Critical Reviews in Environmental Science and Technology, 27(4):319–382 (1997)

The Effect of Static Magnetic Fields on Biological Systems: Implications for Enhanced Biodegradation

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ABSTRACT: Numerous studies of the effects of magnetic fields on biological and biochemical systems suggest the potential application of static magnetic fields to enhance microbial degradation of environmental pollutants. Potentially favorable changes in intracellular processes have been observed in controlled studies, including changes in enzymatic activities, growth and respiration rates, increased motility and membrane permeability, and morphological and developmental effects. The provocative thought of combining the emerging areas of biomagnetism and biological treatment is also supported by consideration of existing paradigms of chemistry and physics. Indeed, the few studies that have been conducted recently for this specific purpose show that that enhanced contaminant biodegradation by static magnetic fields is a bona fide phenomenon. Nevertheless, the underlying mechanisms responsible for the effects are not fully understood. The purpose of this article is to stimulate fundamental research leading to a better understanding and a more widespread acceptance of magnetically modified biological treatment processes as an additional tool for pollution control. Emphasis is placed on providing a balanced review of pertinent studies, beginning with a perspective on the nature of magnetic fields used in experimental systems. The effect of static magnetic fields on biological systems at the molecular and cellular levels are then addressed, ending with a discussion of theoretical models proposed to explain the observed effects and a perspective on future research.

KEY WORDS: biodegradation, bioenantiamorphism, diamagnetic, enzymes, free radicals, geomagnetic fields, hypomagnetic environments, liquid crystals, magnetism.

GLOSSARY OF TERMS AND SYMBOLS

action potential, the potential difference between the outside and inside of a nerve cell (neuron) when the nerve fiber is active and conducting a nervous impulse; **active transport**, movement of dissolved substances across a cell membrane (by attachment to specific membrane-bound proteins) from a region of low concentration to one of high concentration. The process is driven by ATP energy or by the proton motive force; **adriamycin**, a chemotherapeutic agent; **auxotrophic**, the requirement of a microbial colony for a certain nutrient in order to sustain growth; **bacteriophage**, virus that

1064-3389/97/$.50

attacks bacteria; **bioenantiomer**, a molecule commonly found in biological systems such as bacteria that contains a chiral center and thus has two isomeric forms which are mirror images of each other; **biological rhythymicity**, the natural cycle of a biological process or function that recurs in a set period of time. Example: diurnal or circadian rhythm; **biological superconductivity**, a mechanism that has been theorized to explain the ability for biological systems to detect small variations in the magnetic field of its environment. The body or portions thereof is considered to be a conducting loop with a Josephson junction (a "bridge" with no resistance) so that a small change in the external magnetic field will produce a large relative change in the current flow across the junction. Thus, the system behaves in essence like a superconductor; **circadian rhythm**, having to do with a biological or behavioral process that recurs in an innate daily rhythm, as the 24-h cycle of sleep; **Cooper loop**, the circuit or loop in a Josephson junction traveled by spin-paired electrons (Cooper electron pairs), **diamagnetic**, having a negative magnetic susceptibility. An external magnetic field induces a magnetic dipole (Lenz's law) opposite to the direction of the external magnetic field by altering the atomic electron orbits. The resultant magnetic field inside the body is less than the external magnetic field. Practically all organic and inorganic compounds are diamagnetic except for free radicals and transition metal compounds; **diamagnetic anisotropy,** the induced diamagnetization from an external magnetic field prefers to lie along certain crystal directions (easy directions) that yield a minimum in anisotropy energy. Work is required to turn the diamagnetization vector away from these preferred directions which will increase the anisotropy energy; **dichroism**, the property of a uniaxial crystal having a different color depending on the direction of transmitted light through the crystal; **dielectric**, a material having a relatively low electric conductivity such as an insulator; **dip of the GMF**, the angle between the horizontal plane and the direction of the intensity of the total geomagnetic field vector; **diurnal rhythm**, occurring every day or belonging to the daytime; **excluded volume effect**, the difference between the volume occupied by a lipid and the actual volume occupied by the atoms in the lipid is called the excluded volume. In the gel-phase the lipid has a lower excluded volume than the liquid-crystal phase because of the higher degree of packing and nearest neighbor interactions; **functional dissymmetry**, a term coined by heliobiologists that refers to the dissymmetry of biological rhythms and the dissymmetry of individual responses of biological objects; **gene A**, a gene coding for the red or black color on the wings of the insect *Adalia bipunctata* (ladybug); **Hall effect**, the generation of voltage when a current-carrying conductor is placed in a magnetic field. The electromotive forces developed are at right angles both to the magnetic field and to the current and are porportional to the product of the intensity of the current, the magnetic force and the sine of the angle between the direction of these quantities; **heliobiology**, the study of the effects of solar activity, especially the influence of natural magnetic and electric fields, on the vital activities of living organisms; **Helmholtz coils**, two coils that are separated by a distance equal to their radius and carrying equal currents such that their axial fields add. The resultant magnetic field between the coils is very uniform; **high- and low-affinity region**, enzyme reactions based on Michaelis-Menten kinetics sometimes show two regions of different slope on a Eadie-Hofstee plot (V/[S] vs. V) that arises from either two different binding sites on the enzyme or two different conformations. The region or line that has the steeper slope corresponds to the high-affinity reaction and the other smaller slope is due to the low-affinity reaction; **high-spin state**, a term used in transition metal chemistry to denote that the compound has the maximum number of unpaired electrons consistent with the electronic configuration and stereochemistry. Most commonly used for octahedral complexes where, depending on the crystal field splitting two spin states are possible; **hyperfine interaction**, the interaction between the internal magnetic field produced by the motion of the electron and the spin magnetic dipole moment of the nucleus resulting in further splitting of energy levels; **intersystem crossing**, a mechanism for the electronic transition from one excited state to another such as the transition from the triplet excited state to the singlet state; **Josephson junction**, a junction comprised of two semiconductors connected by a thin layer of conducting or dielectric material. The current in this junction is extremely sensitive to very small changes in the magnetic environment resulting in large increases in the current; **Josephson current**, the conduction of electrons in a Josephson junction

circuit; **liquid crystal**, On heating a number of substances, a cloudy liquid is first formed that changes at higher temperature to a clear liquid, each transition occurring at a fixed temperature. The cloudy liquid has a definite ordered structure and it is called a liquid crystal, or more generally, is said to be in the mesamorphic state. Substances that form liquid crystals are composed of molecules that possess a high degree of asymmetry (e.g., long thin molecules or flat planar ones) that tends to allow little rotation in the liquid state at low temperature. Liquid crystals exhibiting two-dimensional order are said to be in the cholesteric or smetic phases; those showing only one-dimensional order are nematic; Lorentz force,the interaction force between a moving charged particle and a magnetic field, B. The Lorentz force (F_L) is described by the equation:

$$\overline{F}_L = \frac{q}{c}\left(\overline{E} + \overline{v} \times \overline{B}\right)$$

where q is the charge on the particle, E is the local electric field intensity, c is the speed of light, and $\overline{v} \times \overline{B}$ is the vector product of the particle velocity with the magnetic field; **low-spin state**, a term used in transition metal chemistry to denote that the compound has the minimum number of unpaired electrons consistent with the electronic configuration and stereochemistry. Most commonly used for octahedral complexes, where, depending on the crystal field splitting two spin states are possible; **lysogeny**, the integration of genetic material from a virus into the host genetic apparatus; **magnetic domains**, small volumes separated by domain walls in which the magnetization is at the saturation value and can vary in direction between different domains. If an applied external magnetic field is large enough, the direction of the magnetization of all the magnetic domains will align parallel to the direction of the applied field. The magnetic domain exists because below a critical size (on the order of a few to a few hundred nm in diameter) the increase in magnetic energy due to the formation of domain walls is larger than the energy loss obtained by splitting the particle into smaller magnetic domains; **magnetosphere**, a zone of radiation that surrounds the earth and extends outward about 40,000 miles; **magnetotactic**, containing magnetosomes that are intracytoplasmic structures consisting of enveloped Fe_3O_4. In magnetotactic bacteria the magnetosomes are arranged in one or two chains fixed along the axis of motility. Such an arrangement causes the microorganism to exhibit preferential orientation with respect to an external magnetic field such as the geomagnetic field of the Earth; **Maxwell stress**, the additional force (along with the Lorentz force) acting on a moving charged particle of volume (V) through a static magnetic field (B) that also has a spatial gradient. The magnetic force (F_M) due to the field gradient or Maxwell stress is described by the equation:

$$\overline{F}_M = \Delta\chi V\left(\overline{B} \cdot \nabla\right)\overline{B}$$

where $\Delta\chi$ is the magnetic susceptibility difference between the solution or medium and the particle; **meristems**, tissue in plants formed of cells that undergo cell division; **Mu-metal**, metal alloy of very high magnetic permeability that deflects the magnetic field by concentrating it within the metal substance; **paramagnetic**, having a positive magnetic susceptibility. The atoms have permanent magnetic dipoles due largely to the spins of the electrons (especially unpaired electrons) that will line up parallel to an external magnetic field. The alignment of the electron orbits results in an enhanced magnetic field relative to the external field; **potential barrier**, a term in quantum mechanics that is used to model the energy required (the height of the barrier) for the transition of a molecule from one energetic state or configuration to another state or stable configuration. It can also be used to represent the energy barrier between two equilibrium positions for an H atom covalently bonded to one atom and hydrogen bonded to another; **potential well**, a potential function curve having a U-shape that is commonly used in quantum mechanics to model oscillators or the relation between energy and interatomic distance of a diatomic system. The distance or length corresponding to the bottom of the "well" is the most energetically stable configuration; **R transmission frequency**, the frequency at which purine is transferred in the genes from parent to offspring; **resting potential**, the potential

difference between the outside and inside of a nerve cell (neuron) when the nerve fiber is inactive and in the resting state; **saw-tooth pulse**, the electronic signal controlling a process or producing a magnetic field is ramped linearly (slopes can vary); **Zeeman separation**, the separation of energy states (normally degenerate) corresponding to discrete orientations of an electron orbital in the presence of an external magnetic field. The possible configurations that the angular momentum dipole moment (produced by the motion and spin of the electron) can have in a magnetic environment depend on the quantum numbers of the orbital.

SYMBOLS

G, gauss, a unit of magnetic induction defined as one magnetic line per square centimeter; TN_{max}, maximum turnover number (sec^{-1}). A measure of the rate of enzyme consumption based on Michealis-Menton kinetics that is analogous to the highest growth rate achieved by a culture, dependent on limiting substrate or nutrient concentration; ε, dielectric constant, a measure of the amount of electrical charge a given substance can withstand at a given electric field strength; Q_{10}, temperature coefficient, the ratio by which the rate of an enzyme reaction increases for a rise in temperature of 10°C; B, magnetic induction, which is commonly used to denote the magnetic field intensity (H). As $B = \mu H$, and the magnetic permeability (μ) is ≈ 1 for paramagnetic and diamagnetic materials, then $B \approx H$; kT, the product of Boltzmann's constant ($k = 1.381 \times 10^{-23}$ Joules/Kelvin) and temperature (T), which results in an energy term that is commonly called thermal energy.

I. INTRODUCTION

The effects of magnetic fields on biological systems have received considerable experimental and theoretical attention. An association between magnetic fields and biochemistry dates back to the last century when Louis Pasteur theorized that the geomagnetic field caused microbially produced tartaric acid to be of one optical isomer in nature, whereas chemical synthesis produced a racemic mixture (Duclaux, 1920). Concern over a potential connection between cancer and low-frequency magnetic fields stimulated the publication of more than 1000 related journal articles during the last 35 years (Oak Ridge Associated Universities, 1993). Although these articles do not present sufficient evidence to demonstrate that magnetic fields are carcinogenic, numerous studies reported diverse biological effects on various forms of life. Some of these studies report effects that could have beneficial applications in environmental engineering. For example, observations of increased biological activity suggest the potential application of magnetic fields to enhance microbial degradation of environmental pollutants.

The thought of combining the emerging research areas of biomagnetism and biological treatment is provocative. Indeed, recent work with an activated sludge mixed culture showed that a magnetic fields could enhance the rate of phenol biodegradation by 30% (Jung et al., 1993), and a patent exists to use magnetic fields to enhance bioremediation of hydrocarbon contaminated soil (Rawls and Provell, 1994). Nevertheless, a survey of the literature reveals numerous examples of apparently

conflicting observations on the effects of magnetic fields on biological systems. A need exists for a critical review of pertinent experiments and proposed mechanisms to evaluate the potential application of magnetic fields to enhance engineered biological processes.

The purpose of this article is to stimulate fundamental research leading to a better understanding and a more widespread acceptance of magnetically modified biological treatment processes as an additional tool for pollution control. Emphasis is placed on providing a balanced review of potentially pertinent studies. There are numerous uncontrolled studies of dubious credibility, and their consideration represents a major challenge in reviewing the large body of literature on the effect of magnetic fields on biological systems. Although blatant pseudo-science was ignored in this review, some attention was given to phenomenological and epidemiological observations lacking a clear etiology.

This review article begins by providing a perspective on the nature of magnetic fields used in experimental systems, including magnetically modified biological treatment processes. The effect of static magnetic fields on biological systems at the molecular and cellular levels is then addressed, followed by a discussion of experiments with non-uniform and intermittent magnetic fields, and environments shielded from the Earth's magnetic field. Selected theoretical models proposed to explain observed biological effects are subsequently outlined and a perspective on future research is outlined. A glossary of pertinent technical and scientific terms is also provided at the beginning of the article.

II. MAGNETIC FIELDS AND EXPERIMENTAL SYSTEMS

Magnetic fields used in experimental systems are commonly generated by electric currents in conductors or by permanent magnets. These fields are vector quantities having a magnitude known as the field strength (H). The strength characterizes the force with which the field acts on a moving charge. The common unit for H is the oersted (Oe), which is defined as one line of force per square centimeter. Although magnetic lines of force are not real, this concept is useful for understanding the properties of magnetic fields. The interaction of a magnetic field with the surrounding medium is the magnetic induction (B), which is related to the field strength by the magnetic permeability (μ) of the medium:

$$B = \mu H$$

In a vacuum (and for all practical purposes air), where $\mu = 1$, the magnetic induction measured in gauss (G) is numerically equal to the field strength measured in oersteds. The field strength can vary from one point to another. This variation is described by a second vector called the gradient of the field (∇H) with units of Oe/cm or G/cm.

There are several types of magnetic fields. Static magnetic fields have a constant strength over time and can be produced by permanent magnets or DC electromagnets. Oscillating or time-varying magnetic fields are produced by AC electromagnets, and their strength varies in a periodic fashion depending on the frequency and waveform type of the magnet. These pulsed magnetic fields are electromagnetic in nature with an associated electric field component that can induce electric currents in stationary biological systems. Homogeneous fields have a relatively constant strength over the space where samples are exposed and are typically produced by flat pole caps or Helmholtz coils. Heterogeneous fields have field gradients that depend on the design of the pole caps or nature of the magnet (e.g., horseshoe permanent magnets or solenoids).

Permanent magnets are recommended for long-term experiments because of the stability of the magnetic field. With negligible operating cost, they do not require auxiliary equipment or thermal regulation of the pole caps. For the study of small samples, strong homogeneous fields up to 20,000 G can be achieved between flat pole caps if the gap is small compared with the face diameter of the pole. If the gap between flat pole caps is equal or greater than the pole diameter, the magnetic field can decrease by as much as 20% from the center to the edge of the pole face. One disadvantage of permanent magnets is that their field strength can only be changed by adjusting the gap between the poles. In addition, the field direction cannot be reversed to study the effect of polarity, or reduced to zero, which makes changing pole caps a problem in large magnets.

As an alternative to permanent magnets, electromagnets can be used. An electromagnet is a pair of Helmholtz coils that are coaxial with either an air or iron core. If the coils are separated by a distance equal to the radius of the coils, then a small region around the axis will be very homogeneous. Homogeneity can be further improved by using ring-shim pole caps or correcting coils. An important advantage in using electromagnets or solenoids is that the field strength can be easily adjusted by controlling the amount of current delivered to the coils in the magnet. The magnetic field can also be easily reversed by changing the direction of current and reduced to zero, which facilitates changing of the pole caps. One disadvantage of large electromagnets is their high current consumption, which requires high power supplies and cooling systems to reduce the heat generated by the magnet coils. This could complicate experiments involving long-term exposure. The temperature in a magnet cooled by tap water can increase by up to 20°C during the course of a day. Special water-cooled copper or aluminum discs may be placed against the pole faces to isolate the sample from temperature variation. Present day electromagnets or solenoids and power supplies incorporate over-temperature sensing devices and feedback protective circuits to guard the equipment against possible cooling-water failure.

