Fabrication of Low-Field Water-Cooled Resistive Magnets for Small Animal Magnetic Resonance Imaging

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ABSTRACT: There are many nuclear magnetic resonance (NMR) and magnetic resonance imaging (MRI) techniques that employ resistive magnets. Resistive magnets are particularly useful for low-field (<0.5 T) imaging and for applications involving the cycling of magnetic fields. This article discusses a general technique for the fabrication of resistive magnets that can be used in small animal MR imaging. A detailed discussion is given of the magnet winding technique, the forced-water cooling system design and construction, and the support structure. Two examples are given of resistive systems built by the authors.
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KEY WORDS: construction technique; resistive magnets; magnetic resonance imaging

INTRODUCTION

Resistive magnets have historically been employed in both nuclear magnetic resonance (NMR) and magnetic resonance imaging (MRI) for several reasons: reduced construction costs, relative ease of construction and maintenance, and versatility of dynamic field control. Low-field imaging over small volumes is especially well suited for resistive magnets because of the lower power requirements. The design and construction of low-field imagers has been described by Redpath et al. (*1*) and Sciandrone et al. (*2*). Recently, noble gas MRI has been performed at low field, motivated by the fact that there is little improvement expected in signal-to-noise-ratio (SNR) with increasing magnetic field (*3–6*). Wong et al. (*5*) and Cross et al. (*3*) discuss systems constructed for use in noble gas imaging.

Magnetic field cycling systems have been made possible by the use of resistive magnets. Fast-field-cycling NMR systems have been constructed by Blanz et al. (*7*) and Lips et al. (*8*) to investigate field-dependent spin effects, whereas field-cycled proton-electron double-resonance imaging (FC-PEDRI) uses resistive magnets to cycle magnetic fields during the imaging of free radicals in biological samples (*9–10*). More recently, field cycling of resistive magnets has been implemented to provide prepolarization in MRI by Matter et al. (*11*) and Gilbert et al. (*12*). The design and construction of such a system is described by Macovski and Conolly (*13*), Morgan and colleagues (*14*, *15*), and Matter et al. (*11*).

In all of the literature cited above, the construction of the resistive magnet system used is explained only briefly, with primary focus given to the design and application of the system. A detailed discussion of the construction methods used to achieve animal-scale resistive systems for MR imaging is therefore lacking in the literature. In this article, a general-purpose technique for the construction of water-cooled resistive magnets for MRI is presented. The design of the cooling system is discussed in detail, as well as the physical support structures used. The fabrication

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method was designed to be modular to make construction and assembly practical for a laboratory environment.

Two important practical considerations when designing and constructing a system that uses actively controlled resistive magnets are 1) ohmic heating of the magnets during operation and 2) eddy currents resulting from changes in flux through closed conducting loops. Forced-water cooling is used to limit heating in the current construction technique. This is done by interleaving cooling plates between adjacent coils. To minimize eddy currents, care is taken in the design of the system to alleviate potential current loops. The construction technique in this article accounts for both of these issues.

MATERIAL AND METHODS

The magnet systems described in this article consist of multiple coils sandwiched together in the longitudinal direction by cooling plates. The entire structure is supported by nylon end-plates, and rests on a specially designed aluminum table. A description of the construction of the system components, as well as the assembly method, is given in the following sections.

Magnet Winding

All coils were wound in-house, in a standard laboratory environment. An industrial cylindrical welding positioner was used to rotate a homemade bobbin on which the coils were wound. A spool of insulated square copper magnet wire was placed in an aluminum frame and tensioned using friction on the sides of the spool. The positioner was slowly rotated to wind the wire onto the bobbin. The wire was manually guided into place, under tension, while being potted with epoxy. The coils were cured at room temperature and subsequently removed from the bobbin. The setup for winding coils is shown in Fig. 1.

The welding positioner, shown in Fig. 1, was a Speed-X Model 500 manufactured by Stahl Equipment Company (Massachusetts, USA). The 0.04–2.5-RPM positioner was controllable by a foot pedal and had a 500-pound capacity for a load at 4 inches from the chuck. A 15-inch diameter chuck was bolted to the positioner table. Sufficient torque was available for turning 100 kg coils under tension. The positioner required a standard 120 V/15 A electrical input. This welding positioner was purchased secondhand for approximately $2,000. Welding positioners with higher weight capacities are also available. There is no minimum diameter coil that can be wound, but a maximum diameter of approximately 2 m exists when coils are wound with their axis in the horizontal direction due to the distance of the chuck from the floor. The table on the welding positioner can be tilted such that the coil axis is at an arbitrary angle (between 0 and 90 degrees) to the horizontal. This would alleviate restrictions on coil maximum diameter; however, this technique was not explored by the authors.

