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MAGNETIC FIELD APPLICATIONS IN MODERN TECHNOLOGY AND MEDICINE

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INTRODUCTION

Magnetism has a long history which dates to the discovery of magnetite in the province of Magnesia during the seventh century B.C. There are numerous literary references which indicate that the ancient Greeks, Romans, Chinese, Hindus and Central American Olmecs independently discovered magnetism in rocks and observed the attraction and repulsion of magnetized materials. In 1269 Petrus Peregrinus published the "Epistola ad Sygerum de Foucancourt Miletum de Magnete," in which he described his experimental observation of magnetic poles that exert either attractive or repulsive forces. Some limited evidence suggests that iron needles magnetized by rubbing them with magnetite were employed as compasses during the latter part of the Middle Ages, and it is well documented that magnetized needles were used as navigational guides during the Renaissance era. In 1570 Robert Norman, a London compass maker, discovered the downward 70° magnetic inclination of iron needles, and this phenomenon was cited by William Gilbert as support for his theory that the Earth behaves like a giant magnet. Gilbert's monumental treatise, "De Magnete Magneticisque Corporibus et de Magno Magnete Tellure," was published in 1600 and represents the first careful scientific study of magnetic phenomena.

During the last two centuries, many of the fundamental properties of magnetic materials and electromagnetism were demonstrated experimentally and described in theoretical terms. Several landmarks in the understanding of magnetic phenomena include:

(1) the discovery by Mitchell and Robison in the 18th century that the attraction and repulsion of two magnets decreases as the inverse square of the distance between their poles;

(2) the independent findings in the early 19th century by Oersted,
Arago, Biot, Savart and Ampere that an electric current produces a magnetic field;

(3) the discovery of electromagnetic induction by Lenz and Faraday in the mid-19th century;

(4) the mathematical development of electromagnetic theory by Maxwell in the latter half of the 19th century;

(5) the experimental and theoretical description of diamagnetism, paramagnetism and ferromagnetism by Weber, Faraday, Ewing, Curie, Weiss, Langevin, and Debye in the latter part of the 19th and the early part of the 20th centuries;

(6) studies during the same period by Lorentz and Zeeman of the effects of magnetic fields on radiation;

(7) the discovery of superconductivity by Kamerlingh-Onnes in 1911;

(8) the experimental demonstration in 1921 by Stern and Gerlach of the magnetic moment of an electron;

(9) the demonstration of nuclear magnetic resonance by Bloch and Purcell in 1946;

(10) the development of the modern quantum theories of magnetism and superconductivity by Van Vleck, Anderson, Bardeen, Cooper, Schrieffer, Josephson, and many others.

The great discoveries of magnetic phenomena made during the past two centuries underlie nearly every modern technological process, and form the basis for several advanced concepts related to energy production and medical imaging. Although it is clearly impossible in a short presentation to describe all of the uses of magnetic fields in research and technology, a brief summary will be given of several major applications of magnetism. In addition, a description will be given of the range of magnetic field
intensities to which humans are exposed in technologies that utilize large stationary magnetic fields. Although magnetic fields with time variations in the extremely-low-frequency (ELF) range are also used in numerous technologies and medical processes, these fields will not be specifically considered here since they form the subject matter of later presentations to be given in this symposium.

STATIONARY MAGNETIC FIELDS IN TECHNOLOGY AND MEDICINE

Major technologies that involve the use of large stationary magnetic fields are listed in Table 1. This list includes research, industrial and medical procedures that are currently in use, along with several other technologies related to energy production and transportation that are only in the prototype development stage at the present time. Throughout this discussion, the magnetic flux density will be given in the c.g.s. Gauss unit rather than the more conventional S.I. Tesla unit (1 Tesla = 10^4 Gauss). The reason for this choice is that many of the current magnetic field calculations and dosimetric procedures express the magnetic flux density in Gauss units.

(1) Energy Technologies

Thermonuclear fusion reactors. The fusion process involves the combination of two light nuclei to form a heavier nucleus with a resultant release of energy. The two fusion reactions being considered for use in controlled thermonuclear reactors are

\[ ^2H + ^2H \rightarrow ^3He + n + 3.27 \text{ MeV} \]

and

\[ ^2H + ^3H \rightarrow ^4He + n + 17.59 \text{ MeV} \]

Of these reactions the second (the deuterium-tritium (D-T) reaction) is most favorable because of the larger amount of energy obtained. However, the D-T
reaction is technologically more complex because of the requirement for generating tritium through a reaction of the released neutrons with lithium contained in the reactor blanket. Nevertheless, the prospect for net power output in a controlled thermonuclear reactor is more favorable with the D-T reaction than with the D-D reaction.