With respect to relative strength, weak magnetic fields are typically on the order of ten's of gauss, such as those commonly produced by household appliances (Table 1). Strong magnetic fields are in the range of thousands of gauss and higher.

TABLE 1
Localized 60-Hz Magnetic Field Intensities (Gauss) Produced by Some Electrical Appliances

Refrigerator	0.001–0.01
Electric iron	0.01–0.1
Calculator	0.01–0.1
Dishwasher	0.01–0.1
Electric toaster	0.1–1.0
Vacuum cleaner	0.1–1.0
Clothes dryer	0.1–1.0
Garbage disposal	0.1–1.0
Color TV	1–5
Food Mixer or Blender	1–5
Electric shaver	5–10
Kitchen stove	5–10
Can opener	5–10
Hair dryer	10–25

From Miller (1974) and Hartell et al. (1972).

Table 2 gives examples of several types of magnets along with the field strengths that can be achieved. Stable magnetic fields between 50 and 100 kG are best produced in superconducting solenoids, which can also be set up in a Helmholtz arrangement for homogeneity. Disadvantages of these systems include the expense of the liquid helium required to cool the magnet coils, insulation of the biological sample, and limitations to the maximum field achievable because superconductivity ceases in strong magnetic fields. High gradient fields cannot be produced by superconducting magnets as well. Fields of 200 to 500 kG can be produced by small solenoids in pulsed operation for the duration of a few milliseconds.

Magnetic field gradients can be produced by specially designed pole caps or combinations thereof. Early experiments used horseshoe shaped magnets to provide a gradient field (Kimball, 1938). A conically tapered pole cap opposed by a tapered pole cap with a flat or slightly concave face of small diameter can produce field gradients of several thousand G/cm over small samples. Very high field gradients ($> 10^6$ G/cm) can be produced near the tips of gold-plated iron needles combined with flat Sm-Co permanent magnets (Sato et al., 1992).

There are several devices available for the measurement of magnetic fields. The nuclear magnetic resonance (NMR) fluxmeter has the highest accuracy with a working range of 1 to 50 kG, providing the field uniformity over the probe volume is less than 1 G. The Hall-effect gaussmeter is the most widely used instrument that is economical yet accurate with a wide measuring range. The very small volume

Table 2
Types and Field Ranges of Different Magnets

Magnet	Upper operating range (kG)	Practical application range (kG)
Permanent magnet	20	0–8
Electromagnet	40	0–30
Supercooled solenoid	100	25–60
Superconducting solenoid	140	30–100
Water-cooled solenoid (intermittent operation)	250	75–150
Liquid-helium-cooled solenoid (pulsed operation)	750	0–400

From Abler (1969).

of the sensing element makes it ideal for field mapping over small biological samples.

III. MAGNETICALLY MODIFIED BIOLOGICAL TREATMENT PROCESSES

The concept of enhancing microbial degradation of environmental pollutants with magnetic fields is new, and has been practiced only at the bench and pilot scales. The few studies that have been recently conducted for this specific purpose show that enhanced contaminant biodegradation by static magnetic fields is a bona fide phenomenon. This has encouraged the USEPA to consider magnetically modified biological treatment process as an additional tool for pollution control at Superfund sites.

Figure 1 describes a pilot-scale set up used by Jung et al. (1993) to investigate the effect of a static magnetic field on phenol biodegradation. This system consisted of a 11.4 × 20 cm cylindrical bioreactor containing beads of immobilized activated sludge. A solution of 28% activated sludge (taken from a sewage treatment plant), 0.5% NaCl, and 1% sodium alginate was added dropwise to a 0.01 mmolar solution of $CaCl_2$ to form beads of immobilized biomass. This was constantly recirculated through the bioreactor, and the dissolved oxygen concentration was monitored. The permanent magnet consisted of 5 × 15 × 1 cm plates, with the field strength dependent on the number of plates stacked. The application of a 4500 G field from the south pole increased the rate of phenol degradation by 30% and the oxygen utilization rate by a factor of 2.5 compared with no-field controls. A significant increase in extracellular protein was also observed. When the polarity was reversed, however,

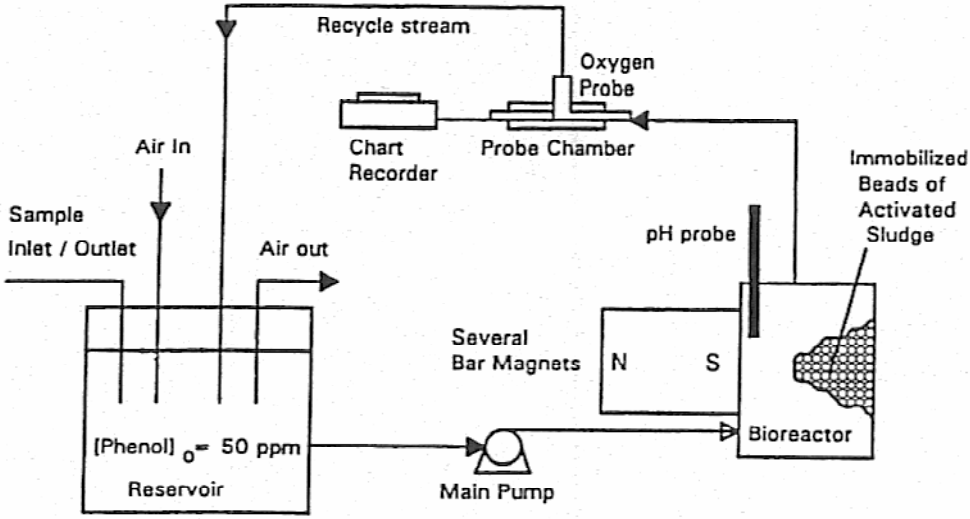

FIGURE 1. Experimental system used to study the effect of a static masgnetic field on phenol biodegradation. (Adapted from Jung et al., 1993.)

the north pole reduced the rate of phenol degradation by 85% and the oxygen utilization rate by about 50%. No explanations were offered for these observations.

In a separate study, Oh and Strom (1995) reported that a 25000 G field from the south pole significantly ($p < 0.05$) enhanced phenol degradation by non-acclimated activated sludge in liquid culture. Higher field strengths (e.g., 45000 G), however, degraded phenol slower than control untreated cultures. Apparently, the range of field strength that results in enhanced biodegradation might be narrow. This suggests that overdosing microorganisms with high field strengths could have detrimental effects and should be a concern in the design of magnetically modified biological treatment processes.

As an example of a magnetically enhanced bioremediation system, Figure 2 describes a patented integrated above-ground and *in situ* approach to treat contaminated sites (Rawls and Provell, 1994). The above ground system treats contaminated groundwater in a similar manner to that described in Figure 1, where the principal component is a biofilm reactor subjected to a static magnetic field from the south pole. This field is supplied by an electromagnet, and it is important that the pumps and dissolved oxygen probes be located away from the effects of the magnet to preclude interference. The treated groundwater is recirculated through the contaminated vadose zone using an infiltration gallery. Percolation of the treated effluent provides moisture, inorganic nutrients, and sloughed active microorganisms to the contaminated soil, which stimulates biodegradation. A magnetic blanket, consisting of 9 in wide, 1/4 in thick strips of pliable magnetic material is laid over at least