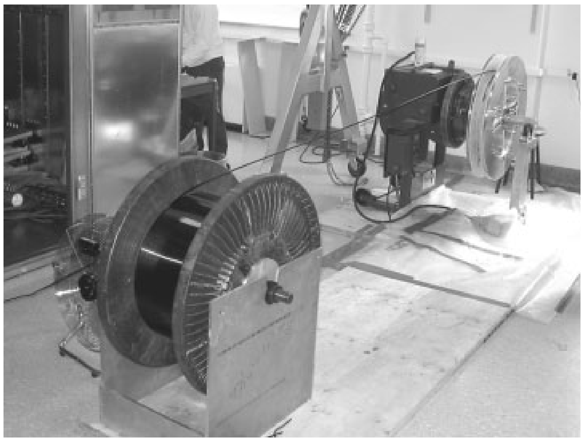

Figure 1 The system employed to wind the magnet coils. The wire is drawn off a tensioned spool (left) onto a bobbin (right), which is rotated by a cylindrical welding positioner (right).

The spooling device, shown in Fig. 1, was a box-like structure made of half-inch-thick aluminum sheet. The structure had two V-shaped grooves cut into its sides to allow for the placement of a 1.5-inch-diameter steel threaded rod, on which the spool of wire hung. The threaded rod was firmly attached to the sides of the spooling device using steel nuts. Aluminum plates, 8 inches in diameter, were placed on the threaded rod. The tension on the spool, restricting its ability to turn, was adjusted by tightening the nuts against the plates. The spooling device was capable of handling the size and mass of both a standard 24- and 36-inch diameter wire spool, weighing 110 kg and 200 kg respectively. The given spools can accommodate 1 AWG wire or higher. Larger spools are required for lower-gauge wire.

The bobbin was built in-house and consisted of removable aluminum side plates, sectioned into six pieces to facilitate its construction. The bobbin is detailed in Figs. 2 and 3. It was found that half-inch-thick aluminum side plates were necessary to provide sufficient lateral support to prevent bowing under the stress produced during placement of wires during winding. Bowing of the side plates results in a coil whose width increases with radius. The side plates were lined with a 1/8-inch-thick Teflon sheet to allow

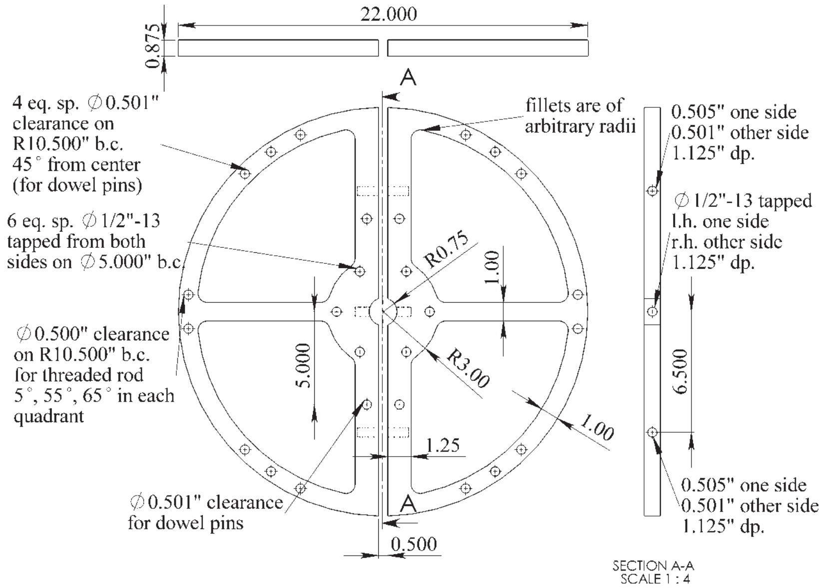

Figure 2 A schematic of the inner portion of the aluminum bobbin. Several plates can be stacked together to form a bobbin of any desired width. The two halves of the bobbin are connected by a left-hand right-hand threaded stud. All dimensions are given in inches. Eq. sp. = equally spaced; b.c. = bolt circle; l.h. = left-hand; r.h. = right-hand; dp. = deep.