Various methods can be used to confine an ignited plasma, including high-intensity magnetic fields and inertial confinement achieved by igniting a D-T fuel pellet with laser beams or particle beams. The magnetic confinement approach was first suggested by Soviet scientists, who were the original developers of the tokamak devices in which a plasma is contained at moderate densities and temperatures within a toroidal magnetic field. For the past three decades, the worldwide research effort has focused primarily on the physics of plasmas contained within tokamak reactors. It is anticipated that the first demonstration of a "breakeven" energy condition ($Q = 1$, where $Q$ is the ratio of energy output to energy input) will be achieved within the next few years using a D-T plasma in the Princeton TFTR reactor. The feasibility of achieving this condition is well established theoretically, and the necessary plasma conditions were demonstrated last year with a D-D plasma in the Alcator-C reactor at the Massachusetts Institute of Technology. In brief, the Alcator-C experiment achieved a product of plasma density and energy confinement time of $8 \times 10^{13}$ sec/cm$^3$, which is considered to be the minimum value necessary for reaching the energy breakeven condition. Although the prospect of a commercial fusion reactor may lie several decades in the future, the successful demonstration at Princeton of breakeven energy conditions in a D-T plasma will represent an important step towards demonstrating the technical feasibility of producing energy through thermonuclear fusion.

Various other reactor designs also utilize large magnetic fields for
plasma confinement, including the mirror reactor, the stellator, the reversed field pinch, the spheromak, and the bumpy torus. The mirror devices have been extensively studied in the United States, Japan and the U.S.S.R. during the past two decades. The mirror reactor is a linear, open-ended device in which the ions of the plasma are reflected at the ends by complex magnetic mirrors such as the Yin-Yang magnets developed at the Lawrence Livermore National Laboratory. In principle, the mirror device has certain advantages over the tokamak design, including the possibility of steady-state operation and a modular construction which facilitates the replacement of components such as the blanket and wall structures. However, the worldwide database on the physics of plasmas contained in mirror reactors is much less advanced than that for tokamaks, and it is not clear at present that the mirror machines will evolve to reach the energy breakeven point. The other types of reactors mentioned above contain closed plasma configurations like the tokamak, but use differing magnetic field configurations to achieve favorable conditions for long-pulse plasma ignition and confinement. Research on these devices is still at an early stage, but results to date with the stellator and reversed field pinch devices are very promising.

It is now generally believed that fields as high as 90 to 120 kG will be required for the sustained magnetic confinement of an ignited plasma. Two methods for achieving such high fields are (1) the use of niobium-tin superconducting magnets, and (2) the superposition of fields from copper coil magnets used in combination with niobium-titanium superconductors (the NbTi conductors alone cannot achieve fields above 90 kG). Several comprehensive designs of future experimental reactors such as the INTOR (International Torus) and STARFIRE designs have incorporated ultrahigh fields. In Figure 1 the fringe magnetic field profile is shown for the STARFIRE reactor design which has a central axis field of 111 kG. Fringe fields up to the level of
500 G will exist at locations outside the main reactor building in areas accessible to operations personnel. Although only a limited number of scientists and maintenance personnel would normally be expected to enter fields of this intensity, it is expected that they will do so for brief periods during normal reactor operation.

Magnetohydrodynamic (MHD) generators. Power generation by MHD separation of ionic charges has been studied as a potential means for increasing the net power output of a gas- or coal-fired electric power facility. The charged combustion products are forced through a transverse static magnetic field of 50 to 60 kG strength, and the net power output in watts is equal to the rate of charge separation in amperes multiplied by the transverse Hall voltage developed across the MHD channel. To a first approximation, a typical MHD generator can be represented as a magnetic dipole with a large net moment of approximately 8000 MA·m² (Hassenzahl et al., 1978). The field level at a distance of about 50 m from the device would then be approximately 100 G, and the field level would fall below 1 G only at distances greater than 250 m.