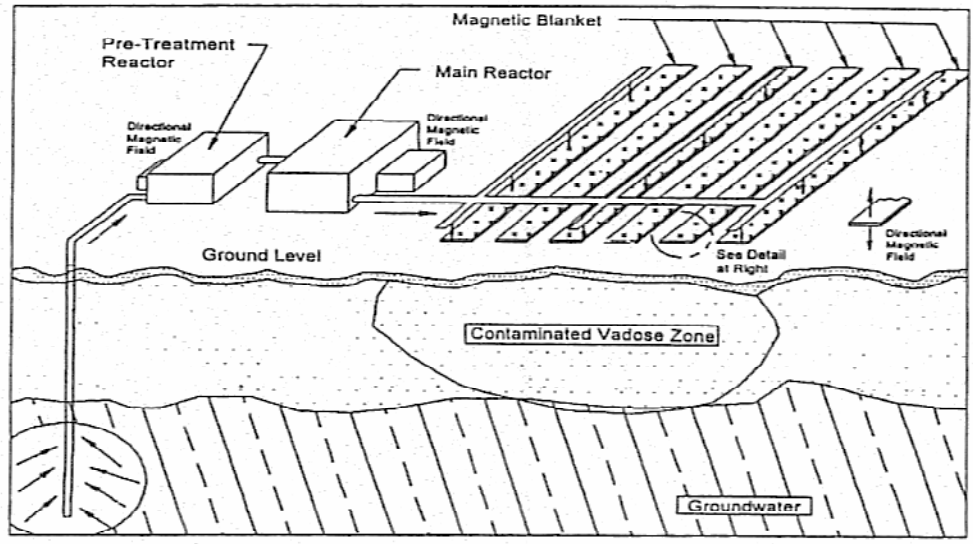

FIGURE 2. Schematic diagram of patented integraded approach for utilization of magnetic fields to enhance bioremediation. (Adapted from Rawls and Provell, 1994.)

a portion of the contaminated soil, thus subjecting it to a south pole magnetic field for enhanced bioremediation.

IV. STATIC MAGNETIC FIELDS AND ENZYMES

Experiments with constant magnetic fields (CMF) on enzyme activity *in vitro* have resulted in a variety of effects (Table 3), suggesting that no clear generalizations exist. For example, numerous studies showed no effect on enzyme activity (e.g., Nazarova et al., 1982; Rabinovitch et al., 1967a; Vadja, 1980). Yet, experiments with the protease enzyme trypsin have also shown both an increase (Cook and Smith, 1964; Smith, 1967) and a decrease in enzyme activity (Karavaev et al., 1974; Smith, 1967). Cook and Smith (1964) observed that an increase in trypsin activity depended on the duration of magnetic exposure, and offered an explanation based on conformational changes in the enzyme resulting from increases in helicity of the polypeptide backbone and in hydrogen bonding. The magnetic studies on the trypsin system also showed a pH dependency (Smith, 1967) and suggest that magnetic experiments with enzyme systems *in vitro* are very sensitive to variables such as temperature, concentration, stirring speed, pH, buffer composition, and ionic strength for example. A correlation between exposure time and percent enzyme reactivation was observed in an experiment where trypsin had been initially

TABLE 3
Summary of Selected *In Vitro* Experiments with Enzyme Systems in Static Magnetic Fields

Enzyme	Temperature and pH	Magnetic Field Strength (Gauss)	Duration of Exposure	Effect of Exposure on Enzyme Activity	Ref.
Acetylcholinesterase	N.R.[a]	17,000	N.R.	Increase	236
Acid phosphatase	N.R.	5000–5700	N.R.	None	40
Alcohol dehydrogenase	25°C pH = 8.8	14,000 4000 G/cm gradient	40 min	None	149
Aldolase-fructose 1,6-diphosphate	T ~ 25°C pH = 7.5	170,000	2 and 10 min	None	178
Alkaline phosphatase	N.R.	5000–5700	N.R.	None	40
Ascorbic acid oxidase	T = 30°C pH = N.R.	11,000	5, 30, 35 min	Increase at low substrate conc., decrease at high substrate conc.	76
Asparaginase		17,000		Increase	195
β-galactosidase	26°C pH = 7.0	10,000	40 min	None	209
Carboxydismutase	4°C pH = 8.0	20,000 (pretreatment)	2 h to 8 d	14–20% increase	6
Catalase	21.8–22.0°C pH = N.R.	60,000	15 min	5–48% increase	88
Catalase	pH = 7, 30°C	8000	1 min	20% Increase	221
Catalase	pH = 8, 25–27°C	15,000	40–50 min	None	89
Catalase	T = N.R. pH = 7.0	Up to 10,000	1 min	None	212

TABLE 3 (continued)
Summary of Selected *In Vitro* Experiments with Enzyme Systems in Static Magnetic Fields

Enzyme	Temperature and pH	Magnetic Field Strength (Gauss)	Duration of Exposure	Effect of Exposure on Enzyme Activity	Ref.
Cytochrome-c oxidase	0–5°C pH = 7.4	700–13,000	1 h	Increase	82
Cytochrome-c oxidase (high affinity range)	25°C pH = 7.4	3 1000	3 h	35% increase 90% increase	155
Cytochrome-c oxidase (low affinity range)	25°C pH = 7.4	0.5–10,000 800	3 h 1.5 h	None None	155
DNAase	25°C pH = N.R.	1200 3200	1.5 h 1.5 h	16% increase 30% increase	117
Ethanolamine ammonia lyase	25°C pH = 7.48	0–2500	N.R.	Decrease followed by increase	93
L-Glutamic dehyrogenase	21.7–25.9°C pH = 8.0	50,000–70,000	17 to 40 min	5–12% Decrease	88
Histidase		17,000		Decrease	195
Lactic dehydrogenase	25°C pH = N.R.	14,000 4000 G/cm gradient	40 min	None	147
Peroxidase	25°C pH = 5.8	85,000 170,000	10 min 3, 10, 20 min	None	178
RNAase	37°C pH = 5.0	100,000 150,000	4, 7, 10 min 6 min	None	178
RNAase	24°C pH = 7.6	0–48,000	5 min	None	130

TABLE 3 (continued)
Summary of Selected *In Vitro* Experiments with Enzyme Systems in Static Magnetic Fields

Enzyme	Temperature and pH	Magnetic Field Strength (Gauss)	Duration of Exposure	Effect of Exposure on Enzyme Activity	Ref.
RNAase	25°C pH = 5.0	14,000 4000 G/cm gradient	40 min	None	147
RNAase	25°C pH = N.R.	3200	1.5 hr	None	117
Succinate-cytochrome c reductase	24°C pH = 7.0	0–48,000	6 min	None	130
Thymidine kinase	27–39.5°C Physiologic pH	2000-14,000	30 min	None	62
Transaminase	N.R.	5000–5700	N.R.	None	40
Trypsin	23, 32, 36°C pH = 8.2	8000 220 G/cm gradient	1–3 h	11% (average), 23% highest increase	42
Trypsin	T = N.R. pH = 3.0 T = N.R. pH = 8.0	13,000	4 h	12% (average), 24% highest increase 7.5% (average), 9% highest decrease	200
Trypsin-BAPA	T = 36°C T = 26 and 36°C pH = 3	220,000 208,000 (pretreatment)	9 min 65–220 min	None None	178

TABLE 3 (continued)
Summary of Selected *In Vitro* Experiments with Enzyme Systems in Static Magnetic Fields

Enzyme	Temperature and pH	Magnetic Field Strength (Gauss)	Duration of Exposure	Effect of Exposure on Enzyme Activity	Ref.
Trypsin	pH = 75, 30°C	100,000	2.5 h	None	148
Trypsin	pH = 3.3, 5.3, 7.2 36.5°C	14,000	2–7 h	None	220
Trypsin	19, 21.5, and 35.5°C	8000–9000	1.5–2 h	Decrease	107
Tyrosinase-L-tyrosine	25°C pH = 6.5	170,000	3 and 7 min	None	179
Xanthine oxidase	T = N.R. pH = 8.0	Up to 10,000	3 min	None	212

Adapted from Tenforde, 1983.

[a] Not reported.

inactivated by egg-white inhibitor (Wiley et al., 1964). In a separate experiment, however, a magnetic field had no effect on trypsin inactivated by UV radiation (similar to carboxydisutase), soy bean inhibitor, or diisopropylphosphoro-fluoridate (Akoyungolou, 1964).

