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Potential Hazards of Magnetic Resonance Imagers to Emergency Medical Service Helicopter Operations

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January 1993



Final Report

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MAR 21 1994

Dear Colleague:

Enclosed is a copy of FAA report DOT/FAA/RD-92/15, entitled "**Potential Hazards of Magnetic Resonance Imagers to Emergency Medical Service Helicopter Operations**".

In recent years there have been several incidents with helicopters where magnetic resonance imagers (MRIs) have interfered with the operation of magnetic sensors. The fringe magnetic field can cause the magnetic sensors to give aberrant readings.

This report documents the characteristics of the MRI and how it operates. It discusses federal regulation of MRIs and any magnetic effects or hazards involved with operating helicopters in an MRI fringe field. Finally, it makes recommendations for safe helicopter operations in and around MRIs.

The American Hospital Association (AHA) estimates there are 1,300 MRIs in the United States. Of these, 1,000 are permanently installed in hospitals or clinics, and 300 are mobile units that travel from hospital to hospital. The AHA estimates that the mobile units serve 1,500 to 1,700 hospitals and clinics. Thus there are MRIs associated with approximately 2,600 hospitals. It is likely that all pilots operating in the air ambulance industry will encounter interference from an MRI. This problem will be even more significant as operations in instrument meteorological conditions (IMC) become reality.

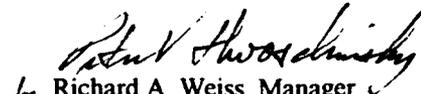
The magnetic field generated by MRI magnets covers a large volume. All aviation and medical professionals who are responsible for air ambulance operations or siting heliports and MRI's should read this document.

We welcome any comments or questions you may have. Please address your correspondence to:

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Sincerely,


Richard A. Weiss, Manager
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Enclosure

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16. Abstract In recent years there have been several incidents with helicopters where magnetic resonance imagers (MRIs) have interfered with the operation of magnetic sensors such as compasses and directional gyroscopes. The magnetic fields generated by the MRI magnet causes magnetic sensors to give aberrant readings. This report documents the characteristics of MRIs and how they operate. It discusses relevant federal regulations of MRI and all magnetic effects and hazards involved with operating helicopters in a strong static magnetic field for both personnel and equipment. Finally, the report makes recommendations for safe helicopter operations in and around MRIs.					
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1.0 INTRODUCTION

In recent years there have been several incidents with helicopters where magnetic resonance imagers (MRIs) have interfered with the operation of magnetic sensors such as compasses and directional gyroscopes. The fringe magnetic field, the magnetic field that leaks outside the MRI's walled-in area, causes the magnetic sensors to give aberrant readings. There is no warning or any indication of a malfunction generated by the helicopter sensors.

These occurrences have taken place at hospital heliports within about 500 feet of the magnet. In one case the compass reading was 160 degrees off from the earth's magnetic north pole. A typical incident is described in the following quote from an FAA Avionics Inspector (reference 1): "The chief pilot informed me that indeed he experienced a problem at ... General Hospital. He explained the [MRI] is mounted in a large van parked adjacent to the heliport. When inbound for landing, he has observed a 60 degree change on the radio magnetic indicator (RMI), while having the heliport in sight and had not changed heading. There were no flags or any indication of malfunction. On startup for the flight out, the error is still present. Switching to the free mode will cause the RMI to operate as it should. The magnetic compass indicated an error in the same direction."

These effects appeared temporary but there was no identifiable source of information on the effects of MRI fringe fields on helicopters and helicopter systems. There has been concern in the emergency medical service (EMS) helicopter industry about the potential hazard of exposure to these fields. It was unknown whether there were other unidentified temporary, permanent, or cumulative effects from exposure to these magnetic fields.

This report will document the characteristics of the MRI and how it operates. It will discuss federal regulation of MRIs and any magnetic effects or hazards involved with operating helicopters in an MRI fringe field. Finally, it will make recommendations for safe helicopter operations in and around MRIs.

1.1 MAGNETIC FIELD MEASUREMENTS

The international system unit of magnetic field strength is the Tesla (T). The former unit under the English Engineering System was the Gauss (G). The conversion between T and G is simple:

$$1 \text{ T} = 10,000 \text{ G}; \text{ or } 1 \text{ G} = 0.1 \text{ mT}.$$

Both units are in common use today. T is usually used when the subject is magnet strength. G is usually used when a map of magnetic field strength is the subject. Since both units are still used in the MRI industry, both units will be used in this report.

By comparison, the magnetic field strength of the earth is approximately 0.2 G to 0.5 G. This is the magnetic field sensed by an aircraft compass system. Typically a 5 G level is considered safe for human activity without a warning notice.

1.2 SCOPE OF THE POTENTIAL PROBLEM

The American Hospital Association (AHA) estimates there are 1,300 MRIs in the United States (reference 2). Of these, 1,000 are permanently installed in hospitals or clinics, and 300 are mobile units that travel from hospital to hospital. The AHA estimates that the mobile units serve 1,500 to 1,700 hospitals and clinics. Thus there are MRIs associated with approximately 2,600 hospitals.

The AHA has 6,000 member hospitals. Therefore, MRIs are located at approximately 43 percent of United States hospitals. Any hospital large enough to sponsor an EMS helicopter operation almost certainly has an MRI. Permanent MRI units are associated with larger, urban hospitals. The mobile units can be found anywhere. It is very likely that every EMS pilot is flying into at least one hospital helipad where an MRI is operational.

An MRI has unique and stringent operational requirements, such as strong magnetic fields, extremely heavy magnets, and cryogenic cooling. These operational requirements limit the number of installation options. An MRI cannot be installed without careful site planning. Whether the installation is permanent or mobile, a site analysis is required by the Food and Drug Administration (FDA) for every location. The purpose of the site survey is to establish the location of a 5 G safety zone around the MRI and to determine 1) the effect the environment (i.e., a helicopter) is going to have on the magnetic field, and 2) the effect the magnetic field is going to have on the environment.

Unfortunately, a magnetic field strength of 5 G will seriously affect the operation of magnetic sensors such as a compass. (A 0.005 G level will cause a compass error of less than 2 degrees.) The site survey evaluates only items that will affect MRI operations and safety of unwarned personnel*. The site survey does not evaluate the effects of the MRI fringe field on the safety of helicopter operations. This study addresses what actions should be taken to ensure safe helicopter operations.

*Note: Persons with pacemakers or other implanted electromagnetic devices should be denied entry into a magnetic field strong enough to cause these devices to malfunction. The FDA requires the use of warning signs restricting access to areas where the magnetic field strength exceeds 5 G.

2.0 CHARACTERISTICS OF MRI

MRI is a computerized, cross-sectional imaging technique. Its value is well established in the medical community. MRIs generate images by radio frequency (RF) stimulation of the nuclei of atoms in a magnetic field. All MRIs operate on the principle of nuclear magnetic resonance (NMR). All the protons (a proton is the positively charged nucleus of a hydrogen atom) in the area of the body to be imaged are lined up along the axis of a strong static magnetic field, similar to hundreds of compass needles all pointing toward magnetic north. The imaged area is then radiated with RF energy at the resonant frequency for protons. This causes some of the RF energy to be absorbed by the protons. When the RF radiation is shut off, the protons release the RF energy. This released energy is detected over the imaged area and digitized. A computer interprets the data and generates an image recognizable to the human eye.

2.1 HISTORY

NMR was developed in the late 1940's. As the name implies, it is a technique to measure the resonant frequencies of the atomic nuclei. RF energy is used to probe the physical properties of the nuclei of atoms. The basic principle of MRI is that the nucleus of a chemical element, when subjected to a constant magnetic field, has a resonant frequency that is characteristic for the element and the magnetic field strength. This means that an element can be identified by the frequency of the RF energy it absorbs. After it absorbs RF energy, the nucleus moves to a higher energy state. When the RF signal is removed, the nucleus returns to a low energy state, and the RF energy will be released at the same frequency. This released RF energy, called an echo, can be detected and used to construct an image. The strength of the echo is proportional to the density of the nuclei and therefore the density of the material being imaged.

Hydrogen is usually the element chosen for NMR in MRI. First, hydrogen is the simplest of all the elements, having only one proton and one electron. This lowers the magnetic field strength required to align the nuclei. Second, hydrogen is the most common element in biological tissue. It is found in water, carbohydrates, hydrocarbons, and proteins. The more nuclei in the sample, the stronger the RF echo will be. The combination of these two factors leads to the strongest NMR signal possible from biological tissue (reference 4).

The imaging of other nuclei, such as phosphorus, copper and manganese, is currently being developed by MRI manufacturers. This may lead to an increase in the application of MRI, since it will allow for further refining of its tissue differentiation capabilities. This will probably require stronger magnets than the ones currently in use. Therefore, the area covered by the fringe field may increase if hospitals obtain new, stronger magnets in the future. On the other hand, most new models of MRI incorporate magnetic shielding and the fringe field problem is better controlled.

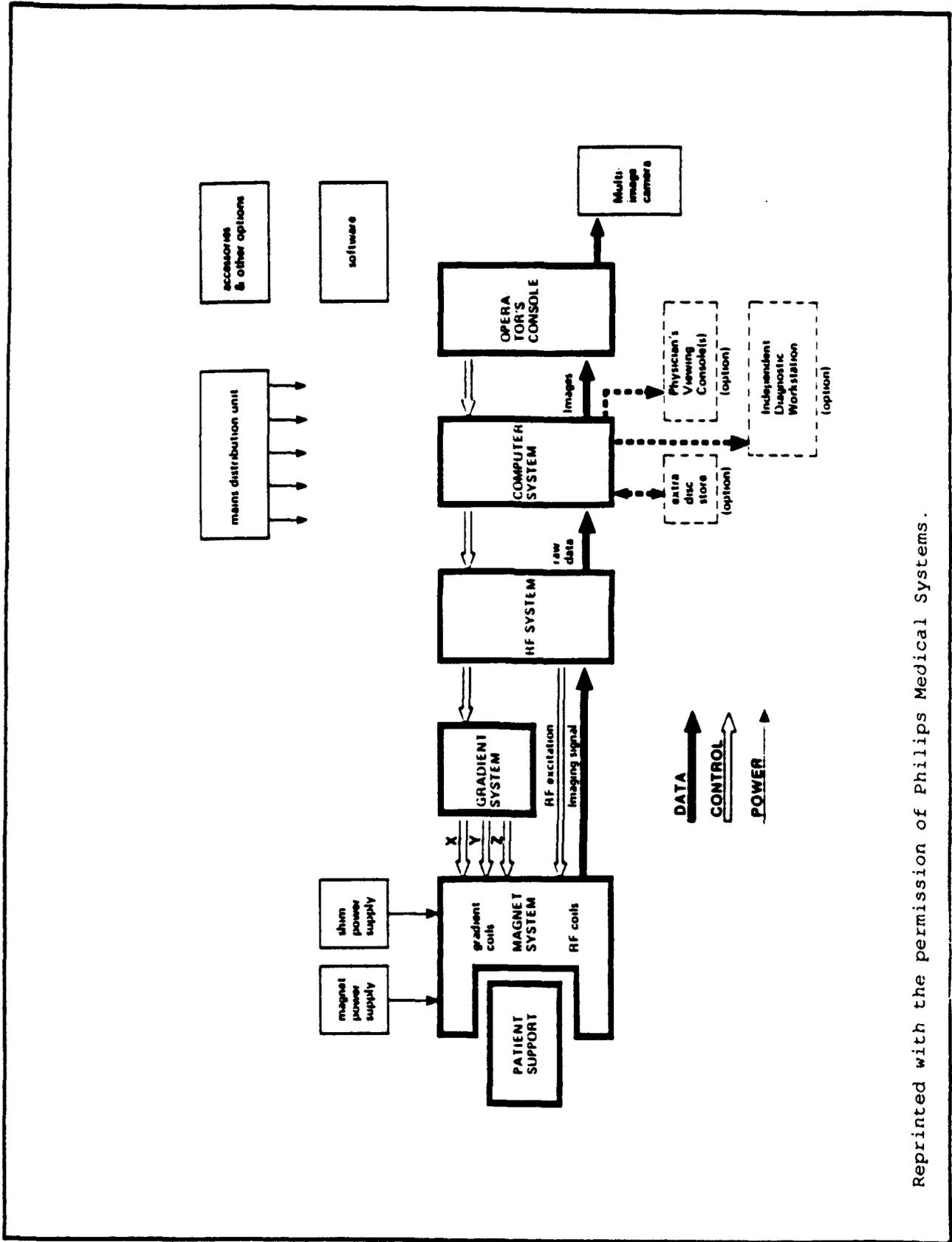
2.2 GENERAL FEATURES OF MRI SYSTEMS

A typical MRI system consists of the following subsystems: a main magnet system, an RF electronics system, a magnetic gradient system, and a computer system. Figure 1 provides an MRI system block diagram of all of the subsystems. Discussion in this section will concentrate on the magnet system, as this is the primary system that affects helicopter operations. In addition, there are two more considerations relevant to a discussion of the effects of an MRI on helicopter operations. First, some MRIs have shielding to reduce the extent of the magnet's fringe field. Second, MRIs are either permanently installed in one location or they are mobile. The mobile units are installed in tractor-trailers and can be moved over the highways. However, weight considerations significantly limit the amount of magnetic shielding for mobile units. Consequently, they usually have large fringe fields. These considerations will also be discussed in this section. The effects of the magnetic field on equipment and personnel will be discussed in sections 4 and 5.

Each proton, or hydrogen nucleus, has a minute amount of intrinsic magnetism, called a "magnetic moment." This magnetic moment is caused by the rotation of the positively charged proton and, in effect, gives every proton a magnetic north and south pole. The main magnet system, shown on the left of figure 1, creates a strong static magnetic field across the object or person to be imaged. Under the influence of the strong, steady magnetic field, most of the protons in the body will align their magnetic poles with the field. This is called "parallel" alignment. In parallel alignment, the north pole of the nuclei will point in the same direction as the north pole of the magnet in what is considered a low energy state. By exciting the protons with RF energy at their resonant frequency, they can be made to absorb energy. Most of the protons will now align their spin axes in a high energy state called "anti-parallel" alignment. When the RF energy is turned off, the protons return to their low energy state and reradiate RF energy in the process. This is crucial to the NMR process. If the protons were allowed to maintain their natural state of random spin orientation, no image could be generated because all of the reradiated RF energy would be random also. However, since most of the protons are aligned, a discrete signal strength can be obtained for each location within the area being imaged. These differences in signal strength are processed by a computer into an image on a monitor.