for slight leeway in the width of the coil, thus facilitating the ease of winding. As a result, the final width of each coil was accurate to within 0.25 mm. The Teflon was sprayed with a silicone-based mould release prior to use, making it easy to remove from the coil after winding. The centers of the aluminum side plates were removed to reduce the mass of the bobbin to a value that would not exceed the capacity of the welding positioner during winding.

The aluminum side plates and Teflon linings sandwiched an inner cylinder. The inner cylinder was split axially and connected by a left-hand right-hand threaded stud, allowing the cylinder to be partially collapsed. The inner cylinder consisted of multiple plates sandwiched together with dowel pins. Multiple plates were employed to allow versatility in the range of coil widths that could be created. Once again, the inner portions of the inner cylinder were removed to reduce the overall mass of the bobbin. A groove was cut into the face of one plate to allow for a starting point during the winding procedure. A schematic of the inner bobbin is shown in Fig. 2. After a coil was wound, the side plates were removed, and the inner cylinder was collapsed by approximately 1/4 inch. The inner cylinder could easily be removed from the coil at this point using a rubber mallet.

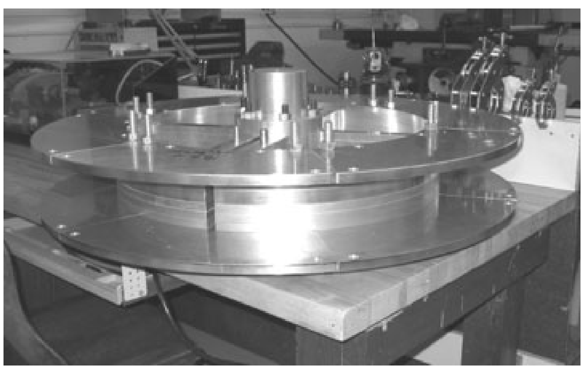

Figure 3 A photograph of the entire collapsible bobbin. The removable side plates sandwich the collapsible inner cylinder.

It was determined that two people were required to wind a coil. To begin, the bobbin was assembled, and the Teflon lining was sprayed with mould release. While the wire spool was under minimal tension, the wire was drawn off the spool by hand, and the end was inserted into the groove in the bobbin. The bobbin was slowly rotated once, while ensuring the wire did not exit the groove. The wire was then flattened by pressing a brass rod against the wire and tapping the rod with a rubber mallet. At this point, the tension on the wire spool was increased, and the rotational speed of welding positioner was increased to approximately 1.5 RPM. One person manually guided the wire, while pressing the wire turns together with the brass rod.

During this process, a second person would apply an epoxy to the windings using a stiff paintbrush. The epoxy used (Durapot 865, Cotronics Corporation, Brooklyn, NY) had a high thermal conductivity (2.28 W m^{-1} K^{-1}) and had a viscosity similar to molasses (10,000 cP) at room temperature. The epoxy was a two-part formulation and had a working time of approximately 1 hour, with a room temperature cure time of 24 hours. Each of the coils described in this work required 0.5–1 gallon of epoxy. Approximately 800 g of epoxy was made at one time to ensure it did not begin to stiffen during the application process. Three to four batches of epoxy were required per coil.

After a single row (fixed radius) had been wound, care was taken to ensure the succeeding row laid flat on the preceding row. If needed, a brass rod was used to flatten the wire. However, excessive force at this point can cause the sides of the bobbin to flex. Due to the finite thickness of the wire, the final turn of each row is less than the full circumference. This effect is more pronounced with wires of larger width due to the increased winding pitch, yet this cannot be avoided and will contribute to an uncertainty in the length of conductor used per coil. This uncertainty varies, but tends to be a small fraction of the coil circumference per winding layer, and is cumulative over each winding layer.

Each coil required approximately 2 to 3 hours to wind. After the coil had been wound, the end of the wire was clamped to the side of the bobbin and cut from the spool. The coil was allowed to turn at approximately 2 RPM for another 12 hours to ensure the epoxy on the outside of the coil hardened with a smooth surface.