Failure to demonstrate changes in enzyme activity may be largely due to subtle variations in conditions of the biological systems and insufficient magnetic exposure of the material. Lack of consistent *in vitro* results are apparently due to differences in experimental conditions, including exposure intensity and duration, temperature, and pH. For example, if the activation energy for enzyme denaturation is considered (40 to 100 kcal/mol [Putnam, 1953]), a 1°C difference in temperature between a magnetically treated sample and a no-treatment control could result in a difference in enzyme activity of up to 20% (Rabinovitch et al., 1967a). One possible reason why the *in vitro* activity of trypsin did not change after exposure to high magnetic fields (e.g., Rabinovitch et al., 1967b; Vadja, 1980) is that these experiments may have been carried out in a temperature range where the temperature coefficient (Q_{10}) of the enzyme reaction was relatively low.

Nossol et al. (1993) studied the effect of magnetic fields on the redox activity of cytochrome-c oxidase, an important member of the electron transport chain in mitochondria that was isolated from beef heart. They reported the existence of "windows" or distinct ranges of field strength (Figure 3) in which the applied magnetic field produced significant increases in the maximum turnover number (TN_{max}) determined from Michaelis-Menten kinetics. The TN value is a measure of the rate of enzymatic activity and is analogous to the specific growth rate of microbial growth. A TN_{max} increase of 35% at 3 G and 90% at 100 G was observed for the high-affinity region of the redox reaction involving cytochrome-c oxidase. It is interesting that a very weak field of a few gauss, such as that produced by common household appliances (Table 1), could influence enzyme activity to such a degree.

Exposure of β-fructofuranosidase *in vivo* to a CMF as high as 200 G produced an inhibitory response (Miskiewicz and Ziobrowski, 1977). A 19% reduction in the activity was measured following isolation from suspensions of *Saccharomyces cerevisiae* (bakers yeast) that had received prior magnetic exposure. The various travel times of the yeast suspensions through the CMF (0.0025 to 2.5 m/s) had no effect on the enzyme activity. Meanwhile, a magnetic field of 600 to 800 G caused a significant increase in the dielectric constant (ε) of lysozyme, a hydrolyzing enzyme (Ahmed et al., 1975). This was attributed to the establishment of a superconducting region in each molecule and a clustering of these regions in the field. In a separate study, no change in the chromatographic migration rate of hemoglobin, cytochrome-c, and catalase enzymes was observed in a 1220 G magnetic field (Montgomery and Smith, 1963).

Exposure of a protein solution (bull serum albumins) to a 5200 G field altered the protein conformations and mobilities, resulting in a higher degree of protein association (Aristarkhov et al., 1977). An increase in rotary transitions was reported by Marlborough et. al. (1969) for the spinach ferrodoxin protein when

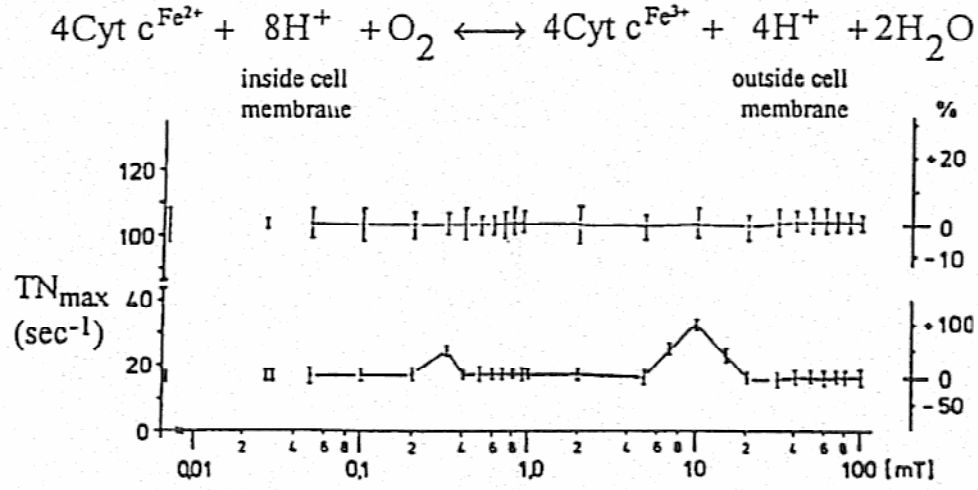

FIGURE 3. Influence of a static magnetic field (0.5 to 1000 G) on the high-affinity (II) and low-affinity (I) reactions of cytochrome-c oxidase. Increases in the activity for the high-affinity reaction are clearly evident at 3 and 100 G exposure. (Adapted from Nossol et al., 1993.)

exposed to a 3000 G field. A solution of DNA molecules in a CMF of 6500 G resulted in the orientation of the rigid segments of the molecule so that the long axis was perpendicular to the magnetic field lines (Mekshenkov, 1965).

The above phenomenological studies indicate that static magnetic fields can, in some instances, have a beneficial or an adverse effect on enzyme activity. While a clear etiology has not been established, some mechanisms have been proposed to explain changes in enzyme conformation and activity. These mechanisms are discussed in Section VI.

V. STATIC MAGNETIC FIELDS AND MICROORGANISMS

A. Homogeneous Fields

Selected experiments on homogeneous magnetic fields applied to microorganisms are listed in Table 4. A variety of macroscopic phenomena have been used to characterize the effects of magnetic fields. These include changes in growth, respiration, motility, and enzyme production rates.

The locomotion of several protozoa can be influenced by even very weak magnetic fields of the same magnitude as the Earth's geomagnetic field (about 0.5 G) (Brown, 1962). Nevertheless, the influence of magnetic forces on locomotion might not be significant for smaller microorganisms, just as the influence of gravitational

TABLE 4
Selected Experiments of Static Homogeneous Magnetic Fields on Microorganisms

Species	Specific parameter measured	Magnetic field intensity (Gauss)	Duration of exposure	Effects observed	Ref.
Bacteria, yeast and mold	Growth rate	3000	48 h 25°C	No effect on the colony size, staining reaction, pigment production and spore formation	103
Streptococcus mutans ATCC-25175 and 27607	Exopolysaccharide accumulation on glass surface	GMF	24 h 34°C	50–60% more exopolysaccharide that were produced by bacteria were found to adhere to glass surfaces facing N compared with glass surfaces facing S; reversal of field by 180° produced similar reversal in direction of preferred accumulation	3,4
Sarcina lutea	Growth rate	14,000	24 h 37°C	No differences in the growth rate with respect to the controls	95
Staphylococcus aureus	Growth rate	14,000	24 h 37°C	Inhibition of growth after the 16 hrs. No effect observed when exposure was interrupted hourly for 3 s	95
Staphylococcus aureus SA 812	Dehydrogenase activity following infection	1400 (pre-treatment of phage 812)	Long-term	Enzyme activity of host cells increases compared to noninfected controls	149
Staphylococcus aureus SA 812	Bacteriophage production	400–1900	Normal cultivation times	Production of bacteriophage 812 is dependent on field strength and exposure times of host cells prior to infection	99
Staphylococcus aureus SA 812	Burst size	400–1900	Normal cultivation times	Burst size of host cells dependent on field strength during cultivation prior to phage infection	96
Streptomycete Frankia sp.	Growth and nitrogen fixation	100–2000	10–13 days 28–29°C	Inhibition of growth and nitrogen fixing activity	237

TABLE 4 (continued)
Selected Experiments of Static Homogeneous Magnetic Fields on Microorganisms

Species	Specific parameter measured	Magnetic field intensity (Gauss)	Duration of exposure	Effects observed	Ref.
Escherichia coli	Gas production and growth rate	14,000	48 h 37°C	Slight difference in hydrogen gas production and slight stimulation in growth	95
Escherichia coli	Growth rate	3000		Magnetic field had no effect on the growth rate	168
Escherichia coli AB1157	Viability and mutation effects	10,000	1 or 5 h 27–30°C	No effect on viability (1 h, 30°C); no lethal or mutation effects	207
Escherichia coli	Biochemical changes	150	>48 h	Biochemical changes noticed 48 h after exposure initiated	119
Escherichia coli B	Viability and in magnetically pretreated medium	2900	1-24 h 37°C	Exposure did not influence growth kinetics; enhanced growth observed in magnetically pretreated (18–48 h) medium; prior exposure of bacteria for 24 and 48 h increased and that for 72 h decreased their radiosensitivity	162
Escherichia coli	Growth rate	117,000		Auxotrophic mutants of *E. coli* grown under the magnetic field did not show any mutagenic or lethal effects; magnetic field stimulated the growth of the bacteria in a complex media and inhibited the growth in a synthetic media	159
Escherichia coli	Growth rate	117,000		Growth inhibited in synthetic media; addition of various amino acids accelerated reduced growth rate; lower T showed an increase in growth rate independent of media	160