2.2.1 Main Magnet System

The main magnet is the most significant aspect of the MRI for helicopter operations. The stronger the magnet, the larger the area covered by the fringe field and the more potential for an effect on the helicopter and the personnel inside. The field strength is measured in Tesla (see section 1.1) and varies depending on the model of MRI. MRIs use three magnet types: superconducting, resistive, and permanent. The characteristics of each magnet type will be developed in the following sections. In addition, table 1 compares the characteristics of the three magnet types. Superconducting magnets are the most powerful and are the only ones likely to create fringe fields large enough to pose a potential threat to helicopters. However, all MRI installations should be treated with caution. The maximum recommended



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FIGURE 1 FUNCTIONAL BLOCK DIAGRAM OF MRI SYSTEM

TABLE 1
COMPARISON OF MRI MAGNET TYPES

	<u>Superconducting</u>	<u>Resistive</u>	<u>Permanent</u>
Representative field strengths of commercial whole-body imagers	0.35 - 2.0 T	0.02 - 0.3 T	0.1 - 0.3 T
Basic geometries	Solenoidal	Solenoidal Iron core H	Ring design Iron core H
Power consumption for maintaining field	None	10 - 80 kW	None
Relative magnet cost	High	Low	High
Large fringe fields in unshielded magnet	Yes	No - Iron core Yes - Solenoid, multiple ring	No
Operating weight	8,000 - 14,000 lb	Solenoidal 2,000 - 10,000 lb Iron core 40,000 - 50,000 lb	H magnet 200,000 lb Ring design 10,000 lb
Major advantages	1) high field strength 2) homogeneity 3) stability	1) low purchase price 2) readily turned off 3) availability 4) no cryogen	1) reliability and stability 2) low operating cost 3) minimal fringe fields 4) no cryogen
Major disadvantages	1) siting difficulties 2) cryogen consumption 3) safety concerns "missile effect" 4) not readily turned off	1) limited field strength 2) power consumption 3) poor stability	1) limited field strength 2) weight 3) inhomogeneities

field strength for safe exposure of unwarned personnel is 5 G. This level should never be exceeded for reasons to be explained in sections 2.2.7 and 3.1.

Another point for the pilot to keep in mind is that these magnets are rarely turned off except during maintenance. Superconducting magnets may run uninterrupted for years. It is prohibitively expensive to shut them down because of the cost of the cryogen coolant. For resistive magnets, stability of the magnetic field depends on temperature stability in the magnetic core. Therefore, if they are shut down it takes several hours to bring them back into reliable operation. Most MRI operators find it more cost effective to leave them running continuously. Permanent magnets cannot be turned off. Mobile MRI's operate even during transit from hospital to hospital.

2.2.1.1 Magnetic Field Characteristics

The magnetic field generated by MRI magnets covers a large volume, as can be seen from the typical plots of the field created by unshielded 0.5 T and 1.5 T magnets in figures 2 through 5. The field extends both horizontally, figures 2 and 3, and vertically, figures 4 and 5, around the magnet. Within this volume, the magnet exerts forces on ferromagnetic objects and on magnetic devices (i.e., oscilloscopes, magnetic data-storage devices, compasses, etc.). At low strength, the field can endanger the functioning of a cardiac pacemaker. At much higher strengths, it can exert a force on surgical implants, influence the functioning of electronic equipment, and corrupt information on magnetic data carriers. However, the field strength falls off quickly with increasing distance from the magnet. As shown in the figure, the maximum extent of the 0.1 mT (1G) line for the 0.5 T and the 1.5 T magnet is 46 feet and 67 feet, respectively. The extent of the field for a 1.5 T magnet is not three times the extent of a 0.5 T magnet.

Although the field extends in all directions, the main axis of the magnet is in the horizontal plane; thus the greatest extent of the field is in a horizontal direction. Figures 6 and 7 illustrate the horizontal and vertical extent of a typical 1.5 T MRI in a mobile trailer. The lines in the figures are isogauss contour lines. Isogauss lines are lines of equal field strength around the magnet, similar to the contours on a topographic map. They are used to show the area beyond which a person or piece of equipment must remain to avoid a certain level of magnetic field strength.

2.2.1.2 Superconducting Magnets

Superconducting magnets are the most common choice for generating the static magnetic field. The National Electrical Manufacturers Association (NEMA) estimates that more than 90 percent of all MRIs in the United States use superconducting magnets. The reasons for this are the high field strength, stability, and homogeneity of the generated field. Superconducting magnets produce field strengths in the range of 0.35 to 2 T. These are the highest field strengths currently in commercial use. The magnet will typically weigh between 4 and 7 tons.

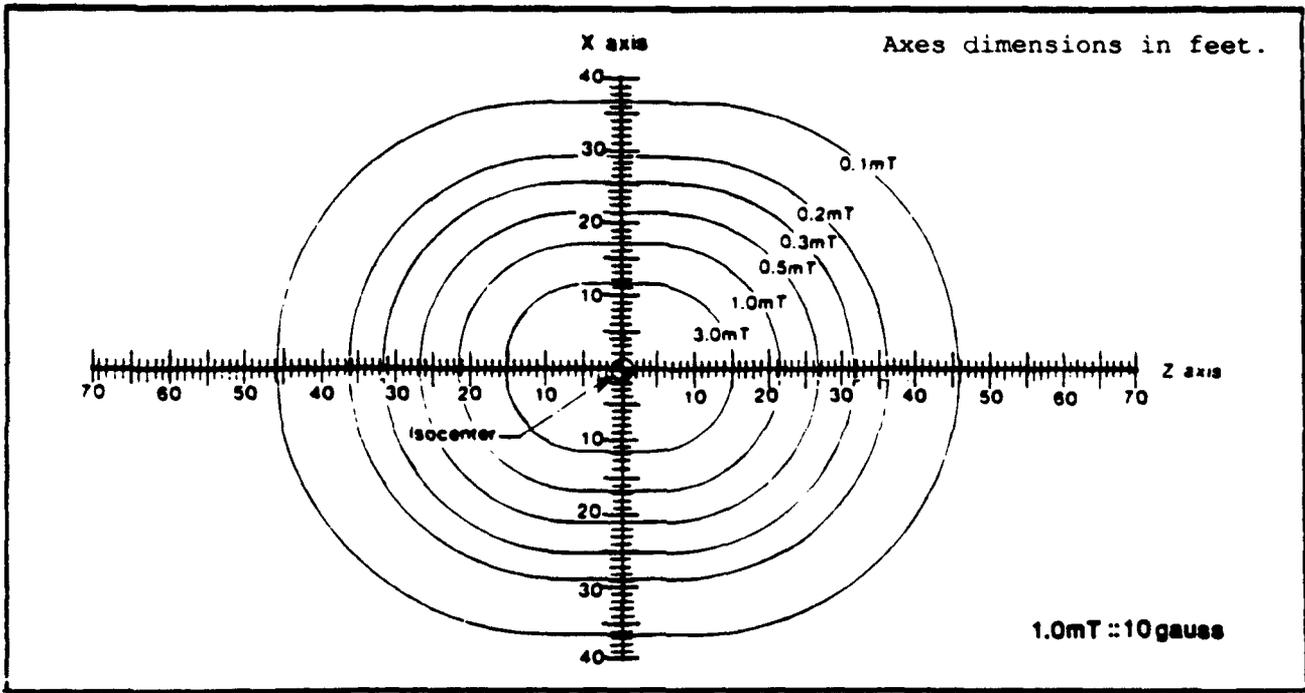


FIGURE 2 PLOT OF HORIZONTAL FIELD GENERATED BY A 0.5T UNSHIELDED MAGNET

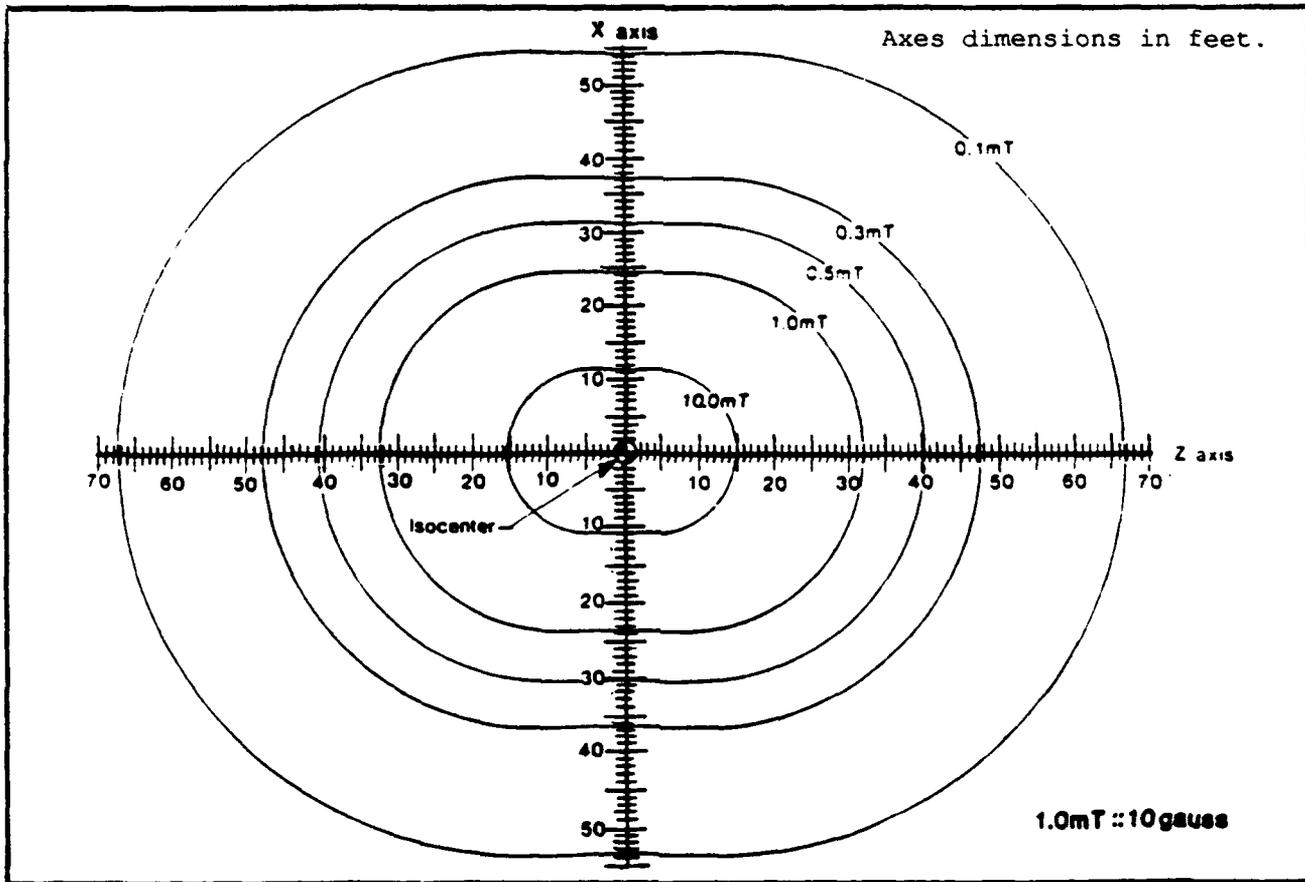


FIGURE 3 PLOT OF HORIZONTAL FIELD GENERATED BY A 1.5T UNSHIELDED MAGNET

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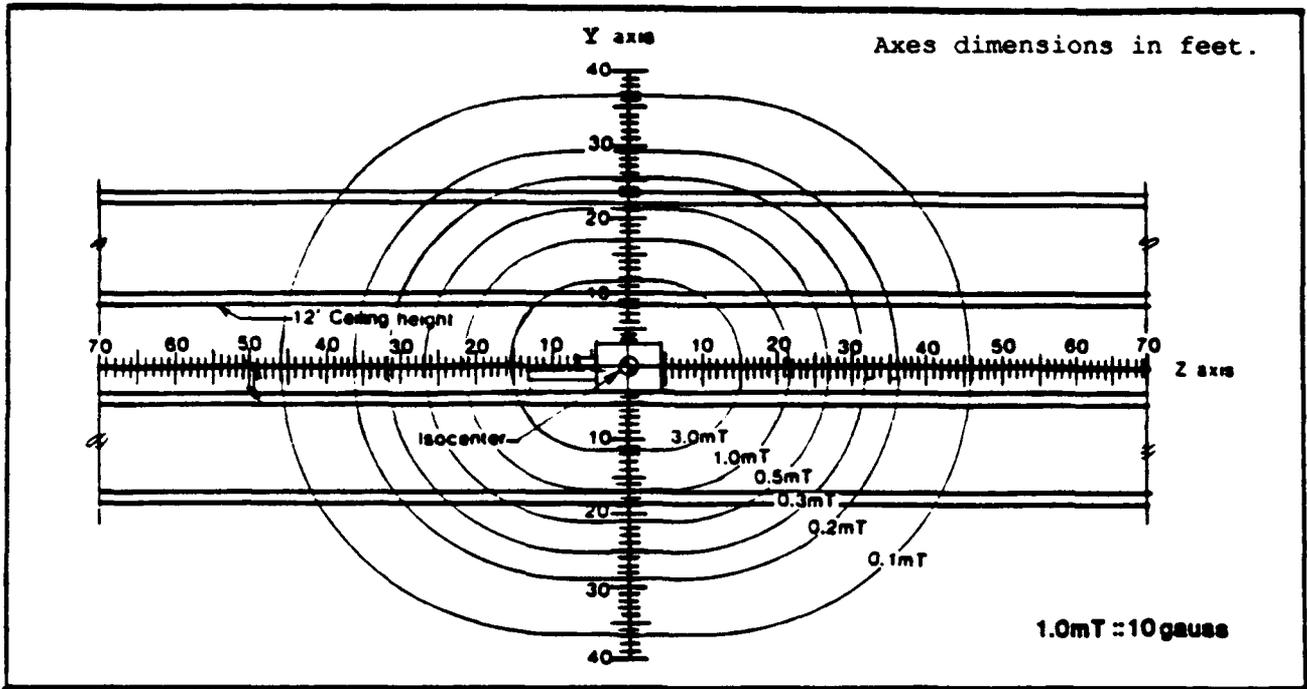