Several MHD test facilities have been developed during the last decade. The largest in the United States is the Department of Energy's Component Development and Integration Facility in Butte, Montana. A prototype MHD converter with a 50 kG central field was also developed in a joint program between the U.S. and U.S.S.R. This unit was constructed in the late 1970's at the Argonne National Laboratory and then sent to Moscow where experimental tests were conducted in the early 1980's. At the present time, there is concern that MHD generators will not be able to perform at efficiencies close to their theoretical maximum of 40 to 60 percent, and the ultimate economic feasibility of these devices has therefore been questioned.
Superconducting magnetic energy storage. The superconducting magnet energy storage (SMES) system is a technique for storing electric power during periods of low utilization, and for supplying power during times of peak demand to achieve "load leveling." The theoretical efficiency of SMES devices is about 90 percent, and they offer promise as a method for effective electric power utilization in the future. During the last decade a prototype SMES device with a 40 kG field and a 30 MJ storage capacity was built and tested at the Bonneville power facility in the United States. This was a ground level facility with fringe fields up to 500 G at operator accessible locations (Alpen, 1979).

Several other designs of SMES systems involving a significantly larger energy storage capacity have been developed through support of the U.S. Department of Energy and the Electric Power Research Institute. All of these new designs have incorporated a trench in which the solenoidal superconducting magnet is buried in order to provide cost-effective mechanical support for the coil. A strong mechanical support frame embedded in granite or other types of rock is required in order to oppose the large transverse magnetic forces that are present when the magnet is operating at a peak field level (typically 40 to 50 kG). Even with a buried SMES design, however, the fringe magnetic fields at ground level above the solenoidal magnet are anticipated to exceed 100 G. This is demonstrated by the fringe magnetic field profile shown in Figure 2 for a conceptual 5500 MWh SMES unit that has a 42.5 kG field level at the coil midplane (EPRI, 1984).

Superconducting generators and transmission lines. Generators have been designed that use superconducting rotor windings with magnetic field strengths as high as 60 to 70 kG. Compared to ordinary generators, the superconducting design is theoretically attractive because it reduces the
system input power requirements. The fringe magnetic field levels associated with these devices are projected to be less than 1 G (r.m.s.) in regions that are accessible to personnel (Hassenzahl et al., 1978).

Both DC and three-phase AC superconducting transmission lines have been designed. The DC line is a coaxial cable and the external magnetic field is therefore negligible. For three-phase AC lines, the external magnetic field depends on the conductor spacing (Hassenzahl et al., 1978). It is projected, however, that burial of the conductors at a depth of approximately one meter should reduce the field at ground level to less than 1 G (r.m.s.).

(2) Research Facilities.

Bubble chambers. During the last three decades, bubble chambers have played a major role in the study of high-energy nuclear reactions. These devices contain liquid hydrogen or liquid propane in a superheated state. When a high-velocity particle from an accelerator enters the liquid it produces ions that act as nuclei for bubble formation. When the pressure on the superheated liquid is then reduced by a small amount (allowing a volume expansion of approximately 3 percent), vapor bubbles are formed and recorded on stereophotographs during a brief light flash. The bubble chamber is contained within a solenoidal magnet operating at field levels up to approximately 30 kG in order to produce oppositely directed spiral trajectories of the positively and negatively charged particles. The length and the curvature of each trajectory provide information on the momentum and energy of the particle producing the track.

Following the invention of the bubble chamber by D.A. Glaser in 1953, several of these devices with diameter ranging from 0.3 to 4.5 m
were constructed at accelerator laboratories in the United States and in Europe. Figure 3 shows the fringe magnetic field profile in the vicinity of a two-meter bubble chamber. At the location where an operator changes the film cassettes, the field is estimated to be approximately 4 to 5 kG at foot level and about 500 G at the level of the head. The film changing procedure requires 5 min to complete, and is carried out approximately three times per day (once per 8-hr work shift). Unfortunately, there have been no direct measurements reported of the magnetic field levels to which operators are actually exposed at the various bubble chambers throughout the world.

Another type of particle detector that utilizes high magnetic fields is the spark chamber. In this device the particle trajectory is visualized by a series of electrical sparks that are triggered by a high-energy particle as it passes through a series of spark gaps. The magnetic fields used to produce curvature of charged particle trajectories in spark chambers are comparable in strength to those used in bubble chambers.