Modular Design

Complete magnets are constructed by combining several smaller coils in series, with cooling plates interleaved between them. The number of windings layers in the radial and the axial directions are determined by the cooling requirements of the magnet. The authors have previously reported on the development of thermal models to predict the thermal evolution of water-cooled resistive magnets of this design (*16*). The physical handling of individual coils during construction is also made easier by this method. Generally, coils were limited to about 100 kg each. To construct simple thick solenoids, coils are placed together co-axially to form a single solenoid, with cooling plates interleaved as necessary. For homogeneous magnets, individual coils are placed in positions determined by the design algorithm, with cooling plates placed on either side.

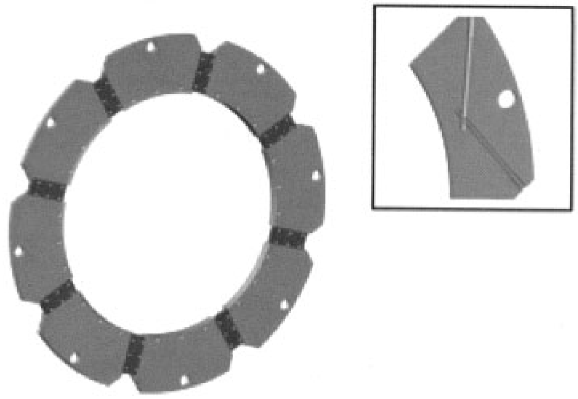

Figure 4 A schematic of a cooling plate used between coils. Cooling plate sections are connected by Delrin insulators to prevent large eddy currents. The inset is a cross-sectional view of a single cooling plate section. A channel is bored through the cooling plate sections to allow for water flow. All eight sections are connected by Teflon tubing; all cooling plates are connected in parallel to a manifold. Supporting aluminum rims are attached to each cooling plate to radially locate the coils.

Cooling System

Solid aluminum cooling plates were placed in thermal contact with the sides of coils to limit the magnet's operational temperature. The cooling plates had bored channels within for forced water flow. Figure 4 is a schematic of a single cooling plate. The inset of Fig. 4 shows the bored cooling channels. The thickness of the cooling plates was chosen to provide ease in construction while still maintaining a reasonable overall winding density for the magnet. The cooling plates were electrically broken into sections to prevent the formation of circumferential eddy currents during rapid changes in the magnetic field. The number of sections for a cooling plate is a design parameter and depends on the size of the cooling plate. Cooling plates with four and eight sections were used for the magnets in this process. The effect of the number and size of cooling plates on magnet performance has been investigated previously (*12*, *16*).

Aluminum tooling plate was used for the cooling plates to increase flatness and maximize thermal contact with the coils. Cooling channels were 1/4 inch in diameter and 10 inches in length. Quarter-inch outer-diameter Teflon tubing connected each section of a cooling plate via 1/8-inch pipe threads. Rims were placed on the inner diameter of the cooling plates to support and radially locate the coils. Rims were anodized to prevent long-term wear on the coils. These rims were constructed separately and screwed onto the main cooling plates. This was done to decrease the