FIGURE 4 PLOT OF VERTICAL FIELD GENERATED BY A 0.5T UNSHIELDED MAGNET

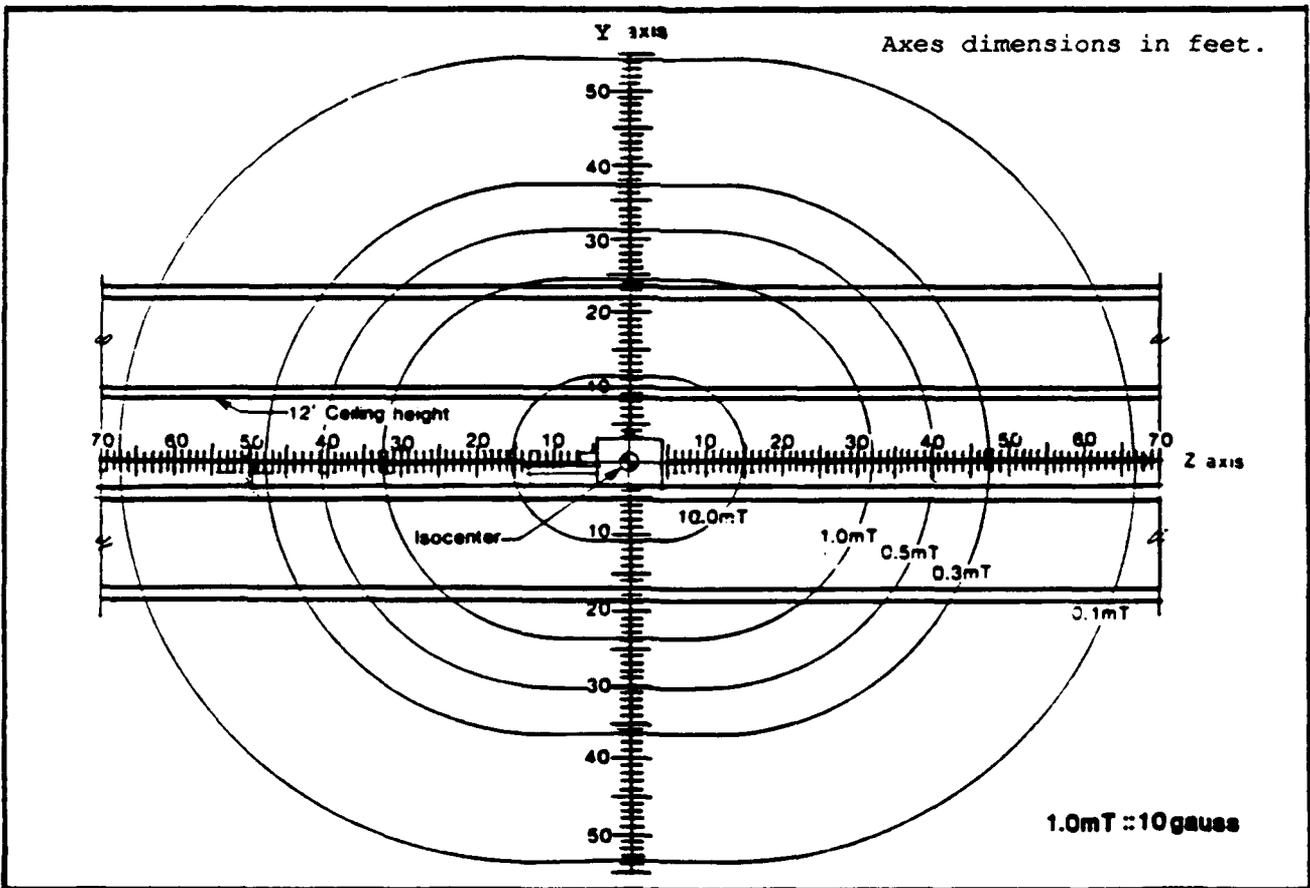
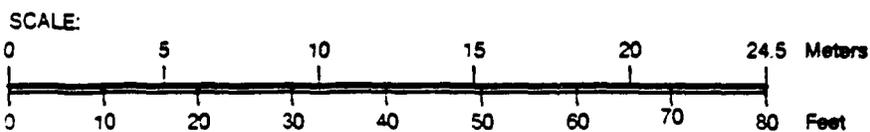
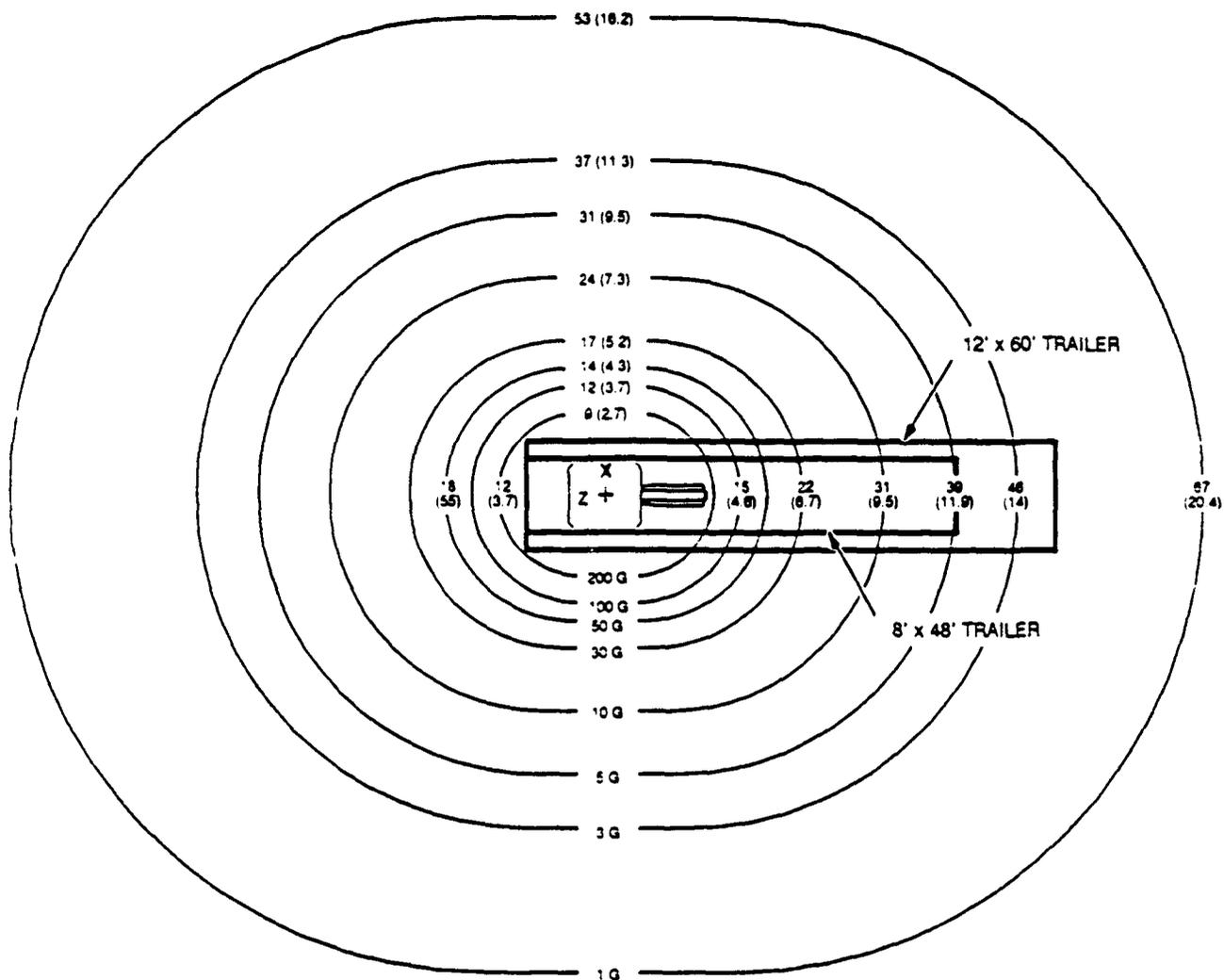


FIGURE 5 PLOT OF VERTICAL FIELD GENERATED BY A 1.5T UNSHIELDED MAGNET

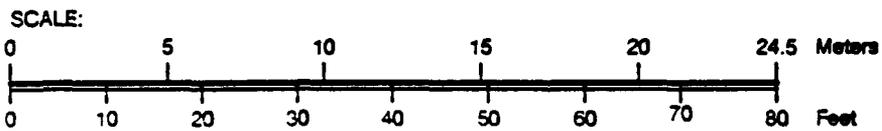
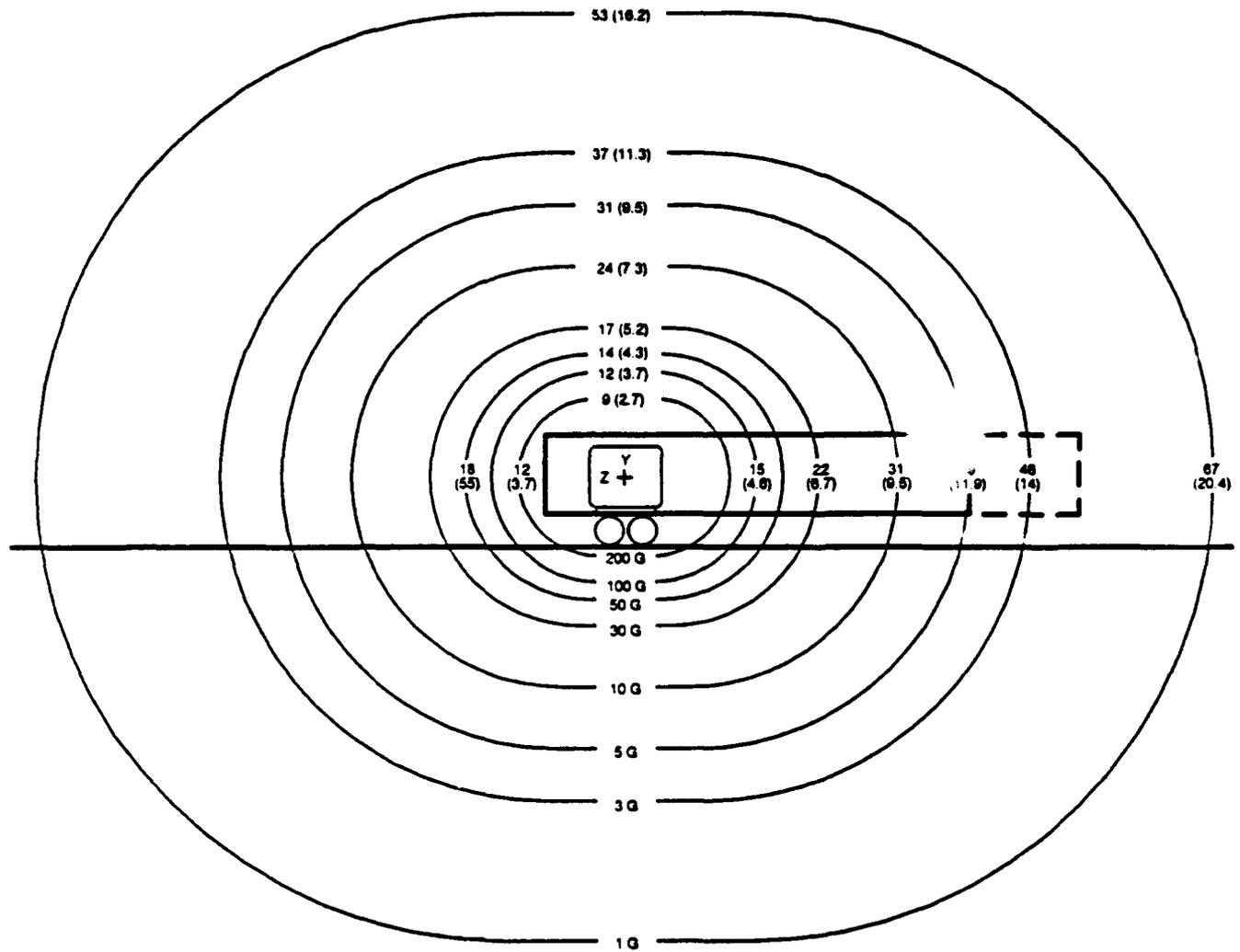
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FIGURE 6 TRAILER MOUNTED, 1.5 TESLA MAGNETIC ISOGAUSS LINE PLOT WITHOUT SHIELDING, HORIZONTAL VIEW



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FIGURE 7 TRAILER MOUNTED, 1.5 TESLA MAGNETIC ISOGAUSS LINE PLOT WITHOUT SHIELDING, VERTICAL VIEW

The magnetic field is generated by running a direct current (dc) through a wire made of a superconducting alloy. This alloy has no electrical resistance at 4.2 degrees Kelvin. Dewar vessels of liquid helium and nitrogen are used to maintain the low temperature required. Once a superconducting magnet is charged, it requires no sustaining electrical supply to maintain its field as long as the superconducting temperature is maintained. The manufacturers report that the current only needs to be replenished every 3 years. Thus, electrical power costs are low.

The only practical way for a hospital to shut off this type of MRI is to allow the cryogen to boil away. This causes the coils to become resistive and terminates the current flow that produces the magnetic field. However, at approximately \$15 per liter, liquid helium is expensive. This makes it economically impractical to shut the magnet off when it is not in use, because several thousand dollars worth of helium will boil away. Therefore, the magnet is normally operating and the magnetic field is usually present with a superconducting magnet.

There are other drawbacks associated with superconducting magnets. Finding a suitable location for the magnet may be difficult because of the large area covered by the fringe field. In addition, there are safety concerns associated with the open bore construction of the magnets. There is a "missile effect" which comes into effect around the 50 G contour. At this field strength, small ferrometalic objects may be drawn into the magnet at high speeds. At 100 G, even large objects may be pulled into the magnet. As shown in figure 4, the 50 G contour line only extends out to a distance of approximately 18 feet on an unshielded 1.5 T magnet. However, special precautions are taken to keep people and ferrous objects out of this area. These precautions are discussed in section 2.5.

2.2.1.3 Resistive Magnets

Resistive magnets are the least popular of all the magnet types. NEMA estimates that less than 2 percent of MRIs in the United States use resistive magnets. The reasons for this are the constant electric power consumption, limited field strength, and poor field stability. Resistive magnets can generate field strengths of 0.02 to 0.3 T. They weigh between 1 and 25 tons. The magnetic field is generated by a direct current conducted through ordinary resistive wire. Resistive magnets also require a circulating water cooling system. High field strength resistive magnets are not practical as power costs and cooling requirements become prohibitive. On the other hand, they have a low purchase price and can be easily turned off.

Configurations of resistive magnets include air core designs and iron core designs. The iron core magnets contain the magnetic field in the body of the magnet and produce no fringe field. The air core designs do produce fringe fields.

2.2.1.4 Permanent Magnets

Permanent magnets are also used to generate the static field required for MRI. NEMA estimates that less than 8 percent of the MRIs in the United States use

permanent magnets. This is due to their high cost and low field strength. The field strength generated is limited to between 0.1 and 0.3 T, and the magnet can weigh more than 100 tons. The field also suffers from inhomogeneities that degrade image quality. However, the magnet requires no electricity and produces minimal fringe fields. This type of magnet should produce no effects significant to helicopter operations.