Superconducting spectrometers. Intense magnetic fields contained within large volumes can be used to separate the fragments produced in high-energy nuclear collisions between accelerated particle beams and fixed targets. Once separated, various detectors can be used to measure the charge, mass, and momentum of the many fragments produced in a single collision. Two of the largest superconducting spectrometers are the "Large Aperture Superconducting Solenoid" (LASS) at the Stanford Linear Accelerator facility, and the "Heavy-Ion Spectrometer System" (HISS) located at the Lawrence Berkeley Laboratory Bevalac facility. The LASS spectrometer contains both a superconducting solenoid operated at field levels up to 20 kG and a conventional resistive dipole magnet operated at a field level
of 12.6 kG. The HISS magnet consists of two cylindrical pole faces which are two meters in diameter and spaced one meter apart. The central field within the gap of the HISS magnet is 20 kG. Both the LASS and HISS spectrometers produce large fringe fields, with levels of several kilogauss at operator-accessible locations. More detailed information on these fringe fields has been obtained by direct measurements with a personal dosimeter, and these results will be presented in a later section of this paper.

**Particle accelerators.** Linear accelerators and synchrotrons have found applications in nearly every scientific field, including high-energy physics, nuclear chemistry, cancer radiotherapy, and isotope production for research and medicine. The scale of these devices ranges from a few meters to several kilometers (for example, the length of the Stanford Linear Accelerator is 3.2 km). Similarly, the focusing and beam extraction magnets employed in various accelerator designs differ widely in the field strengths that are used and in the magnetic field profile. Although the magnetic fields produced by resistive magnets in older accelerators seldom exceed levels of 20 kG, higher fields are now easily achieved through the use of modern superconducting magnets. Although high magnetic fields may be present in the near vicinity of accelerator magnets, personnel are seldom exposed to these fields because of exclusion from the high radiation zone surrounding the beam line. Exceptions arise, of course, during maintenance routines that involve working on or near high-field magnets when no particles are being accelerated. Some representative magnetic field exposure levels measured at four large accelerators using a personal dosimeter are described in a later section of this paper.

**Isotope separation units.** The physical principle of the mass spectrograph has been applied to the separation of isotopes in quantity.
This technique was first developed in the early 1940's by E.O. Lawrence in Berkeley, California, for the separation of uranium-235, and the resulting isotope separation unit was named the "Calutron." The original Calutrons that were installed at Oak Ridge National Laboratory (ORNL) for uranium-235 production used magnetic fields in the range of 3.4 to 6.8 kG. Some limited estimates of personnel exposure to magnetic fields from the ORNL Calutron units was obtained in 1981 by the use of a portable dosimeter produced at the Pacific Northwest Laboratories (E. Newman, unpublished data). Although brief exposures to fields as high as 500 G were recorded, the field levels at operator locations were usually less than 10 G.

(3) Industrial Processes

Aluminum production. The production of aluminum metal starting from bauxite raw material is accomplished by the Hall-Heroult reduction process. The bauxite is first converted to aluminum oxide by an autoclave treatment with soda (the Bayer process), and calcinated to form dry alumina powder. The alumina is next dissolved in a fluorinated compound of sodium and aluminum called cryolite, which melts at a temperature of about 1000 °C. The mixture is then subjected to DC electric current to produce pure molten aluminum metal by electrolysis. This final step is carried out in either a prebake anode cell or a Soderberg cell, and involves a typical DC current of 150 kA applied to the electrodes. The associated magnetic fields near the conductors and electrodes are large, and reach levels of several hundred Gauss in operator-accessible locations. A more detailed description of these fields based on measurements with a personal dosimeter will be given in a later section of this paper.

Electrolytic processes. A number of chemical extraction procedures involve the electrolytic decomposition of salts. Examples of these processes
are the extraction of magnesium by electrolysis of magnesium chloride, and the production of chlorine and sodium hydroxide by the electrolysis of brine. In the course of studies on the health of workers in these industries, Marsh et al. (1982) characterized the magnetic fields in operator-accessible locations using a conventional Hall effect probe and gaussmeter. The mean field level was 76.3 G, and the maximum was found to be 145.9 G. Time-weighted-average field exposures were calculated to be 43.2 and 118.0 G for the mean and maximum field levels, respectively.

Magnet production. Vyalov (1974) has characterized the average magnetic field levels to which Soviet workers in permanent magnet production plants are exposed. He found that the stationary magnetic field at the level of a worker's hands was typically 20 to 50 G. At the level of the chest and head, the field was generally in the range of 3 to 5 G.

