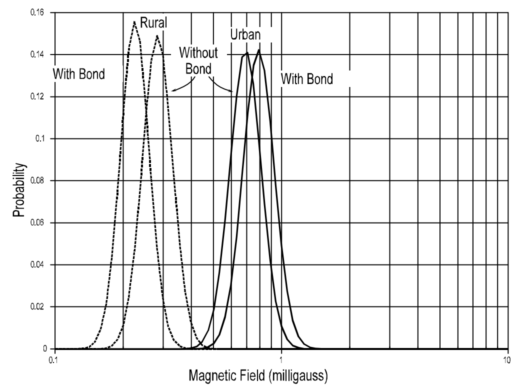

Figure 5. Probability distribution, rural and urban, of means for magnetic field data under drop wires.

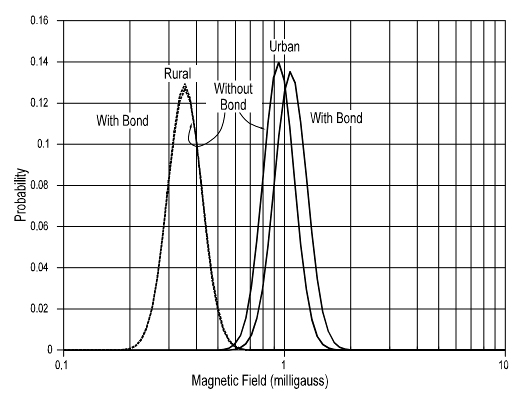

Figure 6. Probability distribution, rural and urban, of means for magnetic field data under pole-top distribution transformer (one meter from pole).

Figure 9 shows the probability distributions of the neutral voltage sample means with the data divided between urban and rural as well as with- and without-tie between the neutrals. There is a clear and unmistakable difference between urban and rural settings. Neutral voltages in urban settings are much less, on average, than corresponding voltages in rural settings. This is intuitively obvious, because neutral voltages are the result of current flowing on neutral wires and grounding electrodes, all of which have a small but finite resistance. This electrical resistance must be smaller in urban environments, where there are a multitude of parallel conductive paths.

Before the neutrals are opened, the neutral voltages form two groups, "Urban-Neutral" and "Rural-Neutral." The urban neutral voltage averages 0.37 V (0.28 to 0.49 V 95%CI), while the rural neutral voltage averages 1.16 V (0.96 to 1.4 V 95%CI). The ratio between the two averages is around 3, the same as has been found for most of the magnetic field measurement samples, but in the opposite direction; i.e., the neutral voltages are lower in urban settings, while the magnetic field measurements are higher.

When the interneutral tie is opened, two separate neutral voltages are then measured, one on the primary side and one on the secondary side of the transformer. With the opening of the interneutral tie, the primary neutral voltage increases and the secondary neutral voltage decreases, in both urban and rural settings. The changes, however, are much more pronounced in rural settings. For rural transformers, the neutral voltage jumps from 1.16 V to 2.6 V on the primary, and drops to 0.22 V on the secondary; there is no statistical ambiguity about these sample changes. For urban transformers the changes are smaller: the neutral voltage jumps from 0.37 V to 0.82 V on the primary and drops to 0.28 V on the secondary. The increase in voltage on the primary neutral when the interneutral tie is opened fits with the interpretation that a current on the primary line neutral is flowing from the primary neutral into the lower-impedance secondary neutral. With the removal of the secondary neutral grounding, the primary line neutral current is forced into the primary line grounding, which has a higher impedance, thus raising the voltage on the primary neutral. The situation is reversed on the secondary neutral: the primary line neutral current flowing into the

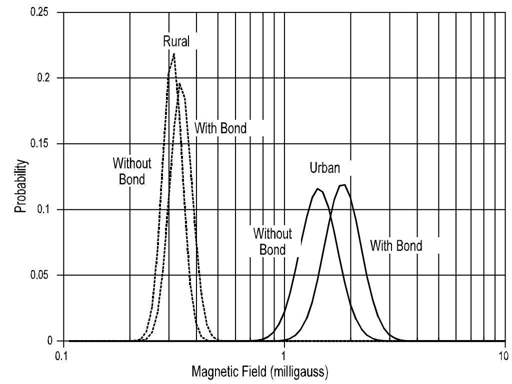

Figure 7. Probability distribution, rural and urban, of means for magnetic field data one meter from kilowatt power meter.