2.2.2 Radiofrequency System

Most MRI RF systems operate in the 16 to 85 MHz band for proton imaging and transmit about 20 kilowatts. This is within the bands used for commercial broadcasting of AM radio, TV, and FM radio. It also covers the band used for aviation marker beacons.

The RF signal, or echo, generated when the protons realign back into their low energy position is very weak. Therefore, all MRIs require a device known as a Faraday shield to prevent commercial broadcasts from overwhelming them. The Faraday shield eliminates most system/environment interference.

Typically, a Faraday shield around an MRI diminishes incoming and out-going RF radiation by 80 dB (1/10,000) to 100 dB (1/100,000) over the relevant frequencies (reference 5). This shielding also protects the external environment from the RF being transmitted by the MRI. Therefore, the helicopter pilot need not be concerned with an MRI RF system interfering with any of the onboard electronics. Realistically, if one of these RF shields were ever to leak, the MRI process would be disrupted before there was any interference to aviation frequencies. However, any interference noticed should be reported to the hospital and the Federal Communications Commission (FCC) at once. The RF system is not operational when the MRI is not in use.

2.2.3 Gradient System

The imaging process depends on the magnetic field being known and precisely controlled throughout the patient's body. The gradient system is used to modify slightly the strength of the main magnetic field in all directions. For most MRI manufacturers, this is denoted with X, Y, and Z axes, as shown in figures 2 and 4. The Z-axis is parallel to the axis of the main magnet and, in the horizontal plane, parallel to the long axis of the human body; the X-axis is orthogonal to the Z-axis and in the horizontal plane; the Y-axis is orthogonal to the other axes and in the vertical plane.

Since the resonant RF frequency at each point in the tissue is proportional to the local field strength, the purpose of modifying the main field strength is to change the resonant frequency across the area being imaged. Thus, the resonant frequency might be 60.1 MHz at coordinates (X_1, Y_1, Z_1) , but it would be slightly different at the adjacent set of coordinates. Only protons at one set of coordinates in the gradient field will resonate at each frequency. The computer generates a picture by changing the transmitted frequency and knowing where the resultant field strength that will resonate at each frequency is. Thus, each RF signal which is returned is tagged with its exact location in the imaged area.

The preceding discussion also explains why inhomogeneity in the magnetic field produces errors in the constructed image. If the field is not completely stable and predictable, the computer will tag an RF echo with the wrong location (reference 6). This explains why most hospitals leave their resistive magnets on, even when they are not being used. It takes several hours for a resistive magnet to warm up and not experience fluctuations in the magnetic field due to temperature fluctuations in the magnet's core.

2.2.4 Computer System

A computer is used to construct a picture that is presented on a computer monitor. This picture shows a cross-sectional view of the patient. The computer analyzes the strength and location of each signal in the picture and uses the data to construct a grey scale image. The grey scale tone is directly proportional to the proton density at each point in the picture. Since hydrogen density varies with tissue type, an image of the tissue is produced. The computer also controls the data acquisition system, and the timing of the RF system and gradient system.

2.2.5 Magnetic Shielding

Magnetic shielding may be used to alter the path of the flux lines of the magnetic field and reduce the area exposed to a given field strength. However, shielding cannot eliminate the fringe fields associated with MRI.

In most cases, magnetic shielding is separate from the RF shielding discussed above. However, the two types of shielding can be combined. All shield designs use steel that, when magnetized by the fringe field itself or by auxiliary electromagnet coils, produces fields opposing and cancelling the fringe field (reference 7).

The net result of magnetic shielding is the reduction of the extent of the static field. The radius of the 5 G, or any other, contour line is reduced by 30 to 70 percent in all three directions. Therefore, the volume of the field is approximately 10 to 20 percent of the unshielded volume, and the horizontal area covered by the field covers only 20 to 30 percent of the unshielded area. The actual reduction is dependent on the amount of steel used in the shield or the size of the auxiliary coils. These factors can vary from site to site if custom shields are developed. Table 2 contains a comparison of the dimensions of the 5 G contour line for various shielded and unshielded magnets.

There are three approaches to magnetic shielding: 1) closed flux path screens, 2) partial screens, and 3) active shields with equivalent current shells (reference 8). Sometimes active shields are referred to as "self-shielding." There is also a fourth option, to use no shielding at all and let the fringe field run its natural course. However, if no shielding is used around a powerful superconducting magnet, the hospital must be prepared to devote a large amount of space exclusively to the fringe field.

TABLE 2
COMPARISON OF 5 GAUSS FRINGE FIELD VOLUME

MRI MANUFACTURER	MAGNET STRENGTH (T)	TYPE OF SHIELD	EXTENT OF AREA WITHIN 5 G CONTOUR (X x Y x Z in Feet)
Diasonics	0.35	None	19x19x25
	0.35	Self	8.5x9.5x12.5
Elsant	0.5	None	21x21x28
	0.5	Self	9x9x14
Philips	1.5	None	32x32x40
	1.5	Closed-Flux	16x16x28
	0.5	None	22x22x28
	0.5	Closed-Flux	13x13x22
Picker	1.0	None	27x27x33
	1.0	Self	8x8x12
	0.5	None	21x21x27
Siemens	0.5	Self	8x8x11
	1.5	None	32x32x40
	1.5	Self	16x16x23
	1.0	None	25x25x33
	1.0	Self	13x13x20

x = lateral dimension, y = vertical dimension, z = longitudinal dimension

2.2.5.1 Closed Flux Path Screens

Closed flux path screens may be used with superconducting and air core resistive magnets to contain the 5 G line at a specific location. This involves the placement of custom designed steel plates in a specific arrangement around the magnet. Usually the shield goes all the way around the magnet. However, in some designs the ceiling of the MRI may not be shielded. This may cause the field to extend further than normal in the vertical direction. The steel in these shields may weigh from 50 to 200 tons and cost from \$100,000 to \$300,000. Closed flux screens are usually found associated with permanent MRI installations.

2.2.5.2 Partial Screens

In partially shielded configurations, the steel plates do not go all the way around the magnet. There may be edge effects along the periphery of shielding that produce field strengths in excess of those present without shielding (reference 9). Many of the garage type screens for mobile MRI units fit into

this category. The General Electric (GE) mobile bay, shown in figures 8 and 9, is an example of this type of shield. The steel plates partially cover the sides, top, and bottom of the magnet, but the front and back are open. The 5 G line of the magnetic field juts out approximately 9 feet from the shield at the open ends. It also extends out approximately 14 feet from the back of the trailer. However, as shown in figure 6, without the partial screen the 5 G line would extend out 30 feet from the back of the trailer. In this case, the partial screen reduces the field strength in all directions.

2.2.5.3 Self-Shielding Magnets

Self-shielding is another means of reducing the fringe field associated with an MRI magnet. The reduction is accomplished by either a counter magnetic field developed within the magnet itself or by adding ferromagnetic material to the magnet housing to absorb some of the excess field. The reduction in the extent of the fringe field for self-shielded magnets is generally between 50 percent and 65 percent of the normal fringe field. Table 2 contains a comparison of the reduction factors associated with self-shielding magnets. Self-shielding can also be used in conjunction with normal steel screens to reduce the extent of the fringe field still further.

2.2.6 Mobile MRI Units

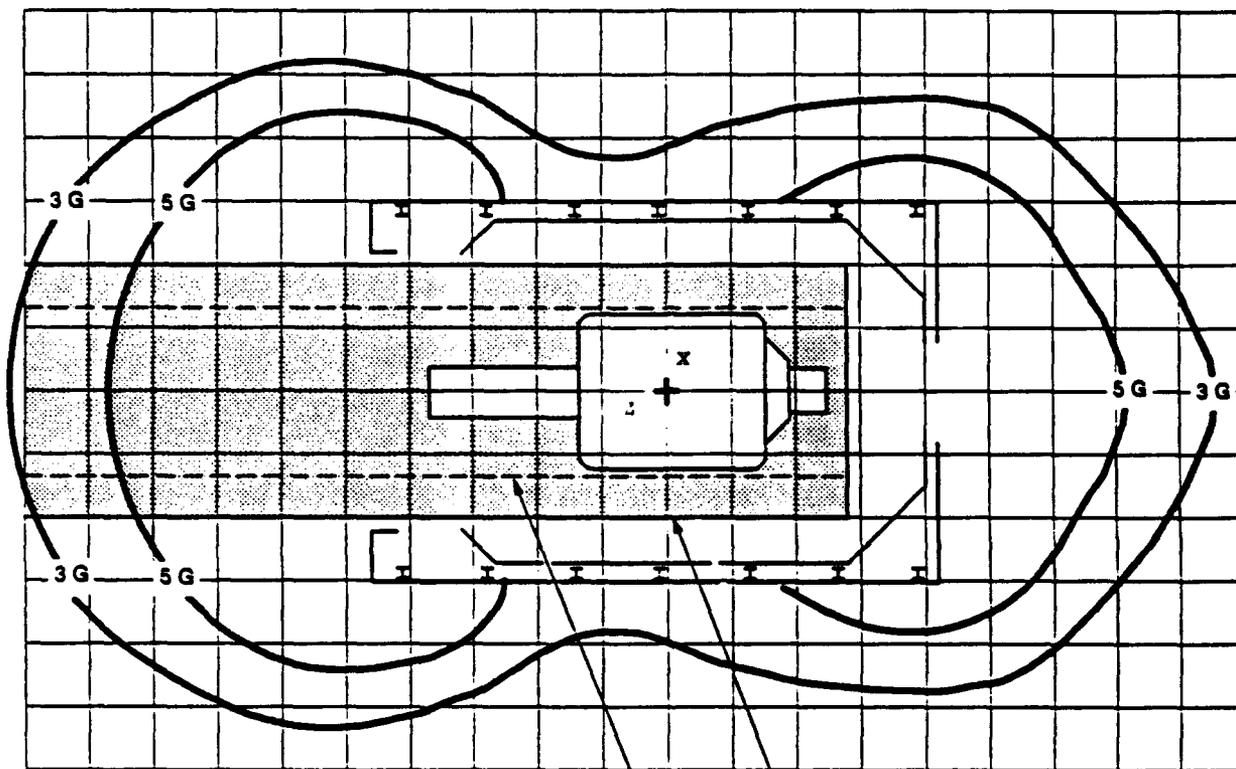
Some hospitals opt to share a mobile MRI rather than bear the full cost alone. Mobile units are mounted in tractor-trailers. All trailers have the magnet and scan room at one end of the trailer and the electrical equipment at the other end. This separation is usually sufficient to keep the computer system and the cathode ray tubes (CRTs) outside a 10 G contour line. In the middle of the trailer, there is either an open area or two separate areas with a private space for the physicians' work area (reference 10).

All trailers must meet Federal bridge and highway standards for height and weight. Standard trailers can be no more than 8 feet wide by 48 feet long and weigh no more than 80,000 pounds, including the tractor. Oversize trailers can be up to 12 feet wide by 60 feet long and require special permits to be moved.

Some mobile systems use self-shielding to contain the 5 G contour line within the 8 foot width of the trailer, as shown in figure 10. Other non-shielded mobile units allow the 5 G line to extend almost 27 feet outside of the trailer walls, as shown in figures 4 and 5. Other locations are constructing garage-like structures out of steel to act as partial shields, as shown in figures 6 and 7.

2.2.7 Volume of Coverage

Figures 6 and 7 illustrate a typical volume of coverage for an unshielded 1.5 T magnet. The 3 G isogauss line on these figures will be used in the following discussion for two reasons. First, it is recommended by the MRI manufacturers that helicopters remain outside of the 3 G contour. Second, with current technology it is probable that 3 G is the maximum exposure a helicopter will get from an MRI in normal operation. The small "+" at the



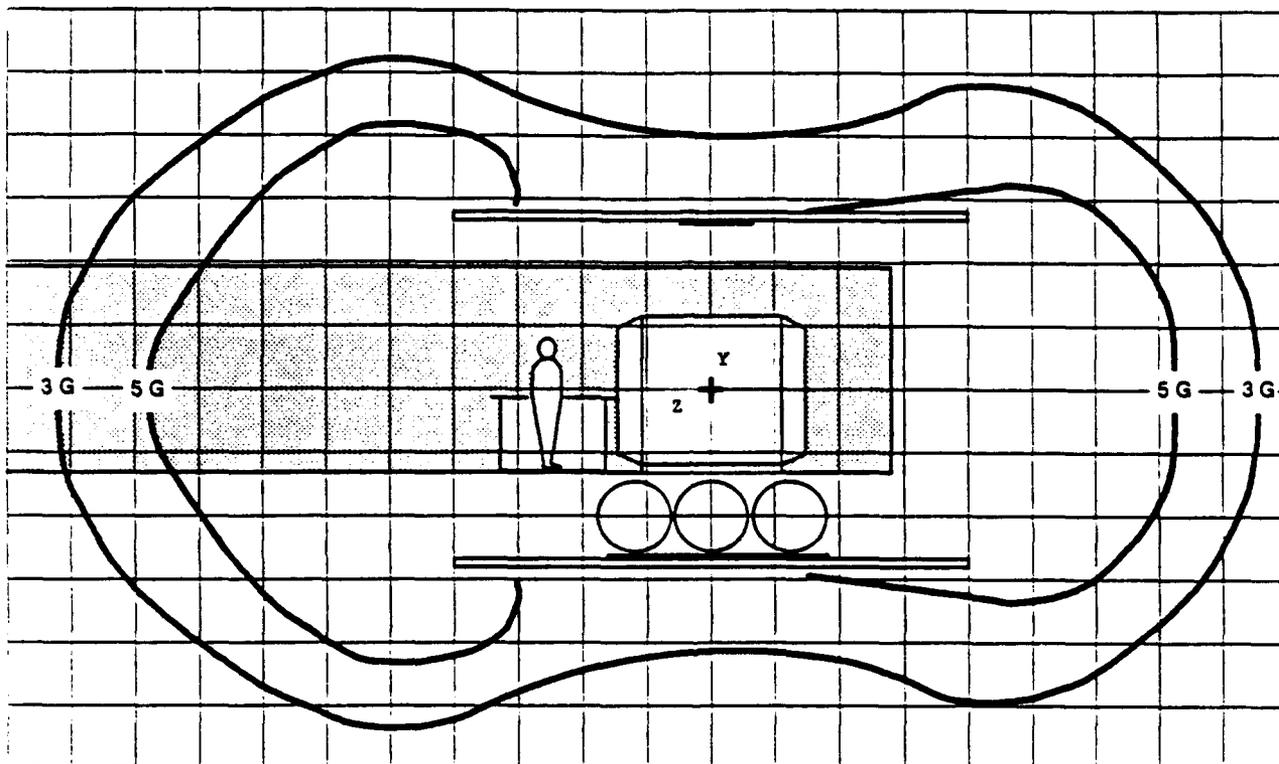
1 SQUARE = 3'0"