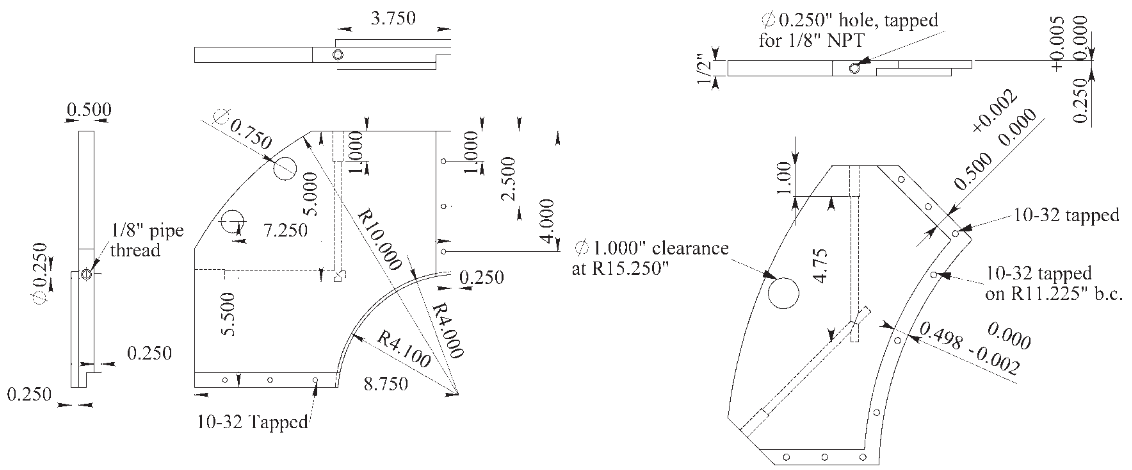

Figure 5 A schematic of a single section of a (left) one-piece four-section cooling plate with rim and (right) an eight-section cooling plate with detachable rim. All dimensions are given in inches. b.c. = bolt circle; NPT = National Pipe Thread.

time and cost of cooling plate construction. Figure 5 shows a cooling plate that was made of one piece. The dimensions of cooling plate sections are given in Fig. 5. Cooling plate sections were connected by Delrin insulators.

Each cooling plate was independently connected in parallel to a manifold, which was driven by a chilled water circulator. The source and return manifolds were each equipped with adjustable-flow shutoff valves. The manifolds were made of 1/2-inch copper tubing connected to 1/8-inch Swagelok pipe threads. The manifolds were connected to standard garden hose, driven by the water chiller. The water chiller has an achievable flow rate of tens of l/min, depending on the number of cooling plates in parallel, and has a maximum cooling capacity of 54 kW. Two water filters (with 5 μm and 1 μm meshes, respectively) were placed between the water chiller and the manifolds to reduce iron buildup in the system. The flow rate, water pressure, and water temperature were measured externally.

Support Structure

Individual coils rest on the rims of cooling plates. The magnet as a whole is supported by brass threaded rods that extend through the outermost radial segments of the cooling plates and to the nylon end-plates (Fig. 6). The diameter and number of the threaded rods was determined by the number and mass of the coils to be supported. Further support for the coil mass was provided by adjustable height nylon braces cradling each coil section from below. A schematic of one of these braces is shown in Fig. 7.

The axial location of the coils can be adjusted by brass nuts located on the sides of the cooling plates on the threaded brass rods. The radial positions of the coils cannot be adjusted. Reducing the number of threaded rods increases ease in adjusting axial coil positions, yet increases the required diameter of the rods.

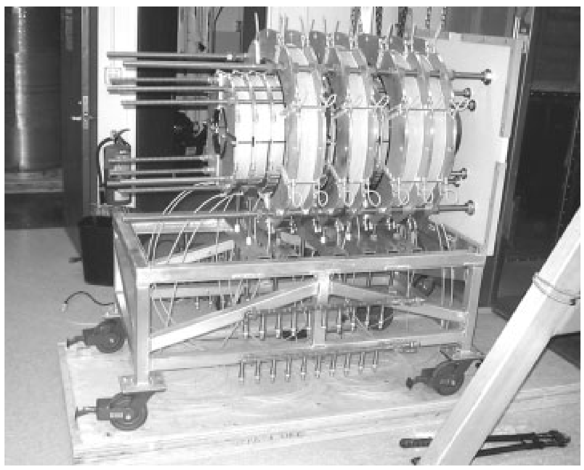

Figure 6 A photograph of a partially assembled field-cycled MRI system. Coils were successively moved into position by a chain-fall gantry. Threaded rods are attached to 1-inch-thick nylon plates at each end, off of which cooling plates and coils are suspended. The coils are supported by adjustable-height nylon braces. The outer homogeneous magnet is the readout magnet, and the inner solenoid is the polarizing magnet (*12*).

Brass nuts and brass jam nuts were placed on the outer ends of the magnet to prevent movement during operation due to the magnetic attraction between coil sections. The force of attraction between coils, when driven at 100 A, is two orders of magnitude less than the force of gravity on a single coil with a mass of 50–100 kg.

The height and width of the nylon end-plates were made slightly larger than the outer diameter of the cooling plates. These 1-inch-thick nylon sheets were reinforced by aluminum channel on their corners. The aluminum channel was discontinuous around the outer edge of the nylon end-plates to prevent eddy currents. Bronze bushings were counterbored into the nylon plates to increase mechanical stability around the threaded rods. In the systems shown in this article, a 10-inch-diameter hole was cut in the center of the nylon sheets to allow for easy access to the 8.25-inch magnet bore.