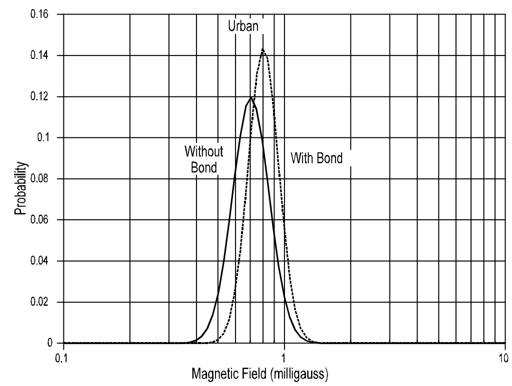

Figure 8. Probability distribution of means for magnetic field data over fire hydrants.

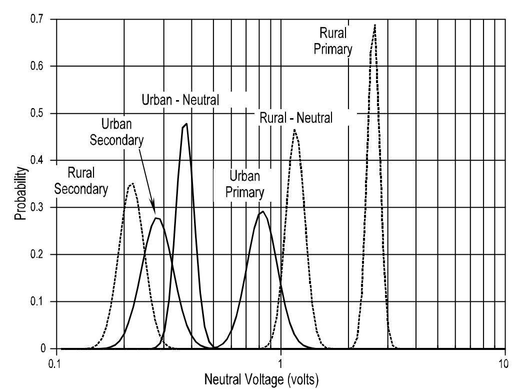

Figure 9. Probability distribution of neutral voltage, rural and urban, at distribution transformer.

secondary neutral, to ground, or to other paths on the water lines, causes an additional voltage to appear on this neutral. This contribution disappears once the current is interrupted by opening the interneutral tie.

The lower voltages on the neutral in urban environments can be deceptive, since the associated interneutral currents are not smaller but larger. The presence of neutral voltages of about 1V on the neutral wire of rural systems relates well with the "stray voltage" problem that has been studied for its effects on farm animal safety and farm production [6].

The voltage drop on the secondary neutral when the interneutral tie is opened in urban settings has a probability value of 98% or more. This is a markedly smaller change compared to changes among all other samples. The cause may be related to the fact that the municipal water lines create many more pathways for interneutral connections, thus lessening the importance of the interneutral tie at the service transformer. This is not to say that the current on the interneutral tie of urban transformers is small; the interneutral current average is higher in urban settings than in rural settings (Figure 10). This current averages 54 mA for urban transformers and 26 mA for rural transformers. The difference between means is significant to a probability factor of more than 99%. Thus, although neutral voltages are smaller for urban transformers, interneutral currents are higher, which correspond to the higher magnetic field measurements in urban settings.

As a note of caution, this is primarily that portion of the distribution line net current that returns to its source via the residential grounding, which was referred to earlier as power line ground current. This current is separate and different from the load net current present on the service transformer secondary main, which is what is generally referred to in the EMF literature as ground current. There is no question that residential load net ground current is drastically affected by the presence or absence of a municipal water system. It is an effect that was definitely present in this survey but was not addressed directly, since the survey focused on the outdoor measurements.

As mentioned earlier, what reconciles these variables is the impedance of the secondary neutral to ground as seen at the transformer interneutral tie. This can be measured directly as the point-to-point impedance between the primary and secondary neutrals, or calculated as the Thevenin impedance from the open voltage and short-circuit current of the interneutral tie. Figure 11 shows the probability distributions of sample data collected in the direct measurement of primary-to-secondary neutral impedance. The average of this impedance is 37.9 Ω (26 to 54 Ω 95%CI) in rural cases and only 4.3 Ω (2.0 to 9.2 Ω 95%CI) in urban cases.

The grounding impedance of the residential main grounding system, as seen from the power line network, is much lower in urban than in rural settings by a factor of almost 10 (4.3 Ω urban and 38 Ω rural). In colder climates, this difference may be exacerbated by the presence of ground frost [7]. In the city, this impedance is lowered by the higher density of grounding electrodes and the water supply network that unites them into a super-grounding grid. This causes both lower voltages and higher currents on urban networks.