8' x 48' VAN 12' x 60' VAN

M163946

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FIGURE 8 TRAILER MOUNTED, 1.5 TESLA MAGNETIC ISOGAUSS LINE PLOT WITH GE MAGNETIC RESONANCE MOBILE BAY HORIZONTAL VIEW



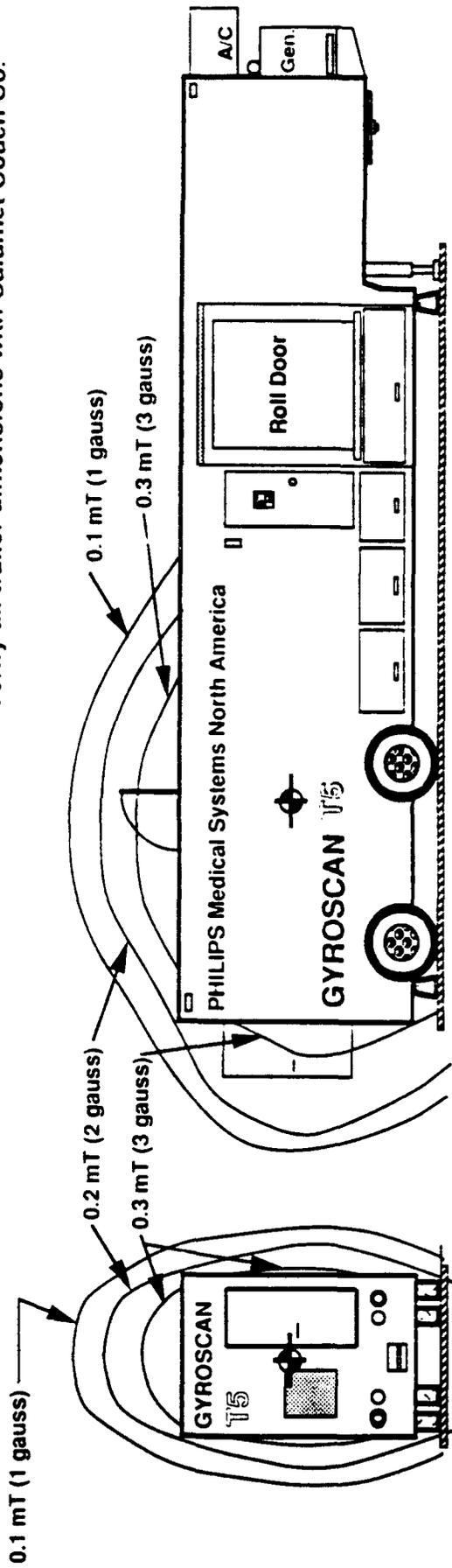
SQUARE = 30°

M1840A2

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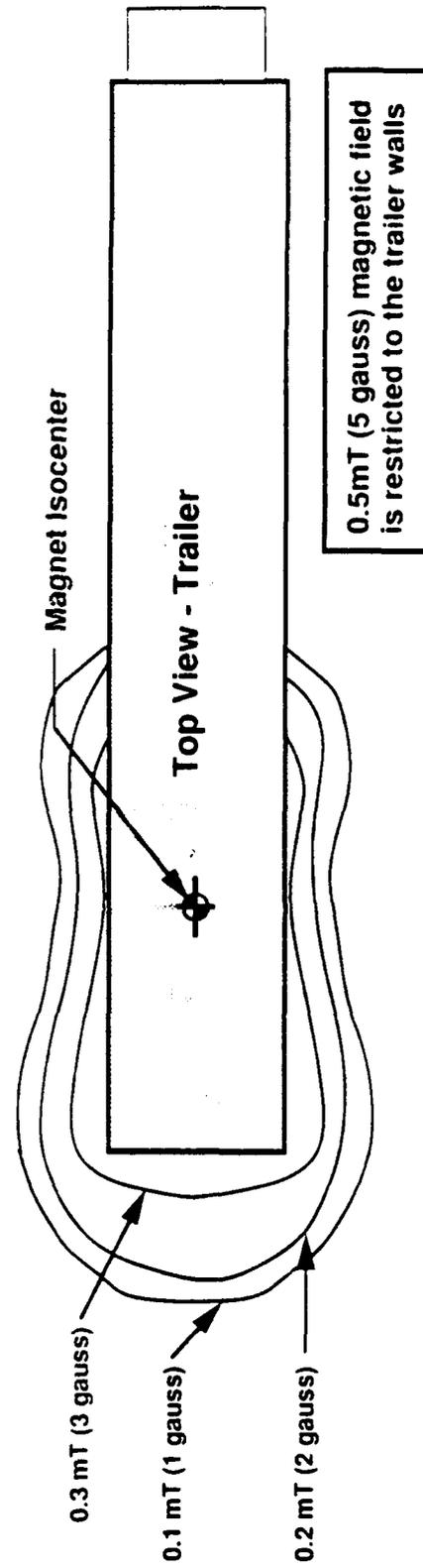
FIGURE 9 TRAILER MOUNTED, 1.5 TESLA MAGNETIC ISOGAUSS LINE PLOT WITH GE MAGNETIC RESONANCE MOBILE BAY VERTICAL VIEW

Verify all trailer dimensions with Calumet Coach Co.



Curbside View

Rear View



Magnetic Field Plan - GYROSCAN T5 Mobile System

Scale: 1/8" = 1'-0"

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FIGURE 10 SELF-SHIELDED 1.5T MAGNET

center of the contour lines represents the center of the magnet. Figure 6 shows that in the horizontal plane the 3 G field strength extends 46 feet from the center along the main axis of the magnet (the Z-axis) and 37 feet along the X-axis. Figure 7 shows that in the vertical plane, the 3 G field strength extends 37 feet above the center of the magnet along the Y-axis.

Figures 8 and 9 illustrate a typical volume of coverage for the same 1.5 T magnet with partial shielding. Again the 3 G isogauss line will be used in the discussion. The shaded area inside the contour lines represents the trailer within which the MRI is installed. The white rectangle inside the shaded area is the MRI itself; "+" in the center of the MRI shows the position of the magnet. The scale is such that each line represents 3 feet. Figure 8 shows that in the horizontal plane, the field strength extends to a distance of 25.5 feet along the main axis of the magnet (Z-axis), and from 12 feet to 15.75 feet along the X-axis. Figure 9 shows that in the vertical plane, the field strength extends to a distance of 12 to 15 feet above the center of the magnet.

The strength of the magnetic field drops off inversely proportional to the cube of the distance. In other words, if the distance from the magnet is increased by two times, the strength of the magnetic field is decreased eight times ($2^3 = 8$). Since 50 feet is two times 25 feet, the field strength is $(3 \text{ G})/8$, or approximately 0.4 G. Appendix A contains a full discussion of the calculations.

Shielding reduces the extent of the field's coverage at a strength of 3 G by approximately 50 percent. However, the reduction is not equal in all directions. The isogauss lines are constricted most within the shielded area. Then they balloon out at the breaks in the steel shield at the back and front of the shield bay. While in this example partial shielding has reduced the overall extent of the field in all directions, this may not always be the case.

3.0 FEDERAL REGULATION OF MRI

This section will identify pertinent government regulations, standards, and guidelines that apply to MRIs now or might apply in the future. There are no existing regulations governing the leakage of MRI static magnetic fields. Currently, only the FDA has the authority to regulate MRI fringe fields. No Federal agency has regulations or standards for testing equipment in static magnetic fields. Trial and error seems to be the method used to determine the permissible exposure limits.

The FDA has issued MRI guidelines concerned with the safety of patients and other personnel. In the bore of the magnet, exposure to no more than 2 T (20,000 G) is the standard. For other personnel, outside the bore, exposure to less than 5 G is the standard. Based on a history of safe operations, these appear to be safe operating standards. In addition, the MRI industry, being aware of the potential hazards of their product, has generally taken prudent precautions that are discussed in section 3.4.

3.1 FOOD AND DRUG ADMINISTRATION

In 1976 Congress passed the Medical Device Amendments to the Food, Drug, and Cosmetics Act. The purpose of the Act was to assure safety and efficacy of medical devices. As a result, the Federal government, through the FDA's Division of Radiologic Health, evaluates new medical technologies and certifies that they are safe and that they perform the tasks the manufacturer attributes to them (reference 11). FDA intervention is necessary for two reasons: 1) it is impractical for physicians to evaluate individually all new medical technologies, and 2) patients are even less able to evaluate the safety and value of new technology. This Act requires the FDA to evaluate all medical devices marketed in the United States. It also gives the FDA authority to require premarket approval for certain medical devices.

The MRI was the first technology to be required to have full-scale clinical testing as an experimental device and premarket approval (reference 12). However, the FDA is limited by the Act to assuring only the safety and efficacy of the device. This act cannot be used to cover the effects of MRIs on helicopter flight operations. The Act is discussed because it is the only Federal standard currently applied to MRIs.

All FDA approvals to market MRIs are made with the condition that pacemaker wearers be warned of the potential risk upon entering fields greater than 5 G (reference 13). This effectively requires the manufacturers to develop a map of the field strength and define a 5 G safety limit at each site. Field strengths weaker than 5 G are not restricted in any way.

The reason that the 5 G line must be identified for pacemaker wearers is to prevent the pacemaker from possible reprogramming. There are numerous heart rhythms possible from some models of pacemakers. The pacemaker senses various bodily indicators and selects a program to produce the proper heart rhythm for the sensed activity of the wearer. As a safety precaution, default mechanisms are incorporated into pacemakers so that external application of a magnetic field will cause the pacemaker to revert to a basic heart rhythm and require

reprogramming before it resumes full functionality (reference 14). The field strength required to trigger this fail-safe response in some older pacemakers may be as low as 7 to 10 G.

However, with advances in pacemaker technology, it is believed that the reprogramming problem in current technology pacemakers starts at the 15 G to 20 G level, not at the 10 G level. Therefore, there may be a change from the current 5 G warning line up to 10 G. There is interest in doing this in the European medical community. If the warning line is increased there, the FDA will probably follow suit (reference 15).

There is another law, The Radiation Control for Health and Safety Act of 1968 (reference 16), which could be used by the FDA to set and enforce performance and/or safety standards on MRIs. This law could be used to protect helicopters from exposure to MRI fringe fields. The following quote is from the introduction to the Act:

The purpose of this Act was to protect the public from unnecessary exposure to radiation from electronic products. Radiation covered in the Act was called "electronic product radiation" and was defined to mean any ionizing or nonionizing electromagnetic or particulate radiation or any sonic, infrasonic, or ultrasonic wave which is emitted from an electronic product as the result of the operation of an electronic circuit in such product. ... A principal objective of the program is to protect the public health through setting and enforcing electronic product radiation emission performance standards.

This act requires the FDA to maintain an electronic product radiation control program. Three of the six parts of the program are quoted below:

(2) plan, conduct, coordinate, and support research, development, training, and operational activities to minimize the emissions of and the exposure of people to, unnecessary electronic product radiation;

(3) maintain liaison with and receive information from other Federal and State departments and agencies with related interests ... on present and future potential electronic product radiation;

(6) consult and maintain liaison with ... appropriate Federal departments and agencies on (A) techniques, equipment, and programs for testing and evaluating electronic product radiation, and (B) the development of performance standards ... to control such radiation emissions. (Reference 17).

Since this Act covers public health and safety, it could be used to impose new regulations on the MRI industry if an unsafe condition is identified in the

future. However, this Act only gives the FDA the authority to regulate. There are no current regulations on MRIs invoked under the Act.

3.2 FEDERAL COMMUNICATIONS COMMISSION

The Federal Communications Commission (FCC) does not actively regulate medical devices. Rather, the FCC defers to the FDA for the regulation of medical devices (reference 18). However, they do maintain liaison with the FDA and are aware of MRIs. Furthermore, all FCC regulations on noninterference with RF bands must be met to obtain FDA approval.

The FCC issues regulations dealing with electromagnetic interference. If MRIs were causing electromagnetic interference to the operation of other electromagnetic equipment, the FCC would have regulatory authority. However, the low end of regulated frequencies stops at 9 KHz. Anything below 9 KHz is considered to be nonradiating. By implication, there is nothing in an MRI fringe field for the FCC to regulate. Appendix C contains a discussion of the coupling of extremely low frequency (ELF) radiation and why FCC tables of regulated frequencies stop at 9 KHz.

The promulgation of any new regulation would require new rulemaking. This would require establishing an FAA/FCC advisory group to study and define the interference. Next there would have to be a notice of inquiry to the public and manufacturers requesting comments on the proposed rulemaking. Then there would have to be a notice of proposed rulemaking, and finally a report and order would be issued. This process would take several years even if it were not contested by anyone.

3.3 OCCUPATIONAL SAFETY AND HEALTH ADMINISTRATION

The Occupational Safety and Health Administration (OSHA) has the authority to regulate anything in the work place that might constitute a hazard to workers. However, the FDA is charged with the same responsibility, including the safety of product radiation for medical patients. OSHA defers to the FDA for regulation of radiation from medical devices such as MRIs. However, all OSHA requirements on sound levels and user protection must be met.

3.4 MANUFACTURERS AND PROFESSIONAL ASSOCIATIONS

The MRI industry is interested in preventing any unsafe conditions associated with fringe fields. They have a well-defined safety program that is discussed in this section. More than that, however, the industry has to prevent any external phenomena from interfering with the homogeneity of the static magnetic field, and prevent the fringe field from interfering with associated MRIs and other medical equipment in the area. The precautions the MRI industry is now taking to prevent the external environment from affecting the homogeneity of the field should preclude any permanent effects on helicopters or the personnel onboard. Of course, the already mentioned temporary effects of the fringe field on magnetic sensors must still be considered.

MRI manufacturers all publish guidance in their site planning guides addressing the maximum gauss field in which various devices may reside. Table 3 is an example of one manufacturer's recommended maximum exposure levels. The American Association of Physicists in Medicine (AAPM) has a similar list (reference 19). The AAPM also recommends the use of four different zones to define various regions of the magnetic fringe field (reference 19). Zones 1, 2, 3, and 4 are defined as greater than 15 G, 5 to 15 G, 2 to 5 G, and 1 to 2 G, respectively. Different types of equipment or activity can then be permitted within these zones in accordance with the manufacturer's recommended exposure levels. Zone 1, greater than 15 G, should be designated by signs that read, "CAUTION - HIGH MAGNETIC FIELD," because this area is not far from the range at which ferrous objects can be pulled toward the magnet. The FDA warning to people with pacemakers is required at the boundary of zone 2. No administrative controls are necessary for zones 3 and 4.