Magnet systems were placed on aluminum tables constructed and reinforced with square tubing. The nylon support plates were rested in aluminum channels that had been welded to the top of the support table (see Figs. 8 and 9). Aluminum plates were welded to the top of the tables to support the adjustable height nylon braces. Swivel casters with brakes, rated to 540 kg each, were bolted to the legs of the table. The 6-inch-diameter casters were made of extra-hard polyurethane to prevent flattening of the wheels over time.

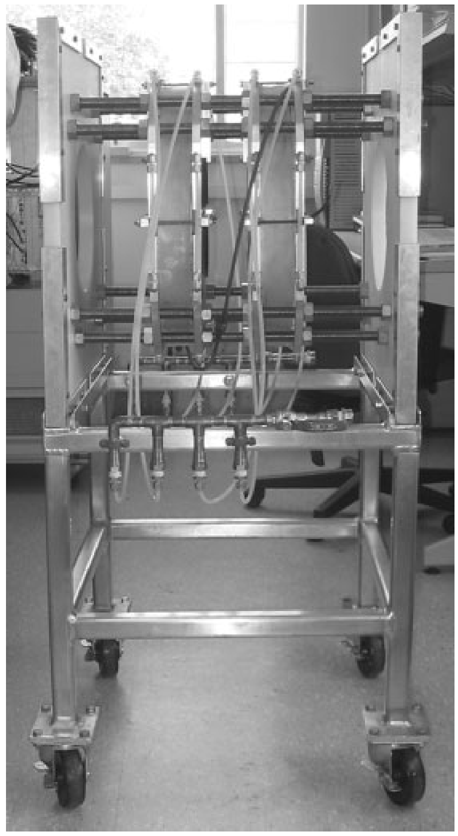

Figure 8 A photograph of a thick Helmholtz pair built and cooled using the construction technique described in this article. The system has a 21-cm inner diameter and weighs approximately 75 kg. The coil pair produces a field efficiency of 1.3 mT/A.

System Assembly

The magnet systems were assembled in a horizontal orientation because it was decided that vertical assembly followed by a magnet rotation at full weight would be too dangerous and difficult. The threaded rods were attached to one side-support nylon plate.

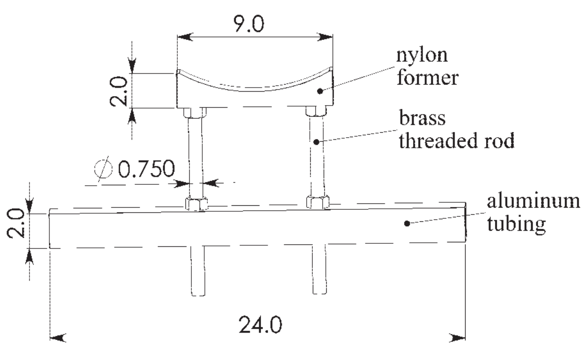

Figure 7 A schematic of a nylon brace used to support the mass of a coil. The nylon brace is adjustable in height. All dimensions are given in inches.

Cooling plates and coils were alternately mounted over the threaded rods, and finally the opposing side-support plate was mounted. Individual coils were maneuvered into placed using an overhead 2-ton chain-fall gantry. Heat-transfer compound (Type 120 Thermal Compound, Wakefield Engineering Inc., Pelham, NH) was applied between coils and cooling plates. Multiple clamps were placed around all magnet sections to improve thermal contact and to increase safety when moving a coil section. Electrical connections were made sequentially during the assembly of the system using homemade brass electrical connectors.

Complete systems were leveled horizontally within 0.3° by adjusting the heights of the supporting nylon braces. It was determined that using these methods, the coils in the system were initially located within 1 mm accuracy in the radial and the axial directions. The ability to adjust the axial positions of the coils along the threaded rod allows for further shimming ability and submillimeter accuracy in axial positioning.