TABLE 4 (continued)
Selected Experiments of Static Homogeneous Magnetic Fields on Microorganisms

Species	Specific parameter measured	Magnetic field intensity (Gauss)	Duration of exposure	Effects observed	Ref.
Pseudomonas aeruginosa and *Candida albicans*	Growth rate	150 and 300	6.4–6.5 h 37°C	Magnetic field produced 38% stimulation in growth of *P. aeruginosa* for 150 G, 5% inhibition in growth for 300 G; magnetic field produced 22% reduct-ion of growth of C. albicans for 150 G, 73% reduction of growth for 300 G	145
Achromobacter delicatulus	Acid production and peroxide metabolites	50–150		Removal of manganese from ores by bacteria increased by 1.4 to 2.8 times	237
Salmonella	Forward mutation assay	100,000	4 h	No toxic or mutagenic effects	199
Salmonella TA98	Potency of mutagenic agents during exposure	1500 –117,500	10 min	Mutagenicity of nitroacenapthene was enhanced and mutagenicity of AF2 was suppressed in a manner dependent on field strength; no genctoxic affects from B field exposure alone	193
Micrococcus denitrificans	Growth rate	8000	5–6 h 28–32°C	Growth rate same as control for first 2–3 h then enhanced with a 5.8–13.3% increase in oxygen consumption after 5–6 h	207
Saccharomyces 211 and S 2094 C1	Effect on survival to UV irradiation	73,000	2.5–16 h 30°C	Increased survival to UV light for cultures grown in a magnetic field prior to irradiation; application of magnetic field after irradiation decreased survival	191
Saccharomyces cerevisae	Growth rate	4600	24–72 h 28 and 38°C	Magnetic field inhibits growth; reduction in cell population observed	226
Saccharomyces cerevisae	Growth and genetic effects	14,900	15 h 30°C	No statistical difference from controls. No adverse genetic effects	131

TABLE 4 (continued)
Selected Experiments of Static Homogeneous Magnetic Fields on Microorganisms

Species	Specific parameter measured	Magnetic field intensity (Gauss)	Duration of exposure	Effects observed	Ref.
Saccharomyces cerevisae ATCC-4134	Growth, glucose consumption, and H^+ delivery	300–600	8 h 28°C	No significant changes was observed compared with the control	66
Saccharomyces cerevisae	Glycolysis	< 4 G > 4 G	20–30 m 29°C	Glycolysis retarded for low magnetic fields (< 4 G) and accelerated for fields greater > 4 G; response dependent on intensity and orientation with respect to GMF	109
Saccharomyces cerevisae	Respiration	7300	1–4 h 37°C	Increased respiration	181
Saccharomyces cerevisae	Growth	5000	Several hours, 28–32°C	Yeast grown under nearly anaerobic conditions; inhibition of growth rate at beginning, then accelerated passing the control	207
Saccharomyces cerevisiae race 14	Enzyme activity, gas production and other physical properties	378–504	Brief (< 1 min) 30–32°C	Saturation of the yeast suspension with O_2 (16 to 20 mg/l) and passing it through magnetic field (1 to 3 m/min) resulted in increases of yeast rising force, gas formation, 1.5- to 2-fold fermentation rate, 3.7-fold maltase activity and 3-fold dough viscosity	137
Saccharomyces elllipsoides	Growth	1000–12,000	N.R.	No observable response for samples compared with controls	144
Claviceps purpurea	Growth, germination of spores (conidia)	11,000–14,000	N.R.	Possible slight influence of magnetic field on germination and growth direction of germ tubes	144

TABLE 4 (continued)
Selected Experiments of Static Homogeneous Magnetic Fields on Microorganisms

Species	Specific parameter measured	Magnetic field intensity (Gauss)	Duration of exposure	Effects observed	Ref.
Clara multicornis	Growth rate and colony size after magnetic field pretreatment	100, 200, and 400	2 h, T ramped from 0 to 18.5°C	Reproduction starts within 6–7 d for 100 G pretreatment, 7–8 d for 200 G, and >12 d for 400 G (same as control); zooids noted 3–6 d after start, and in the order: 100 G > 200 G > 400 G ~ control	108
Euglena algae	Growth	1000		Inhibition of growth	90
Euglena gracilis	Fluorescence and transmittance of cell suspensions	Up to 100,000	N.R.	Preferential polarization of fluorescence in plane perpendicular to magnetic field; dichroism and anisotropic wavelength-dependent light scattering effects induced by the magnetic field; no saturation observed at limits of field strength	70
Chlorella algae	Growth	1000		Inhibition of growth	90
Chlorella algae	Growth and CO_2 fixation	12,000	N.R.	No consistent differences in rate of CO_2 fixation or in algae count or size distribution between controls and samples	144
Chlorella pyrenoidosa and vulgaris	Cell rotation, fluorescence, and transmittance of cel suspensions	Up to 30,000	N.R.	Reorientation of cells; preferential polarization of fluorescence in plane perpendicular to magnetic field; dichroism and anisotropic wavelength-dependent light scattering effects induced by the magnetic field; saturation at ~ 15,000 G	68–70
Nitella flexilis and *translucens*	Action potential and survival	10,000–20,000	Up to 72 h 24–28°C	No evidence of cell damage; no change in the bioelectric activity for either orientation in magnetic field	26

TABLE 4 (continued)
Selected Experiments of Static Homogeneous Magnetic Fields on Microorganisms

Species	Specific parameter measured	Magnetic field intensity (Gauss)	Duration of exposure	Effects observed	Ref.
Nitella flexilis	Resting potential	1000–4500	20 min to 1 d 17–20°C	Statistically significant reduction (~10%) in resting potential that depends on the intensity and duration of magnetic exposure	189
Nitella	Action potential and survival	6000–17,000	5 min 25°C	Transverse and longitudinal fields reduce the action potential; the reduction is larger for parallel fields than perpendicular fields and is irreversible above 6000 G; paralell fields above 10,000 G eventually result in death of cell after 24 h; no control used	11
Scenedesmus obliquus	Cell rotation, fluorescence, and transmittance of cell suspensions	Up to 30,000	N.R.	Reorientation of cells; preferential polarization of fluorescence in plane perpendicular to magnetic field; dichroism and anisotropic wavelength-dependent light scattering effects induced by the magnetic field; saturation at 25,000 G	69
Phormidium luridum	Cell rotation, fluorescence, and transmittance of cell suspensions	Up to 100,000	N.R.	Magnetic field has no effect on fluorescence and scattering of light is independent of orientation with respect to the magnetic field; no reorientation of cells observed	69
Volvox aureus	Locomotion	5	~1 min T = N.R.	B perpendicular to GMF: 75% increase clockwise turning, B parallel to GMF: 43% increase in clockwise turning; 11% increase in standard deviation for perpendicular B orientation compared with parallel B orientation	161

TABLE 4 (continued)
Selected Experiments of Static Homogeneous Magnetic Fields on Microorganisms

Species	Specific parameter measured	Magnetic field intensity (Gauss)	Duration of exposure	Effects observed	Ref.
Paramecium caudatum	Movement	700–800	1 min	Migration to the south pole	115
Paramecium caudatum	Movement	40–2400	18–21°C	Microrganisms seem to spend more time at the south pole than north pole	101
Paramecium caudatum	Body length, width, diameter of posterior contractile vacuole, and contractile cycle	1750	29–149 min 24–25°C	Protozoa were first immobilized by Ni; entrance rate of water and alcohol solutions (7% methanol, 3.5% *n*-propanol and *n*-butanol) decreased due to change in contractile cycle of vacuole, No significant change in body length, width, and vacuole diameter	100
Paramecium caudatum	Direction of migration path	1.3	Several seconds	Amount of turning increased and path distribution altered, standard deviation increased by 6°	29
Paramecium multimicro-nucleatum	L-50 times in various dye solutions after prior magnetic field exposure	750–4800	5–90 min	L-50 times significantly reduced if product of prior magnetic treatment-and exposure time > specific values; minimum B strength is > 750 G. Effect of magnetic field enhances the entry of dye into the organism; size of vacuoles same as the control; no significant alteration in phagocytosis	126

TABLE 4 (continued)
Selected Experiments of Static Homogeneous Magnetic Fields on Microorganisms

Species	Specific parameter measured	Magnetic field intensity (Gauss)	Duration of exposure	Effects observed	Ref.
Saccharomyces fragilis, *Brevibacterium* E-551 and *Bacillus mucilaginosus*	Effect of magnetically pretreated medium on growth rate, biosynthetic activity and biomass accumulation		16–18 h 26–30°C	Treatment influenced the growth rate, biomass accumulation and biosynthetic activity of the cultures; the character and degree of the magnetic field effect were different for each microorganism	58

[a] Not reported.

forces on motility decreases with decreasing size. Indeed, theoretical calculations show that a cell must be at least 10 μm in diameter before responding to gravitational forces (Pollard, 1962), and free swimming bacteria are generally too small (~1 μm) to settle due to gravity. A bacterial response to magnetic fields that is size dependent would partially explain the lack of observed biomagnetic effects in some studies. This concept is discussed later in the context of the influence of the Josephson junction on magnetic sensitivity (Section VI.D).