(4) Transportation

Magnetically levitated vehicles. Several countries, including Japan, Canada and the United States are currently designing and testing prototype vehicles that are suspended and guided by magnetic forces. Superconducting coils in the base of the vehicle provide the fields required for levitation and guidance along the magnetic track, and some designs also contain on-board superconducting coils that produce fields for achieving vehicle propulsion. If successful, the magnetically-levitated vehicle could offer high-speed public transportation (roughly 200 to 400 km/hr), with greatly reduced levels of noise and pollution relative to conventional modes of transportation.

The technical problems of magnetic levitation are, however, very great and include the presence of large fringe fields within the passenger compartment. In some designs the field level at the floor of the passenger compartment is 500 to 1000 G. Estimates of the field at the location of a
passenger's head range from 60 to 600 G in these vehicles (Hassenzahl et al., 1978). Fortunately, the magnetic flux density within the passenger compartment can be significantly reduced by elevating the compartment relative to the on-board magnets. Compensating coils can also be installed to produce fields which cancel those from the levitation magnets at the base of the vehicle. By a combination of these procedures it may be possible to achieve a 5- to 10-fold reduction in the magnetic field levels to which passengers are exposed. The residual fields, however, could still pose some risk for patients wearing demand cardiac pacemakers if they exceed approximately 15 G (Pavlicek et al., 1983). In addition, passengers could experience considerable inconvenience if the residual field levels were sufficient to affect magnetically encoded cards such as those used by banks and other businesses.

(5) Medicine

Nuclear magnetic resonance (NMR) imaging and metabolic studies. NMR applied to living tissues provides a promising new technique for high-resolution medical imaging (Budinger and Lauterbur, 1984). In this technique, nuclear magnetic moments are aligned by the application of a stationary magnetic field, $B_0$, and undergo a precessional motion about the field direction with a characteristic Larmor frequency, $f = \frac{\gamma B_0}{2\pi}$ where $\gamma$ is the gyromagnetic ratio. When a radiofrequency (RF) field with a matching frequency is applied transverse to the direction of $B_0$, a resonant energy absorption occurs that causes the nuclear magnetic moments to change their orientation and adopt a higher energy state. When the RF field is removed, the nuclear moments then return to their equilibrium state and radiate a quantum of energy that is proportional to the resonant Larmor frequency. The strength of the radiated signal reflects the tissue concentration of
magnetic nuclei such as protons, $^{13}\text{C}$, $^{23}\text{Na}$, $^{31}\text{P}$ and $^{39}\text{K}$. The detection of different magnetic nuclei is possible because of their differing Larmor frequencies at a given magnetic field strength. For example, the value of $B_0$ must be 2.5 times higher to produce the same resonant frequency for $^{31}\text{P}$ as for protons.

The decay of an NMR signal occurs with a characteristic time variation that conveys detailed information about the local environment of magnetic nuclei. The return of the magnetic spin state to equilibrium following resonant energy absorption is characterized by two relaxation times, $T_1$ and $T_2$. The $T_1$ parameter is called the "spin-lattice" relaxation time, and reflects the local temperature and viscosity in the vicinity of the magnetic nuclei. The $T_2$ parameter is called the "spin-spin" relaxation time, and reflects the local magnetic field resulting from the nuclear moments of neighboring nuclei. Both the $T_1$ and $T_2$ relaxation times provide information that can be converted into contrast differences in NMR images of tissue proton density. Various NMR imaging methods such as the spin-echo and inversion recovery techniques have been developed that are able to demonstrate differences in the $T_1$ and $T_2$ relaxation parameters between different tissues, and also between normal and pathological regions of the same tissue (Crooks and Kaufman, 1983). In proton NMR images, large contrast differences can be observed between regions of tissue that have significantly different water or lipid content. Figure 4 shows a proton NMR $T_1$ image of the brain of a patient with multiple sclerosis. The regions of demyelination are shown with a greater resolution in the NMR image than in an X-ray tomography image of the same brain section.

In addition to use as a high-resolution imaging technique, NMR spectroscopy based on $^{13}\text{C}$ and $^{31}\text{P}$ signals can provide unique information on tissue metabolism. For example, $^{31}\text{P}$ NMR imaging has been demonstrated
to give quantitative information on phosphate metabolism in the heart and other tissues.