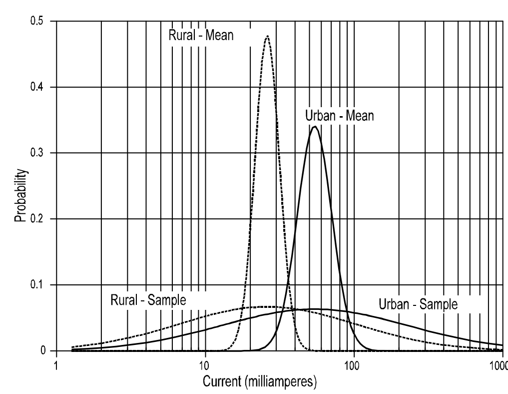

Figure 10. Interneutral current, rural and urban, at distribution transformer.

This impedance, as measured, is formed by the serial addition of two components: the primary line neutral impedance to ground and the secondary neutral impedance to ground (the resistance of the current path through the earth is ignored because it is very small). The primary line neutral impedance to ground is small, typically 2 to 4 Ω. When the primary-to-secondary neutral impedance is much higher than the primary neutral impedance to ground (as is the case in rural situations: primary-to-secondary neutral impedance ≈ 38 Ω), the measurement becomes a good approximation of the secondary impedance to ground. This impedance can also be calculated as mentioned above. Figure 12 shows a scatter diagram for the measured versus the calculated values of this impedance for both urban and rural situations. Above 10 Ω, there is good agreement between measured and calculated values. Below 10 Ω, where the impedance of the primary neutral to ground starts becoming a significant component, the correspondence starts to deteriorate. Indeed, the correspondence becomes less and less significant as the impedance value approaches 1 Ω. There is a drift of the data toward the measured value of 2 Ω, a clear indication of the bias that the primary neutral-to-ground impedance introduces when the secondary impedance to ground is measured in this fashion.

Conclusions

This study indicates that there is a clear and statistically based difference between rural and urban electrical environments outside the residence. The magnetic fields, being a manifestation of the electrical environment, are also found to be different.

In this study, socioeconomic differences were assumed to be negligible. The rural-versus-urban differentiation is a technical one based on the water system. All residences are within a two-square-mile area, and housing is very uniform. The magnetic field measured in this survey just outside the residence is typically less than 1 mG.

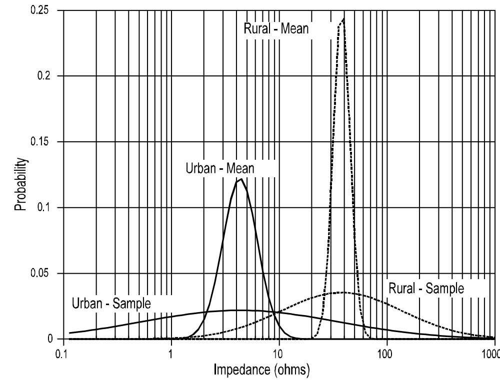

Figure 11. Interneutral impedance, rural and urban.

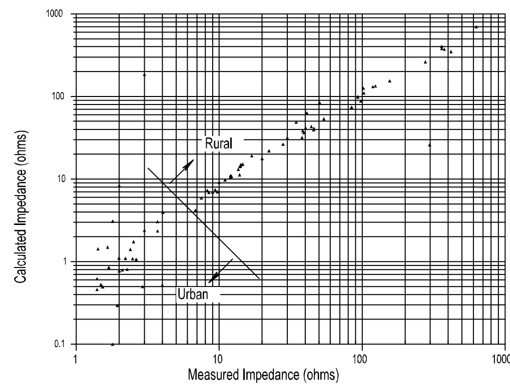

Figure 12. Calculated versus measured interneutral impedance, rural and urban.

This magnetic field is higher in an urban environment (typically by a factor of three) than in comparable rural situations. Nearly equivalent field levels were measured in the city under the service transformer, under the drop wires, and over fire hydrants (away from the power wire). The higher magnetic field levels outside urban residences seem to relate to the presence of a municipal water system, which contributes improved grounding for residences and increased ground-current pathways.

This study has opened new perspectives and will require further analyses to investigate more fully the correlations among the data. There are, however, limitations in this study because of the incidental nature of how the data were assembled. A renewed effort with an expanded scope is needed to address variables and factors not addressed here, such as measurements inside the residence. The findings in this study provide additional insights into the magnetic field question that might be useful in interpreting epidemiological data or in the setting up of epidemiological studies. They also shed more light on the engineering aspect of the problem by delineating more clearly the relationships among the physical plant characteristics and the magnetic field. This additional knowledge may help in providing a more informed viewpoint for any consideration given to magnetic field management.

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