Moore (1979) proposed that a magnetic field could have a direct effect on the microbial respiratory apparatus. He observed that hypoxic cultures of the bacterium *Pseudomonas aeruginosa* exposed to a 150 G magnetic field were stimulated to grow faster than controls not exposed to magnetic field (Table 4). In a separate experiment, the protozoan *Trichomonas vaginalis* exhibited a two-phase growth pattern in which growth was first stimulated then inhibited at higher magnetic field intensities (Genkov et al., 1974). The opposite trend, however, has been observed with *Staphylococcus aureus* (Hedrick, 1964).

No adverse effects at the genetic level have been observed in bacteria subjected to intensities of 10^4 to 10^5 G (Thomas and Morris, 1981). A forward mutation assay on *Salmonella* exposed to a 10^5 G field for 4 h did not reveal any mutagenic effects (Skopek et al., 1986).

Experimental evidence suggests that the interaction of magnetic fields with microorganisms is directionally dependent. As discussed in Section III, Jung et al. (1993) found that the rate of phenol biodegradation (by 100 g of alignate-immobilized activated sludge) was enhanced 30% by the magnetic field from the south pole of a permanent magnet. The magnetic field from the north pole of the same magnet had an inhibitory effect reducing the phenol degradation rate by as much as 85%. Furthermore, there are two independent reports of the preferential accumulation of *Paramecia* at the south pole face of a magnet (Isquith and Swenson, 1987; Kogan and Tikhonova, 1965).

B. Heterogeneous Fields

Selected experiments with heterogeneous magnetic fields applied to microbial systems are listed in Table 5. The tumor production by *Bacterium tumefaciens* on the plant *Pelargonium zonale* was inhibited by a heterogeneous magnetic field. Nevertheless, growth and morphology of this microorganism were not affected (Magrou and Manigault, 1946). A non-uniform magnetic field (15,000 G center, –2300 G/cm gradient) applied to *Serratia marcescens* and *Staphylococcus aureus* bacteria resulted in a two-stage growth pattern (Gerencser et al., 1962). Similar to the previously mentioned experiment with *P. aeruginosa* and *T. vaginalis,* the growth rate was inhibited at first, and then it was enhanced. This change in growth pattern was attributed to adaptation of the cells to the applied magnetic field.

TABLE 5
Selected Experiments of Static Heterogeneous Magnetic Fields on Biological Systems

Species	Specific parameter measured	Magnetic field intensity (Gauss)	Average gradient (Gauss/ cm)	Duration of exposure	Effects observed	Ref.
Bacterium tumefaciens	Tumor production	15,000	2300 and	10 h	Tumor production on *Pelargonium zonale* retarded, growth and morphology of bacteria not affected	129
Serratia marcescens	Colony size and morphological changes	15,000	2300 and 5200	10 h 27°C	Inhibition of growth at 6 h (max. at 8 h) but then diminishes until at 10 h, colony size is is the same as control; enhancement of growth (5200 G/cm) after 3–6 h, then inhibition (max. at 7 h) but diminishes until at 9 h, colony size is same as control; no morphologica differences observed	74, 75
Staphylococcus aureus	Colony size and morphological changes	15,000	2300 and 5200	10 h 37°C	No significant difference in colony size from control; enhancement of growth (5200 G/cm) after 3–6 h, then inhibition (max. at 7 h) but diminishes until at 9 h, colony size is same as control; no morphological differences observed	74, 75
Saccharomyces cerevisae	Growth and colony size	11,000	N.R.[a]	5–80 min T = N.R.	Orientation of magnetic field perpendicular to agar plate; decreases in cultures less than 2 h old, while no inhibition of growth observed compared to control in older cultures	111
Phycomyces blakesleeanus)	Curvature in growth	4000	5600	Up to 4 h 25°C	Only early stage of development (Stage I) gave curvatures (90%) that were towards lower magnetic field gradients; fungi were rotated to eliminate effects due to gravitation	230

[a] Not reported.

Homogeneous magnetic fields can produce magneto-mechanical effects, such as the electromotive force generated in moving protozoa (Roberts, 1970), the force exerted on moving charge carriers or radicals (Kinouchi et al., 1988), and the torque exerted on rod-shaped bacteria (Neurath, 1964). A heterogeneous magnetic field can exert an additional force that increases the stress on a microbiological system. This force, or Maxwell stress, is related to the vector product of the field strength and gradient. Kinouchi et al. (1988) showed that a typical heterogeneous magnetic field of 10,000 G and 10,000 G/cm gradient would not significantly affect the diffusion of individual diamagnetic proteins in physiologic saline solution. Nevertheless, the Maxwell stress is dependent on particle size, and can have an influence on the diffusion of larger molecular aggregates such as colloids (Kinouchi et al., 1988). Bacterial cells are composed of diamagnetic organelles that have colloidal properties (e.g., phospholipid membranes). This suggests that the Maxwell stress from heterogeneous fields could influence some diffusion processes in microorganisms.

C. Intermittent or Pulsed Fields

A 50 Hz pulsed magnetic field of 500 to 1500 G had a significant bactericidal effect (>99% mortality) on flowing solutions of *E. coli* with initial concentrations ranging from 10^4 to 10^5 cells/ml (Chizhov et al., 1975). Based on these results, the use of time-varying magnetic fields was offered as a possible method for disinfection of reclaimed water. Conversely, a pulsed field of 300 to 2000 G (120/s) had a stimulating effect (maximum at 600 G) on the growth of *Saccharomyces cerevisiae* (yeast) (Galar and Martinez-Sanchez, 1985). The application of a magnetic field in intermittent periods (10 min on, 10 min off) ranging from 80 to 10,000 G over 2 h increased the respiration of yeast cells by about 40%, with a minimum threshold value between 80 and 85 G (Cook et al., 1969). Similar results were observed in a separate study with an intermittent magnetic field of 6000 G (Fardon et al., 1966).

Moore (1979) studied four bacterial and one yeast culture in pulsed (0.3 Hz) magnetic fields with strengths ranging from 150 to 600 G. The Gram-negative bacteria (*P. aeruginosa* and *Halobacterium halobium*) showed a greater stimulatory growth response to magnetic fields than the thicker-walled Gram-positive bacteria (*Bacillus subtilis* and *Staphylococcus epidermidis*) or the yeast, *Candida albicans*. The growth pattern of *P. aeruginosa* showed maximum stimulation at 150 G, then inhibition (maximum at 300 G), followed by a gradual enhancement in growth. Pretreatment of the culture medium did not produce any observable difference in growth. As turbidity and viable cell counting procedures gave the same results, the inhibitory effect on microbial growth by magnetic fields of appropriate strength was attributed to a decrease in the rate of multiplication rather than an increase in the rate of death. The effect of using pulsed fields of ultra low frequency resulted in a higher stimulation of *P. aeruginosa* growth compared with an equivalent static

field. A static magnetic field inhibited growth of the yeast, *C. albicans* while a pulsed magnetic field produced a stimulatory response.