The present generation of NMR imaging devices employ stationary magnetic fields with intensities up to 20 kG and RF fields with frequencies up to 100 MHz (the proton resonant frequency in a 20 kG field is 85.15 MHz). In addition, weak spatial gradients of the stationary magnetic field are used to define the tissue location of NMR signals. This technique for achieving spatial localization of magnetic nuclei was first demonstrated by Lauterbur (1973), and is fundamental to the production of an NMR image. The magnetic field gradients that are used in NMR imaging are weak, typically on the order of 10 to 15 G/m. However, the gradient direction is rapidly switched from one projection axis to the next in order to reconstruct the entire image of the specimen. These rapidly switched gradient fields produce a time-varying magnetic field within the tissue volume. In the NMR imaging devices that are currently in existence, the maximum time rate of change of the magnetic field is approximately 15 kG/sec (personal communication from Dr. G. Kambic, Technicare Corporation, Cleveland, Ohio).

The feasibility of using stationary magnetic fields with strengths greater than 20 kG is also being explored as a means of increasing the signal-to-noise ratio in NMR images. In addition, the use of higher fields could significantly reduce the time required to obtain chemical shift images, which provide high-resolution information on the relative spatial distribution of $^{31}$P nuclei and protons associated with tissue water and fat. However, the higher-frequency RF fields that must be used in combination with larger stationary fields will have a decreased depth of penetration into tissue and may cause a significant level of heating. These factors, together with the relative lack of knowledge concerning the biological effects of stationary fields greater than 20 kG, may place an upper limit on the field
strength that can be used for NMR imaging.

MAGNETIC FIELD MEASUREMENTS WITH A PERSONAL DOSIMETER

Because of the increasing use of large stationary magnetic fields in modern technology, a program was initiated in 1979 with support from the U.S. Department of Energy to construct a compact battery-operated dosimeter for characterizing the magnetic fields to which personnel are exposed under routine working conditions. During the following two years, a portable magnetic field dosimeter was developed that contains three thin-film Hall sensors positioned along orthogonal axes, a programmable microprocessor-based logic circuit, and 4096 12-bit words of permanent and random access memory (Fujita and Tenforde, 1982). The dynamic operating range between the highest and lowest field levels recorded by the dosimeter is 2048 to 1. The Hall sensors are operated in a pulsed mode with a 3 percent duty cycle, and the time rate of change of the magnetic field, dB/dt, is determined from values of B recorded during consecutive 75 msec sampling intervals.

The final prototype magnetic field dosimeter, which weighs 230 g and is approximately the size of a cigarette package, is shown in Figure 5. In Table 2 a summary is given of the magnetic field information recorded by the personal dosimeter. Also listed in Table 2 is the additional information that is calculated and plotted by a bench-mounted computer to which the dosimeter is connected through an RS-232-C serial interface at the end of each workday. It should be noted that the square root operations and calculation of the integrated exposure in Gauss-hours are performed by the readout unit in order to conserve the memory capacity of the dosimeter.

Following completion of the magnetic field dosimeter in 1981, a series of field tests were undertaken at various industrial and research facilities.
These tests were performed by the author in collaboration with A.B. Geyer, K.S. Bristol, T.Y. Fujita and Dr. T.F. Budinger. Figures 6 and 7 illustrate the types of data that are obtained with the magnetic field dosimeter. In this specific application of the dosimeter, the person wearing it was operating a Van de Graaff electrostatic generator in an area located a distance of approximately 7 to 10 meters from the 23.5 kG magnet of a large alpha particle synchrocyclotron. The Van de Graaff generator itself produced local fields of less than 10 G, but the average and peak fields recorded by the dosimeter increased to much higher levels as the operator moved within his work area to positions close to the synchrotron magnet. The time rate of change of the magnetic field resulted primarily from movement of the worker through the gradient of the field produced by the synchrotron magnet. Figures 6 and 7 both give histogram representations of the percentage of work time spent in the average and maximum values of $B$ and $dB/dt$ that were recorded by the dosimeter during 5-min data storage intervals. The total integrated exposure during the 4-hr work shift was 40 G-hr.