All manufacturers ensure the magnet is in a secure area defined with barriers and warnings. All entrances have positive locking mechanisms to keep out unauthorized persons. Metal detectors and patient checklists are used to prevent inadvertent introduction of potentially hazardous metallic objects into the secure area. Most manufacturers recommend that this secure area start before about the 50 to 100 G line (reference 21). Depending on the ferrometallic alloy of the object, this is the area where small objects can be drawn into the bore of the magnet with lethal force or permanent magnetism can be induced. This area is usually inside the RF screen room in a permanent installation (reference 22).

However, on some unshielded mobile units this area may extend outside of the trailer. In this case, some positive means of preventing a helicopter from coming in contact with such a strong field should be present (i.e., signs warning of the high magnetic field). In addition, a helicopter should be prevented from landing on the roof of an unshielded MRI. Such intense exposure to the pilot and passengers would be a violation of the FDA limit and the MRI industries' recommended security zone. It could also lead to a forced or crash landing, since the helicopter might be pulled down with great force.

TABLE 3
MAXIMUM GAUSS FIELD IN WHICH VARIOUS DEVICES MAY RESIDE

<p>Less than 0.5 Gauss:</p> <ul style="list-style-type: none"> o Nuclear Cameras <p>Less than 1 Gauss:</p> <ul style="list-style-type: none"> o Positron Emission Tomography Scanner o Cyclotrons o Electron Microscope o Accurate Measuring Scales o Linear Accelerators o Image Intensifiers o Color Television o Video Display (Color, B/W, Monochrome) o CT Scanner o Nuclear Tomography Scanner o Ultrasound Equipment o Lithotripter <p>Less than 3 Gauss:</p> <ul style="list-style-type: none"> o Passenger and Freight Elevators o Power Transformers o Main Electrical Distribution Transformers o Moving Steel Equipment such as: <ul style="list-style-type: none"> - Vehicular Traffic - Fork Lift Trucks - Dumb Waiters - Electric Transport Carts - Loading Dock (Truck Traffic) - Elevators - Escalators - Helicopters* <p>Less than 5 Gauss:</p> <ul style="list-style-type: none"> o Cardiac Pacemakers o Neurostimulators o Biostimulation Devices 	<p>Less than 10 Gauss:</p> <ul style="list-style-type: none"> o Major Mechanical Equipment Room o Water Cooling Equipment o HVAC Equipment o Large Steel Equipment such as: <ul style="list-style-type: none"> - Emergency Generators - Commercial Laundry Equipment - Food Preparation Area - Air Conditioning Chiller - Fuel Storage Tanks - Motors Greater Than 5 Horsepower o VCR o X-Ray Tubes o Magnetic Tapes and Floppy Disks o Credit Cards, Watches, and Clocks o Telephone Switching Station o Film Processor <p>Less than 30 Gauss:</p> <ul style="list-style-type: none"> o Remote Console o Multiformat Camera <p>Less than 50 Gauss:</p> <ul style="list-style-type: none"> o Telephones o Metal Detectors for Patient Screening o Distant Remote Amplifier Cabinet <p>Less than 100 Gauss:</p> <ul style="list-style-type: none"> o Laser Camera
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* Verify operating limits with provider of helicopter service.

Reference 41.

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4.0 MAGNETIC EFFECTS ON HELICOPTERS

This section will discuss permanent, cumulative, and temporary effects of MRI fringe fields on helicopters. In addition, background information on electromagnetic fields will be provided to help the reader understand how these effects couple with aircraft.

4.1 ELECTROMAGNETIC FIELDS

There are three types of electromagnetic fields: 1) static electric, 2) radiated electromagnetic, and 3) static magnetic. Although this report is mainly concerned with the static magnetic field, a short description of all three field types will be presented to inform the reader of the potential dangers of electromagnetic fields other than static magnetic.

4.1.1 Static Electric Fields

Static electric fields are caused by charge (electron) separation, measured in volts. When the voltage difference becomes large enough to ionize the air or other insulator providing the charge separation, a rapid equalization of the voltage difference occurs in the form of a dc current. The most common example is the static electric charge generated on one's body by rubbing one's feet on a carpet, and then discharged by touching an uncharged or grounded object like a door knob. This same principle is the cause of atmospheric lightning. Lightning can produce current flow in excess of 200 amps (reference 23). A current flow that large can destroy electronics and induce permanent magnetism. This is why all aircraft have lightning protection.

4.1.2 Radiated Electromagnetic Fields

Radiated electromagnetic fields are caused by charge acceleration. This is why TV and radio signals have a frequency; the charge flow that creates these signals is constantly changing direction at a constant frequency, hence the term alternating current (ac). Current flows in one direction, stops, and reverses direction in a sinusoidal pattern. If the current flow is in an antenna (e.g., a wire half a wavelength long), some of the energy in the current will be lost. The lost energy is radiated into the air or space. This electromagnetic energy can be received by another antenna where it induces an alternating current and voltage. If the energy coupled into the antenna is anticipated, it can be harnessed to transmit information or power. On the other hand, if the coupled energy is not anticipated, it can be destructive. It can destroy or interfere with digital and analog circuits.

4.1.3 Static Magnetic Fields

Static magnetic fields are caused by charge movement or permanent magnets. The charge movement is usually a dc current, such as in resistive and superconducting magnets. However, other forms of charge movement also cause static magnetic fields. For example, the earth's magnetic field is caused by the rotation of the earth on its axis. The rotation causes the electrons in the iron in the earth's core to generate a static magnetic field.

The fact that it takes energy in the form of electric current to produce a static magnetic field in an electromagnet is easily understood. However, it is not obvious that once the magnetic field is established, it takes no energy to maintain it. No power is lost from the magnetic field. An example of this is a permanent magnet; once it is magnetized, no more power is required to maintain the field. Appendix D contains a more detailed discussion of the electromagnetic theory behind this fact.

Superconducting and resistive magnets will lose their fields if the current stops flowing, but all the energy from the field comes back into the magnet. No power is radiated from the magnet. No power couples into anything in the external environment. In actual operation, MRIs with superconducting magnets run for approximately 3 years before the current in the magnet needs to be replenished. This explains why static magnetic fields are much less dangerous to helicopter operations than the other types of electromagnetic fields. There is no coupling of voltage or current into electronic devices exposed to the field.

4.2 STANDARDS AND TEST REQUIREMENTS FOR STATIC MAGNETIC FIELDS

There are no standards or test requirements in industry, the military, or the FAA for susceptibility to static magnetic fields. Three major helicopter manufacturers, Bell, Sikorsky, and Aerospatiale, were contacted and none do any testing for susceptibility to static magnetic fields. Two avionics installers and two avionics manufacturers were contacted with the same result. The helicopter certification branch of the FAA, ASW-300, was contacted and they knew of no standards or tests for static magnetic fields.

All branches of the military have been contacted by the Army Corp of Engineers regarding the superconducting magnetic energy storage (SMES) project (reference 24). SMES is a project that stores energy in large static magnetic fields. Electric power generated during periods of low demand is stored in a magnetic field and reclaimed during periods of high demand. No regulations, or even major concerns, were identified within the military.

A new FAA advisory circular on HIRF is currently in the draft stage (reference 25). It does not address static magnetic fields. In fact, it specifically excludes high impedance fields of 10 to 100 kHz because they are so difficult to couple to an antenna.

4.3 TEMPORARY EFFECTS OF MRI FRINGE FIELDS

4.3.1 Magnetic Sensors

An MRI fringe field will cause anomalous readings in magnetic sensors such as wet compasses and magnetic flux valves. Appendix E contains a discussion of how these devices are used onboard a helicopter.

However, these sensors will not be permanently damaged or magnetized by MRI fringe fields. The wet compasses's needle is made of a permanently magnetized iron alloy that has high remanence and high coercivity (reference 26). Remanence is the alloy's ability to retain magnetism. Coercivity is the

alloy's ability to resist the effects of external magnetic fields (i.e., change the polarity of the magnet). Thus, the needle of a wet compass cannot be permanently affected by MRI fringe fields. It would take exposure to a field on the order of 100 G or more to permanently affect a wet compass (reference 27).

A flux valve is made of soft ferroalloy with an extremely low remanence. This means a flux valve is difficult to magnetize. Thus, it cannot become permanently magnetized by exposure to a magnetic field as weak as an MRI fringe field. It would take something like a lightning strike, which would change the crystal structure of the alloy, to permanently magnetize a flux valve (reference 28).

4.3.2 Cathode Ray Tubes

Cathode ray tubes (CRTs) may suffer noticeable effects at low field strengths of about 1 G (reference 29). This is because CRTs operate by shooting a slow moving electron beam at a phosphor-covered screen. The magnetic field exerts a force on the electron beam that causes it to curve. A 2 percent nonlinearity can be induced by a 3 G field, and a 5 percent nonlinearity can be induced by a 5 G field in an unshielded color CRT. Noticeable rotation of the display begins at 13 G (reference 30).

4.3.3 Photomultiplier Tubes

A photomultiplier is an electronic device that amplifies light energy. It contains a photocathode which releases electrons when struck by a photon of light. Thus, the effect of static magnetic fields on these devices is the same as discussed above for CRTs.

Photomultiplier tubes are used in night vision goggles (NVGs). They are susceptible to the fringe field of an MRI. MRI manufacturers recommend that photomultiplier tubes not be exposed to a field strength of more than 1 G. It is very probable that a helicopter could encounter a field strength of this magnitude when operating near an MRI.

Since there is currently some discussion about allowing EMS operators to use night vision goggles in their operations this issue will have to be considered before any FAA approval can be granted. However, this is probably not an operationally relevant issue. Hospital heliports should have adequate lighting. In fact, they typically have so much light that NVGs would be of limited value. Even though it may not make operational sense to use NVGs near a hospital helipad, pilots should be warned of this effect as part of the training requirements for use of NVGs.

4.4 CUMULATIVE EFFECTS OF EXPOSURE OF MATERIALS TO MRI FRINGE FIELDS

There are no cumulative effects from exposure of ferrometallic alloys to static magnetic fields. Exposure to these fields has an all-or-nothing effect. If the external magnetic field is strong enough (on the order of 50 to 100 G), the crystalline structure of the ferromagnetic alloy will be changed and some

level of permanent magnetism will be induced. If the critical magnetic field strength is not reached, no magnetism is induced in the alloy.

Atoms of non-ferrometalic material are even less affected by the fringe field than are ferrometalic materials. Therefore, there can be no cumulative or permanent effects on this type of material from MRI fringe fields.

4.5 PERMANENT EFFECTS OF MRI FRINGE FIELDS

There are no known permanent effects from exposure to MRI fringe fields. The field strength is too low to realign the crystalline structure of ferromagnetic alloys and induce permanent magnetism. The amount of magnetism required varies greatly with the specific alloy. However, a review of engineering texts and discussions with scientists at the National Institute of Science and Technology indicates that this effect does not begin until field strength approaches 100 G (references 31 and 32). This is within the region of the security zone of the MRI's high field.

A helicopter is not physically able to enter a field strength of anything close to 100 G from ground level direction. The rotor blades would strike the sides of an MRI trailer or building if a helicopter got close enough in the horizontal direction. However, if a helicopter were to land on the roof, half a story above an unshielded MRI, it could come into a 100 G field. If it did, it would in all probability be forcefully drawn into the roof because of the steel in the transmission and rotor mast. However, this would also require violating existing FDA and industry recommendations. Existing site planning guidelines already preclude this from happening except for cases of negligence.

4.6 MRI FRINGE FIELD EFFECTS ON HELICOPTER OPERATIONS

This section will discuss helicopter operations around a typical mobile MRI trailer both with and without shielding. A 1.5 T mobile MRI was chosen because it represents the worst case, the closest, a helicopter can come to an unshielded 1.5 T magnet MRI fringe field. A permanent installation would probably have more space all around the magnet simply for convenience and efficiency of the medical operators. The following discussion is for example only. Every MRI site has its own contour maps that should be referred to in order to ensure that the 3 G contour line is never crossed by the helicopter.

The "Heliport Design Guide" recommends that the final approach and takeoff area (FATO) be "at least one rotor diameter from the edge of the takeoff and landing area" (reference 3). In addition, there shall be "at least 1/3 rotor diameter, but not less than 10 feet, horizontal clearance between the takeoff and landing area (TOLA) and buildings, fences, ... and objects which could be struck by main or tail rotors." In addition, 8 feet of the distance along the Z-axis and 4 feet along the X-axis are inside the trailer. If a helicopter has a 33 foot rotor diameter, the closest it should come to the magnet along the Z-axis in normal operation is 52 feet (8 feet from the magnet to the rear of the trailer, 33 feet of TOLA, and 11 feet from the edge of the pad to any obstruction). As shown in figure 6, this will put the passenger compartment of the helicopter in the 1 to 3 G region of the field. In normal operation,

if a helicopter had to park off the FATO, it would taxi to the side of the TOLA away from any buildings (i.e., the MRI). However, in a worst case situation, a helicopter might taxi toward the MRI trailer. Even in the worst case, the closest the helicopter will ever come to the magnet along the Z-axis is 35.5 feet (8+16.5 feet of TOLA + 11 feet). A separation of 35.5 feet would put the helicopter between the 3 and 5 G contour lines. Along the X-axis the closest a helicopter should come in normal operation is 48 feet (4+33+11). A separation of 48 feet would put the helicopter just within the 1 G contour line. In the worst case, the closest the helicopter will ever come to the magnet along the X-axis is 31.5 feet (4+16.5+11). A separation of 31.5 feet would put the helicopter between the 3 and 5 G contour lines. These are extremely weak field strengths that will affect nothing but magnetic sensors. Section 5.0 will discuss the field strengths necessary to affect personnel.

For a 1.5 T magnet with partial shielding, the strongest field a helicopter is likely to be exposed to is 0.4 G as shown in figure 8. The closest a helicopter in normal operation should get to the shield is still approximately 50 feet. This is twice the distance that the 3 G line extends out from the center of the magnet. However, the pilot should always be aware of the possibility that partial shielding may cause the field to balloon outward in certain directions.

The overall conclusion a pilot should draw from this discussion is that at distances of approximately 50 feet from the center of the magnet, field strength can be on the order of 3 to 5 G. This represents a field strength approximately 10 times the strength of the earth's magnetic field. The wet compass and magnetic flux valves connected to the directional gyros onboard the helicopter will indicate the direction of the MRI fringe field's north pole and not the direction of the earth's north pole. Appendix B contains a discussion of how magnetic fields combine and the effects this has on magnetic sensors.