Exposure of a culture of *E. coli* to a 15 G sawtooth pulse (200-μs rise time, 20-μs fall time) for 1 h changed the distribution of protein fractions by a factor of 2 or more (Goodman et al., 1994). Some of the protein fractions that were altered are associated with gene translation and amino acid transport. A pulsed magnetic field has also been shown to alter membrane properties and cell division rates in *Paramecium* (Dihel et al., 1985).

D. The Geomagnetic Field

There is some evidence that the GMF at the surface of the Earth may affect biological systems. The magnitude of the earth's geomagnetic field varies around the world between 0.3 and 0.7 G, with an average of about 0.5 G (Figure 4). The GMF is the sum of (1) constant fields arising from complex induction currents associated with deep layers of the earth and (2) variable fields associated with currents in the ionosphere and magnetosphere. Although the magnitude of the variable field is less than 2% of the overall GMF, it is the principle source of the daily minor fluctuations in the GMF that are on the order of 10^{-4} G. These "quiet" variations show a geographical dependence and include solar and lunar diurnal variations with periods equal to the solar and lunar day, as well as annual variations. Irregular, sharp disturbances in the GMF caused by solar flares can result in changes on the order of 0.002 to 0.006 G. It has been proposed that these GMF variations could cause noticeable effects on biological processes (Dubrov, 1973; 1975). For example, it has been claimed that diphtheria bacilli become less toxic in years of maximum solar activity, and fluctuations in size and populations of marine algae have been correlated to the 11-year cycle of solar activity (Presman, 1970). A correlation between solar activity and the incidence of various infectious diseases, such as plague, cholera, and influenza, was first proposed in the 1930's (Chizhevskii, 1964).

Dubrov (1978b) proposed that changes in components of the GMF could alter the electromagnetic conducting properties of membranes and cell current systems associated with them. According to this theory, a change in parameters associated with the GMF could alter the electromagnetic conducting properties of membranes and cell current systems associated with them. This could alter the rate at which ions and informational molecules such as DNA and proteins enter the cell, potentially leading to a change in genetic processes. This concept of "geomagnetic mutations" has also been claimed to account for present micro-evolutionary processes involving the appearance of new forms of bacteria and viruses, virus latency in animals, and genetic disease in humans (Dubrov, 1975; 1978b). While membrane permeability has been proven to affect genetic processes in experiments on the effects of

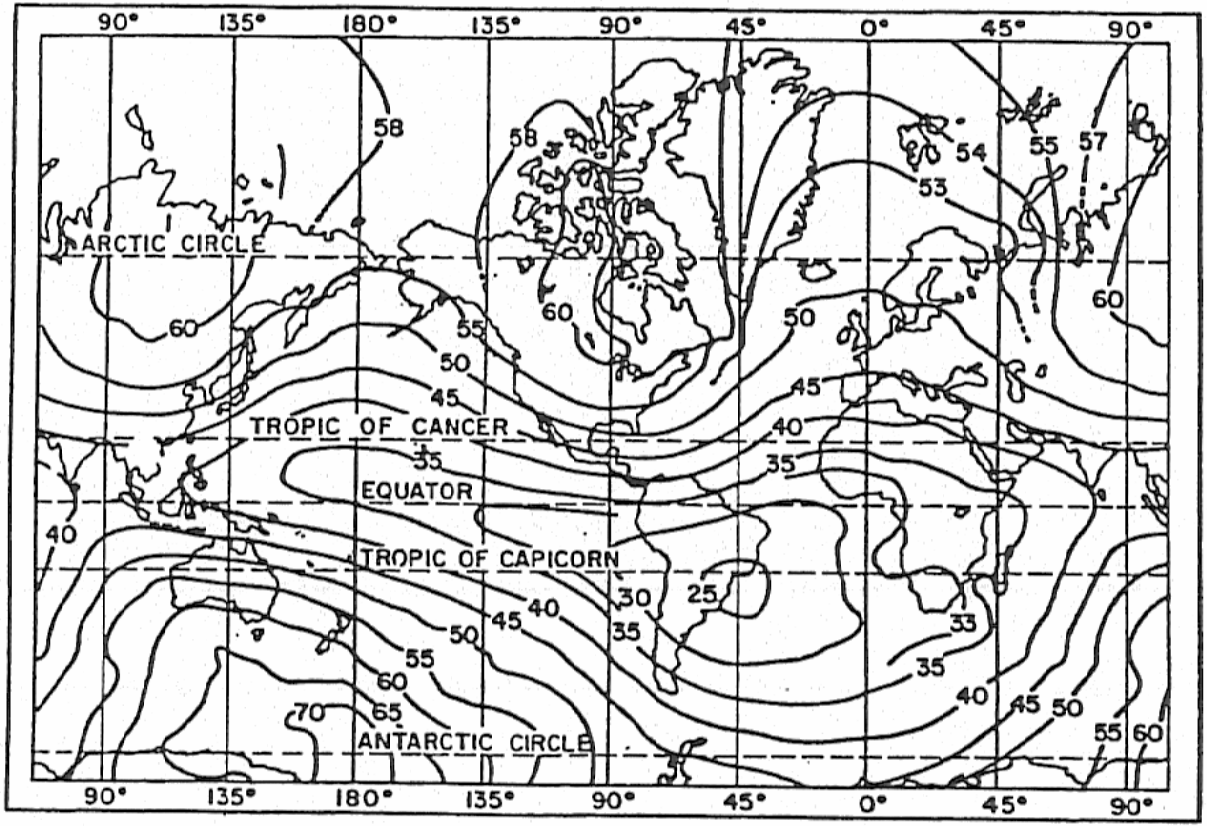

FIGURE 4. Map of the total intensity of the Earth's magnetic field. Expressed in kgammas (0.01 G). (Source: U. S. Geological Survey No. 1703.)

various ions on dipterans gene activity in (Gopalan, 1973; Lezzi and Gilbert, 1970; Shires et al., 1974), Dubrov's theory remains unproven.

Some interesting correlations have been reported between measurements of the vectorial components and direction of the GMF over decades and independent investigations of various biological systems. For example, changes in the occurrence of gene A in the ladybug beetle, *Adalia bipunctata*, and mitotic activity of human skin cells coincided with variations of GMF components (Dubrov, 1973). The sex ratios, enzymatic polymorphism, and chromosome inversions for various species of *Drosophila* as well as DNA synthesis of *Crepis capillaris* plant cells have shown a dependence on the cyclic variations of the GMF (Dubrov, 1975). Reported correlations between minor and major variations in the GMF and biological systems, such as the proliferation of germs and viruses, and changes in blood composition (Dubrov, 1975; Levashev et al., 1973) suggest that the GMF may have a role in the regulation of biodegradative systems. Furthermore, changes in diurnal variations of the GMF components have been associated with synphasic and synchronous associations with circadian, seasonal, and annual biological rhythymicity. For example, the GMF could indirectly affect the biological rhythymicity of a cellular function by periodic changes in the membrane permeability and the resulting cyclic variations in cellular processes. Thus, it conceivable that biological rhythymicity could be influenced by diurnal variations of the GMF.

The influence of a 50% increase and decrease of the GMF on the activity of the enzymes hydroxyindole-o-methyltransferase and *N*-acetyl-serotonintransferase has been demonstrated *in vivo* and *in vitro* (Cremer-Bartels, 1984). *Streptococcus mutans* bacteria showed a 50 to 60% increase in accumulation on the geomagnetic south side of a glass surface compared with the north side (Adamkiewicz and Pilon, 1983; Adamkiewicz et al., 1987). Such results suggest that microbial growth rates may be influenced by both the magnitude and direction of the GMF.

With these concepts in mind, it is provocative to contemplate that the efficiency of a biological treatment process could be influenced by its location due to geographical variations of the components of the GMF. Such minor fluctuations in the GMF over time, whether it is a diurnal, circadian, or annual variation, could affect biodegradation. Nevertheless, the extent to which this would occur is unknown.

E. Hypomagnetic (< GMF) Environments

The advent of the space age prompted several studies of biological systems in null magnetic environments to assess the possible effects on humans traveling in interplanetary magnetic fields. Although there are a variety of ways to attenuate the GMF from a sample, the two most common methods involve using a special metal to deflect the magnetic field lines away (e.g., Mu metal, which contains about 70% nickel) or through compensation with Helmholtz coils, or both. The results of some selected studies of null fields on microorganisms and plants are listed in Table 6,