Table 3 lists the maximum values of $B$ and $dB/dt$ that were recorded with the personal dosimeter during field tests at eight different research and industrial facilities. Several general observations based on the results of these tests are the following:

(1) The largest personnel exposures reached levels of several kilogauss in areas close to the LASS and HISS spectrometer magnets used for high-energy physics experiments.

(2) In facilities where calculations had been made of the fringe magnetic field profile, the actual exposure levels recorded by the personal dosimeter were generally lower than expected because of shielding provided by large metal structures such as platforms, support braces, and so forth.
(3) Workers performing similar tasks in the vicinity of similar devices were found to be exposed to average and peak fields that differed substantially from one worker to the next. An example of this variation is shown in Figure 8, where a personal dosimeter was used to characterize the average magnetic field levels to which personnel were exposed during anode changes on three different aluminum prebake cells in the same facility.

(4) Magnetic field levels in control room areas were found to be less than 10 G in all cases, and were usually less than 5 G.

(5) The fields monitored by personal dosimeters at various accelerator facilities were typically less than 50 G, primarily because workers are excluded from the high ionizing radiation zones near the beam transport lines in which the magnets are located.

(6) Relatively small time variations of the magnetic flux density occurred as the result of the movement of personnel through stationary magnetic field gradients. In general, the measured time rates of change were much less than the values of dB/dt that produce known biological effects. For example, the minimum values of dB/dt that elicit magnetophosphenes have been found to be 12.6 kG/sec for sinusoidal AC fields (Lovsund et al., 1980) and 13 kG/sec for pulsed fields (Budinger et al., 1984). These values of dB/dt are approximately five times larger than the maximum value of dB/dt recorded by the personal dosimeter in any of the field tests that were conducted.
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REFERENCES


TABLE 1

STATIONARY MAGNETIC FIELD SOURCES

ENERGY TECHNOLOGIES:

- Thermonuclear fusion reactors
- Magnetohydrodynamic systems
- Superconducting magnet energy storage systems
- Superconducting generators and transmission lines

RESEARCH FACILITIES:

- Bubble chambers
- Superconducting spectrometers
- Particle accelerators
- Isotope separation units

INDUSTRY:

- Aluminum production
- Electrolytic processes
- Production of magnets and magnetic materials

TRANSPORTATION:

- Magnetically levitated vehicles

MEDICINE:

- Nuclear magnetic resonance imaging and metabolic studies


**TABLE 2**

**DATA ACQUISITION AND COMPUTATION ROUTINES**

( Portable dosimeter and bench-mounted readout unit )

**DOSIMETER**

- $|B_x|, |B_y|, |B_z|$ [AVERAGE VALUES]
- $|B|^2$ [AVERAGE, PEAK AND NUMBER OF SUPRATHRESHOLD VALUES]
- $|dB_x/dt|, |dB_y/dt|, |dB_z/dt|$ [AVERAGE VALUES]
- $|dB/dt|^2$ [AVERAGE, PEAK AND NUMBER OF SUPRATHRESHOLD VALUES]

**READOUT UNIT**

- $|B|$ [AVERAGE AND PEAK VALUES]
- $|dB/dt|$ [AVERAGE AND PEAK VALUES]
- $\int |B|dt$ [SUMMATION OVER TIME]

---

Average values, peak values and number of suprathreshold values are based on a 5 min storage period, with data obtained in 75 msec sampling intervals.
<table>
<thead>
<tr>
<th>Application</th>
<th>MAXIMUM B (Gauss)</th>
<th>MAXIMUM dB/dt (Gauss/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LARGE APERTURE SOLENOID SPECTROMETER (Stanford Linear Accelerator)</td>
<td>5735</td>
<td>2710</td>
</tr>
<tr>
<td>HEAVY ION SPECTROMETER SYSTEM (Lawrence Berkeley Laboratory)</td>
<td>3200</td>
<td>1875</td>
</tr>
<tr>
<td>KAISER ALUMINUM PRODUCTION TEST FACILITY (Permanente, California)</td>
<td>570</td>
<td>290</td>
</tr>
<tr>
<td>TANDEM MIRROR FUSION REACTOR (Lawrence Livermore National Laboratory)</td>
<td>375</td>
<td>230</td>
</tr>
<tr>
<td>184-INCH CYCLOTRON (Lawrence Berkeley Laboratory)</td>
<td>190</td>
<td>145</td>
</tr>
<tr>
<td>76-INCH CYCLOTRON (University of California at Davis)</td>
<td>100</td>
<td>40</td>
</tr>
<tr>
<td>BEVATRON (Lawrence Berkeley Laboratory)</td>
<td>40</td>
<td>170</td>
</tr>
<tr>
<td>88-INCH CYCLOTRON (Lawrence Berkeley Laboratory)</td>
<td>30</td>
<td>30</td>
</tr>
</tbody>
</table>
FIGURE LEGENDS