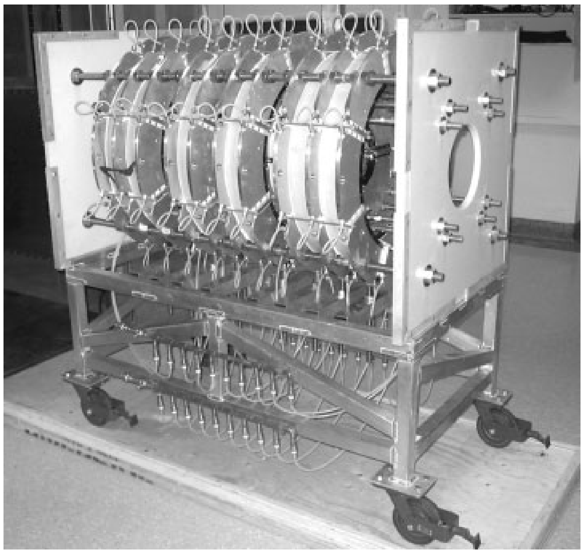

Figure 9 A photograph of two concentric magnets and the support structure. The system was built and cooled using the construction technique described in this article.

RESULTS

Figure 8 shows a thick Helmholtz pair constructed using the methods discussed previously. The two 35-kg coils are supported by eight 3/4-inch-diameter brass threaded rods. The threaded rods provide adequate support for the magnet mass, thus no underlying braces were needed. The cooling plates were split into four sections each.

Figure 9 shows a complete field-cycled MRI system consisting of two separate concentric magnet systems. The inner magnet is a simple thick solenoid consisting of eight 45-kg coils. It is supported by eight 3/4-inch brass threaded rods and two braces. The outer magnet is a uniform field system consisting of six 90-kg coils. It is supported by four 1-inch-diameter brass threaded rods and six braces. No detectable sag was present in the threaded rods. The complete system weighs approximately 1,000 kg and is 86 × 86 × 152 cm long. The most massive single component of the system is less than 100 kg. Because of the system's modular design, any single component can be replaced without complete reconstruction of the system.

Construction and assembly of the simple magnet system shown in Fig. 8 was completed in approximately 35 man-hours. The magnet system shown in Fig. 9 required approximately 400 man-hours to construct and assemble. Winding of the system's 14 coils required 60 man-hours, and the construction of the cooling system and support structure required approximately 240 man-hours. Assembly of the system was completed in approximately 100 man-hours.

Heating tests conducted on the magnet system shown in Fig. 9 demonstrated an average equilibrium temperature of less than 100°C when supplied with 100 A at constant current. Thermal (heating) time constants of 16 and 21 minutes were measured for the inner and outer magnets, respectively. Table 1 summarizes the geometric, electromagnetic, and thermal properties of this magnet system.

DISCUSSION

The primary application for the magnets described in this article is field-cycled MRI; therefore, special care was taken in the system design to reduce all potential sources of eddy currents. This included dividing the cooling plates with Delrin insulator sections, as well as with the use of nylon side plates, as opposed to aluminum plate. The aluminum support tables have potential current loops, yet they are at a considerable distance from the bore of the magnet and oriented perpendicular to the main magnetic fields. The nearest ferromagnetic material is steel located in the casters of the support table, yet these are positioned far enough from the bore of the magnet as not to significantly perturb the magnetic field. In applications where magnets will not be rapidly cycled, some of the construction elements described could be changed. In particular, the cooling plates and supporting end-plates could be constructed entirely of aluminum.

Although the cooling system described has proven to be adequately efficient (see Table 1), the cooling system is also a design parameter. The authors are currently investigating the use of hollow wire as a method of cooling in this architecture (*11*, *17*).

Table 1 Measured Geometric, Electromagnetic, and Thermal Properties of the Magnet System Shown in Fig. 9

	Inner Magnet	Outer Magnet
Field efficiency (mT/A)	2.8	1.1
Resistance (Ω)	1.80	1.57
Inductance at 100 Hz (mH)	374	330
Mass (kg)	350	500
Inner diameter (cm)	21	56
Outer diameter (cm)	42	69
Length (cm)	66	99
Number of cooling plates	10	10
Avg. equil. temp. at 100 A (°C)	92	84
Thermal time constant (min)	16	21

Hollow wire allows for an increased cooling capacity, yet there are the added difficulties of attaining sufficient hydraulic pressure and current density. It is expected that the techniques described in this article would be applicable for the construction of hollow wire magnets.

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