A level of 3 or 5 G is going to swamp the helicopter's magnetic sensors. Only the direction of the MRI field will be indicated by the compass system at this level. Although a helicopter can probably function in a 10 G field, it would be dangerous to do so. The 10 G isocontour is within 20 to 25 feet of the trailer walls of a mobile unit. The rotor blades would be very close, on the order of 2 to 7 feet from the MRI trailer or building. In addition, this area is very close, on the order of 10 or 15 feet, to the 50 G region where ferrous metal objects could start to be drawn into the magnet.

Moreover, the helicopter will start to interfere with the homogeneity of the magnetic field, and thus image quality, at 3 G. For these reasons, it is doubtful whether a helicopter will ever come within the 3 to 5 G contour line in normal operating circumstances.

5.0 EFFECTS OF MRI FRINGE FIELDS ON PERSONNEL

No harmful effects on human tissue have been identified from either intense or rapidly changing magnetic fields (references 33 and 34). Many literature reviews on the biological effects of static magnetic fields have revealed no harmful effects for fields of commercially obtainable strength. Few, if any, effects have been identified below field strengths of a few hundred gauss (reference 35). In three different lab studies specifically looking for the effects of ELF magnetic fields, only one was observed and that occurred after lengthy exposure time. There were no effects on electroencephalographs (EEG), electrocardiographs (EKG), blood pressure, or body temperature (reference 36).

The levels of exposure at which effects were observed could only be experienced in the bore of the magnet. The FDA limits the exposure of patients in the bore to 2 T, or 20,000 G (reference 37). Thus, patients are exposed to field strengths 4,000 times more powerful than the 5 G field to which a pilot might be exposed.

6.0 CONCLUSIONS

1. The main hazard from MRI fringe fields is that they can cause magnetic sensors to give aberrant readings. These fields are strong enough to influence magnetic sensors (compasses and flux gates) on a helicopter out to a distance of 500 feet from the center of the MRI magnet. As long as the pilot is aware of the possibility of anomalous readings, this should not be considered a hazard for VFR flight. A pilot is usually getting visual cues from outside the cockpit and not looking at the magnetic sensors within 500 feet of the helipad on a VFR approach or departure. One possible danger would be if a pilot looked at the compass for direction while still on the ground and then took off in the wrong direction. Under VFR, this should not cause a dangerous situation because it is the pilot's responsibility to see-and-avoid obstacles.

However, under IFR this could mislead a pilot enough to cause him or her to fly into unprotected airspace. For this reason, the allowable strength of MRI fringe fields must be severely limited if IFR operations are approved to the hospital helipad.

2. There are no cumulative effects from repeated exposure to magnetic fields. Magnetic fields have an all-or-nothing effect on materials. Ferromagnetic alloys may become permanently magnetized from exposure to field strengths of approximately 100 G. However, it is highly unlikely that a helicopter could come into an MRI field that strong, except in a case of negligence.
3. Fringe fields from an MRI are strong enough to influence CRTs and night vision goggles. Although no occurrences of distortion on helicopter avionics have been documented, EMS operators and the FAA should consider this effect when considering operations near MRIs.
4. Maintaining adequate separation from MRI magnets is the most effective means of avoiding adverse effects of MRIs on helicopter systems. A distance of 50 feet will usually keep the helicopter outside of the 3 G field. A distance of 500 feet will usually put the helicopter outside the 0.005 G field of high-powered, unshielded MRI. This will usually keep even an unshielded MRI from affecting magnetic sensors.
5. Vigilance of flight crews, helicopter operator, and hospital administrators is required to minimize potential hazards from MRI fringe fields. Cooperation among all three groups is necessary to ensure that a helicopter is never inadvertently exposed to a fringe field.
6. Most MRIs operate continually because of the high cost of shutting them down. Pilots should never assume that an MRI has been shut off. Rather, they should assume that the magnetic fringe field is always present and that the fringe field will affect magnetic sensors.

7. There is a possibility that the RF transmissions from an MRI could cause interference with radio communications. Any interference noticed when operating at a hospital helipad should be reported to the hospital administrator and the FCC.

7.0 CONTROL OF POTENTIAL MRI HAZARDS TO AVIATION

The main hazard to aviation identified during research into the effects of MRI fringe fields was that magnetic sensors will give aberrant readings without any warning to the pilot. In addition, CRTs and photomultiplier tubes may have some distortion in their display screens. These findings should eliminate many concerns of EMS operators and pilots. However, the fact that the wrong navigational information can be displayed to an EMS pilot in the vicinity of an MRI cannot be taken lightly. If a pilot was unaware of the presence of MRI fringe fields and took off into marginal VMC or instrument meteorological conditions (IMC) using an incorrect magnetic heading, a collision could result.

7.1 RECOMMENDATIONS

The following recommendations for the FAA, EMS helicopter operators, and EMS flight crews should prevent inadvertent flight into an MRI fringe field. If these recommendations are followed, there should be no possibility of a pilot flying into an MRI fringe field without full knowledge of its existence and its effect on the magnetic sensors.

7.1.1 FAA Actions

The FAA should alert helicopter operators to the possibility of anomalous compass readings within MRI fringe fields. This alert could possibly be put in "Heliport Design" (Advisory Circular 150/5390-2) in the section on hospital heliports, in "Emergency Medical Services/Helicopter" (Advisory Circular 135-14), or in a separate advisory circular on this subject.

Consideration should be given to marking hospital helipads with a distinctive symbol to indicate the presence of an MRI fringe field that will affect compass readings. A large arrow or triangle indicating the direction of the magnet's effect could be made into a national standard to warn pilots of the presence of a fringe field.

The FAA should issue education material warning pilots of the potential hazard of MRIs. This material should advise limiting the exposure of helicopters to no more than 3 G for VFR operations. This could be accomplished by preventing helicopters from coming any closer than 50 feet to the center of an MRI magnet. As discussed in section 4.6, there is already an existing recommendation in the "Heliport Design" advisory circular that a 30 foot separation be maintained between the rotor blades and a building. This recommendation will usually provide 50 feet of separation between the helicopter and the MRI magnet. However, reiteration in the section of the design guide on hospital heliports will help to make EMS heliport designers more conscious of the hazard.

The exposure limit for IFR approaches and departures must be on the order of 0.005 G. Appendix B explains the rationale for the 0.005 G limit. Field strengths this low are extremely difficult to measure. Therefore, instead of measuring the field directly, the field's effect on a compass should be measured. No more than a 2 degree deviation of the compass needle from

magnetic north should be allowed for IFR operations. Appendix F explains a method of determining the magnitude of an MRI fringe field's effect on a compass.

A warning of the effects of magnetic fields on NVGs should become part of any training requirements for their use.

7.1.2 EMS Helicopter Operator Actions

EMS operators should identify all medical facilities within their operating area that have any type of MRI equipment. The operator must ensure that all pilots are informed of the effects of an MRI on magnetic sensors. A map of the field strength of the MRI fringe field at the helipad should be obtained from the hospital. The map also should indicate the north axis of the magnet so that the direction that compasses will be indicating can be determined. Tests should be conducted at these facilities to determine the actual effect of the magnet. Appendix F includes a test to determine whether there is any effect at a heliport. This will inform the operator whether or not an independent contractor should be brought in to double-check the field strength map provided by the hospital.

Information acquired from the field strength map and testing should be included in the helicopter operator's "Landing Zone Directory" or equivalent heliport information guide. These directories should be readily accessible to flight crews and dispatchers, and periodically updated.

For those hospitals identified as having an MRI, the administrator should be contacted and apprised of the findings of the tests conducted by the operator. If any magnetic influence is discovered during the tests, the administrator should be informed. Furthermore, the hospital should be asked to notify the operator when any change occurs in the status of their MRI. Configuration changes such as a new MRI, shielding, or multiple MRI installations should be reported to the operator immediately.

The operator also could request that some distinctive marking be placed upon a mobile MRI trailer. Perhaps a similar marking to the one chosen for marking the helipad, as discussed in section 6.1.1, could be used. This would make the presence or absence of the MRI much easier for a pilot to determine.

7.1.3 Flight Crews

MRI fringe field influence is very localized in nature. For operational reasons, the risk to VFR helicopter arrivals at those facilities is minimal. However, when departing a facility where an MRI fringe field is present, all magnetic sensors may be skewed. Gyros normally slaved to the magnetic flux valve should be put in free mode and not brought on line until 500 feet away from the MRI facility. This will guarantee that the helicopter is outside of the MRI fringe field and there will be no effects on magnetic sensors.

Any variances in the information provided by the helicopter landing zone directory or dispatcher should be reported as soon as possible.

Disruptions to aircraft communications while operating in the vicinity of the MRI could indicate a possible leak in the Faraday shield for the RF portion of the MRI. Any interference should be reported to the hospital and the FCC at once.

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LIST OF ACRONYMS

AAPM	American Association of Physicists in Medicine
AHA	American Hospital Association
CRT	Cathode Ray Tube
DG	Directional Gyroscope
EEG	Electroencephalograph
EKG	Electrocardiograph
ELF	Extremely Low Frequency
EMS	Emergency Medical Service
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
FDA	Food and Drug Administration
GE	General Electric
HIRF	High Intensity Electromagnetic Radiated Fields
IMC	Instrument Meteorological Conditions
MRI	Magnetic Resonance Imager
NEMA	National Electrical Manufacturers Association
NMR	Nuclear Magnetic Resonance
NVG	Night Vision Goggles
OSHA	Occupational Safety and Health Administration
RF	Radio Frequency
RMI	Radio Magnetic Indicator
SMES	Superconducting Magnetic Energy Storage
TV	Television
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions

APPENDIX A

CALCULATION OF THE REDUCTION IN MAGNETIC FIELD STRENGTH WITH DISTANCE

Calculation of the reduction of magnetic field strength with distance can be very complicated close to the isocenter of the magnet and at points other than on the X, Y, and Z-axes. It also requires knowing the dipole moment of the magnet. These issues will not be addressed here.

For distances greater than 10 feet from the magnet and along the axes, the equation reduces to a simple ratio, where the field strength is inversely proportional to the cube of the distance. In other words, if the field strength is known in one location along an axis, it can be found for all other points along the same axis by finding the proportion of the original distance to a second distance and dividing the original field strength by the cube of the distance proportion. For example, if the field strength is 5 G at 50 feet along an axis, the field strength is 0.005 G at 500 feet along the same axis. 500 feet is 10 times as far out as 50 feet ($10^3 = 1000$ and $(5 \text{ G})/1000 = 0.005 \text{ G}$).

Similarly, if the field strength is 5 G at 25 feet from the magnet along an axis, field strength is 0.625 G at 50 feet along the same axis. 50 feet is twice as far out as 25 feet ($2^3 = 8$ and $(5 \text{ G})/8 = 0.625 \text{ G}$).

APPENDIX B
VECTOR ADDITION OF MAGNETIC FIELDS

The United States Air Force recommends not allowing IFR flights when the magnetic sensors are skewed by more than 2 degrees (reference 38). For variations less than 2 degrees, the effect is considered minor enough to ignore. Title 14 of the Code of Federal Regulations, Part 91, section 205 (14 CFR 91.205) requires every standard-category United States aircraft to have a functioning "magnetic direction indicator" (i.e., compass). 14 CFR 23.1327(a)(2) requires "The compensated installation may not have a deviation...greater than ten degrees on any heading." Therefore, the USAF limit of 2 degrees is well within the requirements of 14 CFR.

The aircraft itself affects the magnetic field detected in two ways: 1) the aircraft produces fields that add vectorially to the earth's field because of current carrying conductors and permanently magnetized structural members, and 2) the ferrometallic structural members warp the direction of the earth's field. These factors alone can cause the compass to deviate more than 2 degrees in the course of normal operation and usually must be compensated for. There are also diurnal changes in the magnetic declination of the earth's field on the order of ± 0.1 degrees; a long term change on the order of ± 0.1 degrees per year; and random changes due to magnetic storms of ± 0.1 degrees (reference 39). In order to ensure that an MRI fringe field will skew a magnetic azimuth no more than 2 degrees, the fringe field must be on the order of 0.005 G. This value is derived from the calculations below.

Two assumptions are made in these calculations: 1) at its weakest point, the earth's magnetic field is approximately 0.2 G, and 2) the MRI fringe field is at a 90 degree angle to the earth's magnetic field (see figure B.1). This is the worst case scenario. If the angle between the two fields were not orthogonal, the effect of the MRI field would be smaller. This is because the MRI field would be composed of both an I and a J vector instead of only an I vector. Some examples of the vector addition are provided below.

In the following calculations, the earth's field is pointing due north, or 0 degrees in the I direction, and the MRI field is 90 degrees off from magnetic north, or due east in the J direction. The MRI's fringe field will be reduced an order of magnitude at a time in four steps, from 5 G to 0.005 G. A compass should indicate 0 degrees in the absence of an MRI field.

These examples will illustrate the magnitude of the fringe field's effect on a compass at each of the orders of magnitude. It can be used to gauge which order of magnitude is present at a helipad when used in conjunction with the test in appendix F. If the compass needle is skewed more than 85 degrees, the fringe field's magnitude is on the order of 5 G or more. If the needle is skewed approximately 68 degrees, the fringe field's magnitude is on the order of 0.5 G, and so on.

If the MRI field strength is 5 G:

$$\mathbf{n} = \frac{5\mathbf{j} + 0.2\mathbf{i}}{\sqrt{5^2 + 0.2^2}} = 0.999\mathbf{j} + 0.04\mathbf{i}$$

$$\text{Arccos}(0.04) = 87.7 \text{ degrees}$$

Thus, the compass indicates 87.7 degrees instead of 0 degrees.