Figure 1. Calculated magnetic field profiles are shown for the STARFIRE fusion reactor, which is a conceptual design of a commercial tokamak reactor. [Adapted from Figure 9-31, p. 9-65 in Volume 1 of a report by C.C. Baker et al., entitled "STARFIRE: A Commercial Tokamak Fusion Power Plant Study." Argonne National Laboratory, Argonne, Illinois. September, 1980.]

Figure 2. Calculated magnetic field profiles are shown for a conceptual design of a 5500-MWh superconducting magnetic energy storage system. [Adapted from Figure 4-3, p. 4-6 of the Electric Power Research Institute report cited in the reference list as "EPRI, 1984."]

Figure 3. Fringe magnetic fields in the vicinity of a 2-meter bubble chamber at the Brookhaven National Laboratory (Upton, New York). [Adapted from Figure 1, p. 29 of the chapter cited as "Alpen, 1978" in the reference list.]

Figure 4. Comparison of an X-ray computed tomography image and an NMR $T_1$ image of the brain of a patient with multiple sclerosis. Arrows on the NMR image point to regions of demyelination that are more clearly visualized than in the CT scan. [The CT and NMR images were kindly provided by Dr. Thomas F. Budinger, University of California, Berkeley.]

Figure 5. Photograph of the final prototype of a microprocessor-controlled magnetic field personal dosimeter developed at the Lawrence Berkeley Laboratory.

Figure 6. The average and maximum values of magnetic field strength recorded by a personal dosimeter are shown during a continuous 4-hr period for a worker at a Van de Graaff generator located in the vicinity
of a 23.5-kG synchrotron magnet. The bottom two panels give a histogram representation of the percentage of work time that was spent in average and maximum field levels ranging from 1 to 100 G. The total integrated exposure based on the 5-min average values of B recorded by the dosimeter was 40 G-hr during the 4-hr work shift.

Figure 7. The average and maximum values of dB/dt recorded by a personal dosimeter are shown during a continuous 4-hr period for the same Van de Graaff operator. The bottom two panels give a histogram representation of the percentage of work time that was spent in average and maximum levels of dB/dt ranging from 1 to 100 G/sec.

Figure 8. The average field strengths recorded by a personal dosimeter are shown during anode changes on three prebake cells at the Kaiser Aluminum Test Facility in Permanente, California.
STARFIRE FUSION REACTOR
GENERAL SITE PLAN
Fringe Magnetic Field Profile

Tritium Reprocessing and Cryogenics

Main Reactor Building

Turbines

Administration

Electrical and RF Supply Building

Main Switchyard

FIGURE 1
SUPERCONDUCTING MAGNET
ENERGY STORAGE SYSTEM (5500 MWh)
(Fringe Magnetic Field Profile)

FIGURE 2
FIGURE 3

BUZZLE CHAMBER FRINGE MAGNETIC FIELD PROFILE

Central plane

Scale 1 meter

Axis

250
500
1000
2000
4000
6000
8000
10,000
15,000
20,000
30,000

XBL 788-3478A
EVALUATION OF MULTIPLE SCLEROSIS PATIENT

CT SCAN  NMR T₁ IMAGE

FIGURE 4
VAN DE GRAAFF GENERATOR
(ADJACENT TO 184-INCH SYNCHROCYCLOTRON): BERKELEY, CALIFORNIA

Maximum B (-)
Average B (---)

Time (Clock Hours)

Frequency of Average Field Levels

Frequency of Peak Field Levels

FIGURE 6
VAN DE GRAAFF GENERATOR
(ADJACENT TO 184-INCH SYNCHROCYCLOTRON):
BERKELEY, CALIFORNIA

FIGURE 7
ANODE CHANGES ON PREBAKE CELLS
(Kaiser Aluminum Test Facility; Permanente, California)

Magnetic Flux Density (Gauss)

Anode No. 7
Anode No. 10
Anode No. 14

Time (min.)

FIGURE 8
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