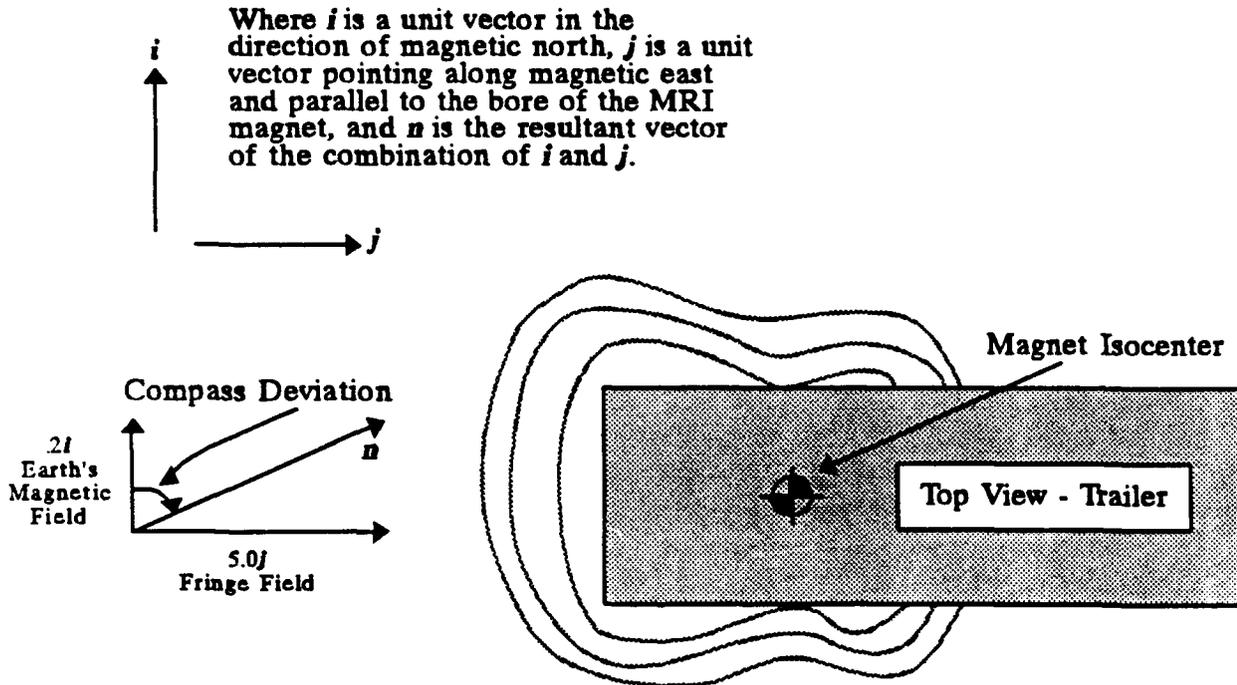


FIGURE B.1 VECTOR RELATIONSHIPS OF MAGNETIC FIELDS

If the MRI field strength is 0.5 G:

$$\mathbf{n} = \frac{0.5\mathbf{j} + 0.2\mathbf{i}}{\sqrt{0.5^2 + 0.2^2}} = 0.928\mathbf{j} + 0.371\mathbf{i}$$

$$\text{Arccos}(0.371) = 68.2 \text{ degrees}$$

Thus, the compass indicates 68.2 degrees instead of 0 degrees.

If the MRI field strength is 0.05 G, similar calculations show that the compass indicates 15 degrees instead of 0 degrees.

Finally, if the MRI field strength is 0.005 G, similar calculations show the compass indicates 1.4 degrees instead of 0 degrees. This is within the USAF requirements for IFR flight and the 14 CFR requirements for magnetic direction indicators referred to above.

APPENDIX C
ANTENNA EFFICIENCY OF LOW FREQUENCY ELECTROMAGNETIC FIELDS

Wavelengths of electromagnetic fields become longer as frequency becomes lower. The FCC does not regulate frequencies below 9 KHz because the wavelengths are so long they are considered to be non-radiating fields. Antennas become extremely long and inefficient as the wavelength gets long. If an antenna is less than half a wavelength long, not enough of the electromagnetic wave comes in contact with the antenna to couple and induce a voltage.

The equation for calculating the wavelength is: $L = C / F$.

where: L = wavelength in meters

C = the speed of light = 3×10^8 meters per second

F = frequency

A typical example is the Loran-C signal which has a frequency of 100 KHz.

$$L = (3 \times 10^8) / (100 \times 10^3) = 3,000 \text{ meters} = 3 \text{ kilometers.}$$

Thus, an antenna would have to be at least 1.5 kilometers long, half a wavelength, before it could start to transmit or receive significant amounts of power. It is very difficult to transmit power at this low frequency, but once it is radiated, it travels a long distance because there is little in the environment to absorb it.

Obviously, no aviation antenna is that long. That is why all Loran-C receiver antennas must have an electronic coupler and a preamplifier. The coupler is designed to adjust the length of the antenna electronically so it couples more efficiently. However, even with the coupler, a preamplifier is necessary to boost the still weak signal up to a usable level.

If the frequency is reduced to 10 KHz, the same calculation gives a wavelength of 30 kilometers. An antenna would have to be 15 kilometers long before it could efficiently couple to any radiated power. Basically, nothing but powerlines could possibly couple to this extremely low frequency. Certainly, nothing the size of a helicopter could couple. Below 9 KHz, electromagnetic fields are basically static fields that cannot couple to vehicles of practical size.

APPENDIX D
INDUCED VOLTAGE FROM MAGNETIC FIELDS

The magnitude of the voltage that can be induced into an antenna by a magnetic field is determined by the following formula:

$$V = - (d\Phi / dt)$$

where: V = voltage

$\frac{d\Phi}{dt}$ = rate of change of magnetic flux over time

For a static magnetic field, the flux (Φ) is constant. Therefore, the rate of change of the flux is zero and the induced voltage is likewise zero.

APPENDIX E HEADING REFERENCES

Heading references for aircraft come from three categories of equipment: 1) those ones dependent on sensing the earth's magnetic field, 2) those dependent on a low-drift gyroscope to retain a preset azimuth, and 3) gyrocompasses that depend on sensing the earth's rotation (reference 40). The magnetic sensors, wet compasses, and flux valves used in the first category can be affected by MRI fringe fields. In addition, the gyroscopes used in the second category are often slaved to flux valves to correct the inherent drift present in these gyroscopes.

The simple magnetic compass is familiar to all pilots. Compasses are heading references that operate by self-alignment of a freely swinging magnetic needle to the earth's magnetic field. The magnet is typically attached to a buoyant body floating in a liquid.

The major problems of the simple compass for aircraft use are as follows: 1) the damping action of the liquid causes a significant lag during turns, 2) the pendulous magnet is not level during turns, 3) there is no means of obtaining a signal for interfacing with other equipment, and 4) it must be located where it can be directly read (reference 40). These factors all contribute to navigational errors.

A directional gyroscope (DG) can be used with a compass to correct for the first two errors. A DG is a gyroscope driven by vacuum pressure through the use of a pump or venturi tube. It has no directional properties of its own. However, it will maintain, for a short period of time (10 to 15 minutes), any direction to which it is set. Its indications are affected by precession, or gyration of its spin axis, and must be reset at frequent intervals. Each time the DG is reset, or caged, the spin axis of the gyroscope is aligned with the horizontal plane of the aircraft.

However, within this limitation, a DG measures accurately the degree of turn. It provides the pilot with a steady indication of direction without the lag or oscillation associated with a compass. With the combination of a DG and a compass, the compass is used for heading information in straight flight; however, before starting a turn, the DG is manually set to give heading information while in the turn. This provides directional guidance for approximately 15 minutes without either lag error or turn acceleration error. The drawback to this combination is that the pilot must manually reset the DG at regular intervals.

In order to solve the third and fourth problems with simple compasses, most present day magnetic heading reference systems use a magnetic flux valve. These sensors have three iron paths and excitation coils arranged in a triangular fashion. The earth's magnetic field passes through the iron path and is modulated by an ac current flowing in the coils. The iron paths are arranged so that the voltage induced by the excitation coils is zero, and any voltage induced by each coil is proportional to the component of the earth's field or the MRI's fringe field which flows through the coils. (If it were not

for the ac modulation, or frequency, induced by the excitation coils, no voltage would be induced. Thus the voltage in the presence of a strong static field is no greater than the voltage induced by a weak static field and the operation of a flux valve is not affected except for the direction indicated.) The voltage goes to zero when the flux valve is aligned with the earth's magnetic field and increases as the aircraft swings away from magnetic north.

Thus, there is a voltage that can be used to control other avionics, i.e., a signal that can automatically reset the DG. In addition, the flux valve can be positioned in a remote area of the aircraft, away from most sources of electrical interference. In most helicopters, the flux valve is located in the tail boom.

APPENDIX F
TEST FOR MAGNETIC EFFECTS AT A HELIPORT

The following test will indicate whether an MRI fringe field is skewing the azimuths indicated by magnetic sensors and by how much. This test can be used to determine whether the fringe field's effects are within the recommended 2 degree variation allowable for IFR operation at the helipad.

The test consists of seven steps which are repeated two or three times. All position letters refer to figure F.1.

- 1) Stand on the helipad at point "0" as close to the MRI as a helicopter is likely to get, probably no closer than 50 feet from the MRI's building or trailer, but each site will have its own "0" based on its own unique operating requirements.
- 2) Use a lensatic compass to take an azimuth to a point "A," preferably a non-metallic pole driven in the ground for this test, at least 500 feet away from the center of the magnet and 90 degrees off of the Z-axis. If it is not possible to set the point 90 degrees off of the Z-axis, set it as far off the axis as possible and proceed.
- 3) Record the reading, the azimuth, and mark the spot where you are standing, preferably with another non-metallic pole.
- 4) Move to the point "A" used in step 2.
- 5) Use the same lensatic compass to take a back-azimuth to the point used in step 1.
- 6) Record the reading. Proceed to either step a) or b):
 - a) if the azimuth is greater than 180 degrees,
 $AZIMUTH - 180 \text{ degrees} = BACKAZIMUTH$; or
 - b) if the azimuth is less than 180 degrees,
 $AZIMUTH + 180 \text{ degrees} = BACKAZIMUTH$.
- 7) If the calculated back-azimuth of step 6 is within +/- 2 degrees of the measured back-azimuth, there is no magnetic effect from the MRI at the helipad; if the result is greater than 2 degrees, the fringe field is skewing the magnetic sensors. The examples of vector addition in appendix B should provide an estimation of how strong an effect is present.
- 8) As a check, especially if it was not possible to set the point "A" 90 degrees off the Z-axis in step 2, move the point "A" in step 2 90 degrees in either direction to point "B" and repeat steps 1 through 7.
- 9) If both tests reveal less than 2 degrees difference, the effect of the fringe field is less than 0.005 G and the pad can be used safely.

Magnetic north may be in any direction and is not relevant for purposes of this test.

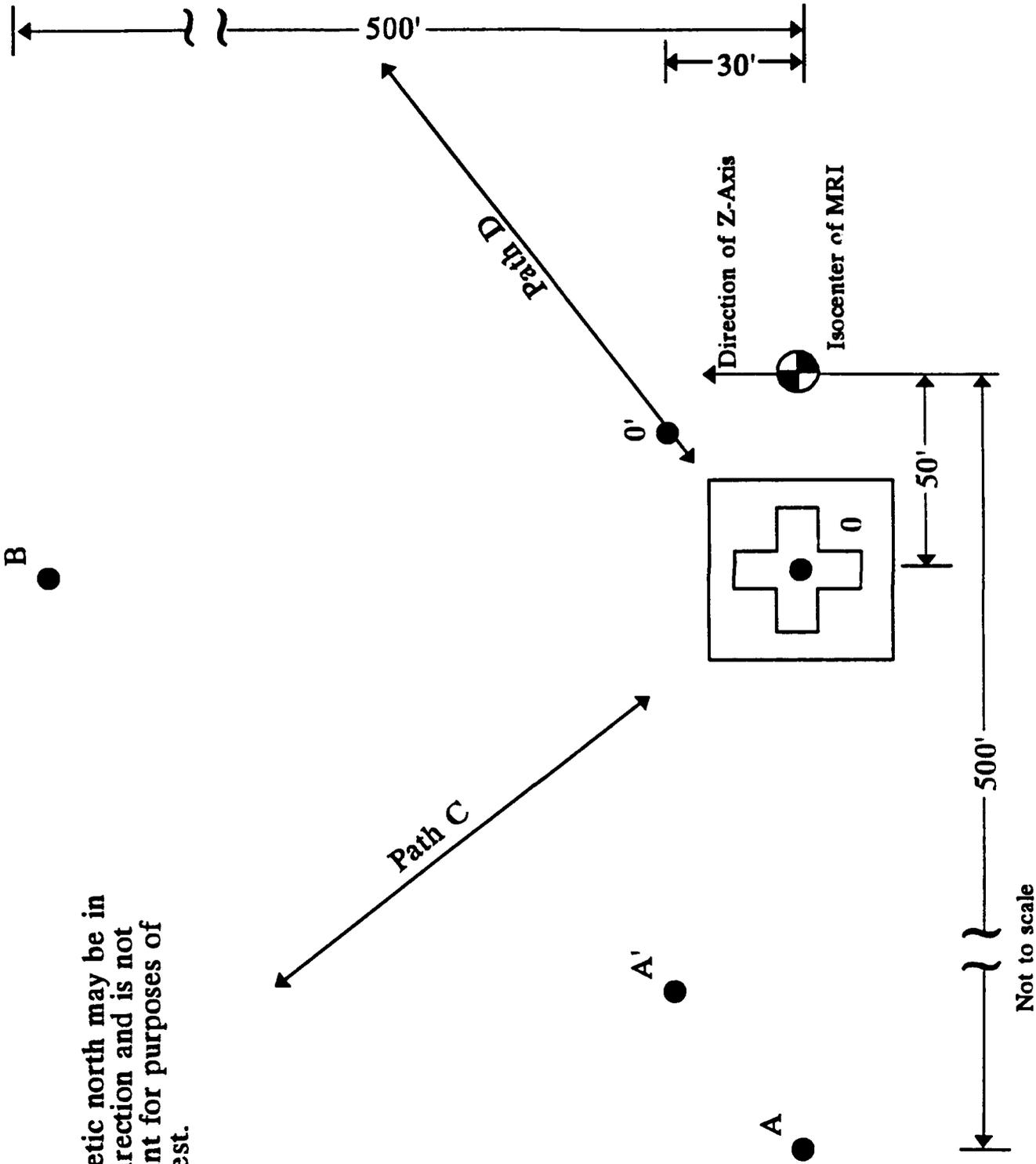


FIGURE F.1 TEST FOR MAGNETIC EFFECTS AT A HELIPORT

- 10) If the distance between some point on any of the approach/departure paths and the MRI is smaller than the distance between the point "0" chosen in step 1 and the MRI, go to that point and repeat steps 2 through 8. For example, path "C" has no points closer than point "0" and therefore no more testing is required. On the other hand, path "D" does have a point "0'" that is closer to the MRI than point "0." Chose point "0'" as the new point "0" and repeat steps 2 through 8. (Note that a new point "A" should also be selected.)
- 11) If both tests dealing with the worst cast point on an approach/departure path reveal less than 2 degrees difference, the fringe field is less than 0.005 G and that specific approach/departure path can be used safely.
- 12) It is possible other phenomena are responsible for a detected magnetic effect; for example, an electric power line or a large metal deposit might be responsible for the magnetic field variation.