

March 18, 1969

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3,434,085

MAGNETS HAVING LOGARITHMIC CURVED POLE CAPS FOR PRODUCING
UNIFORM FIELDS ABOVE SATURATION

Filed May 8, 1967

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FIG. 1

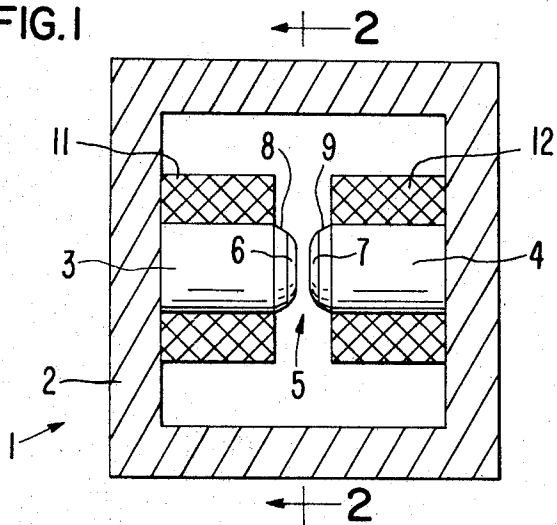


FIG. 2

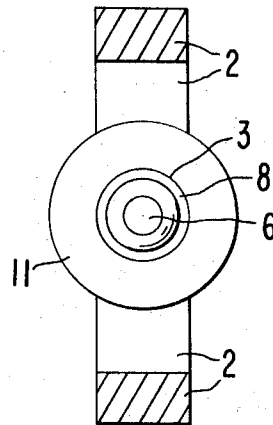


FIG. 3

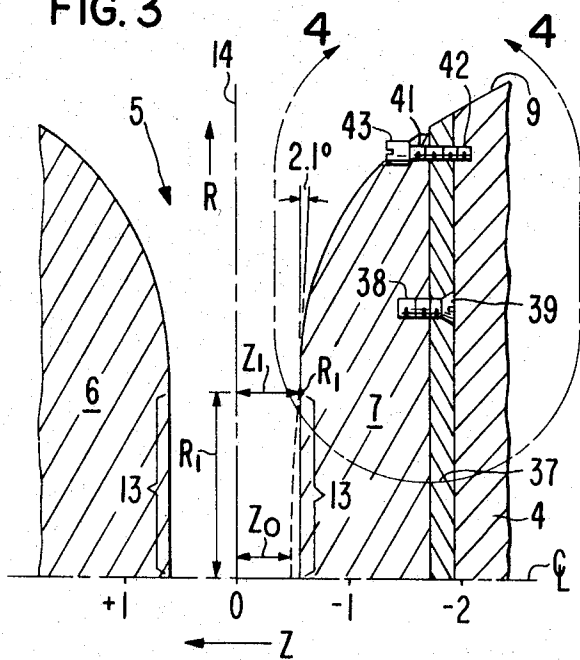
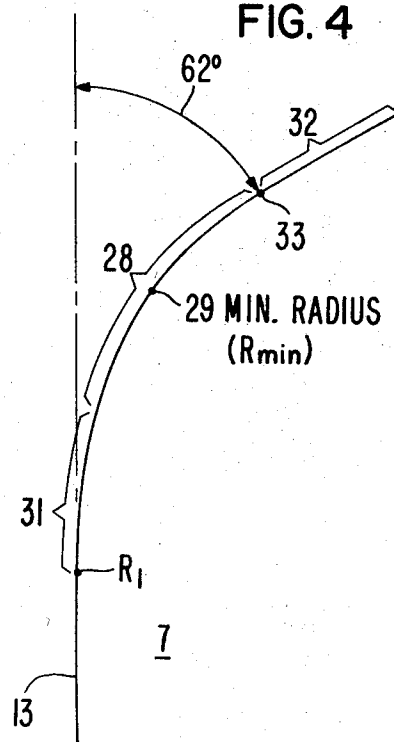


FIG. 4



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FIG. 5

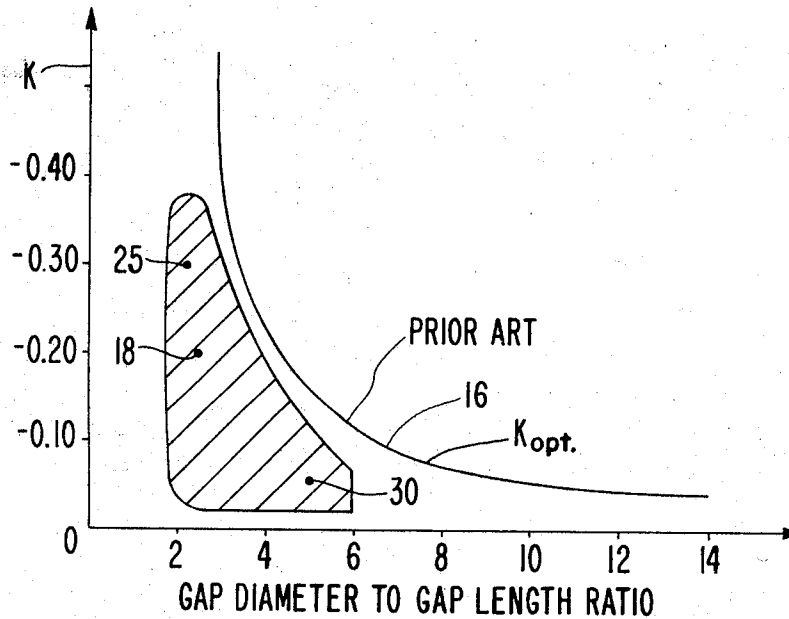
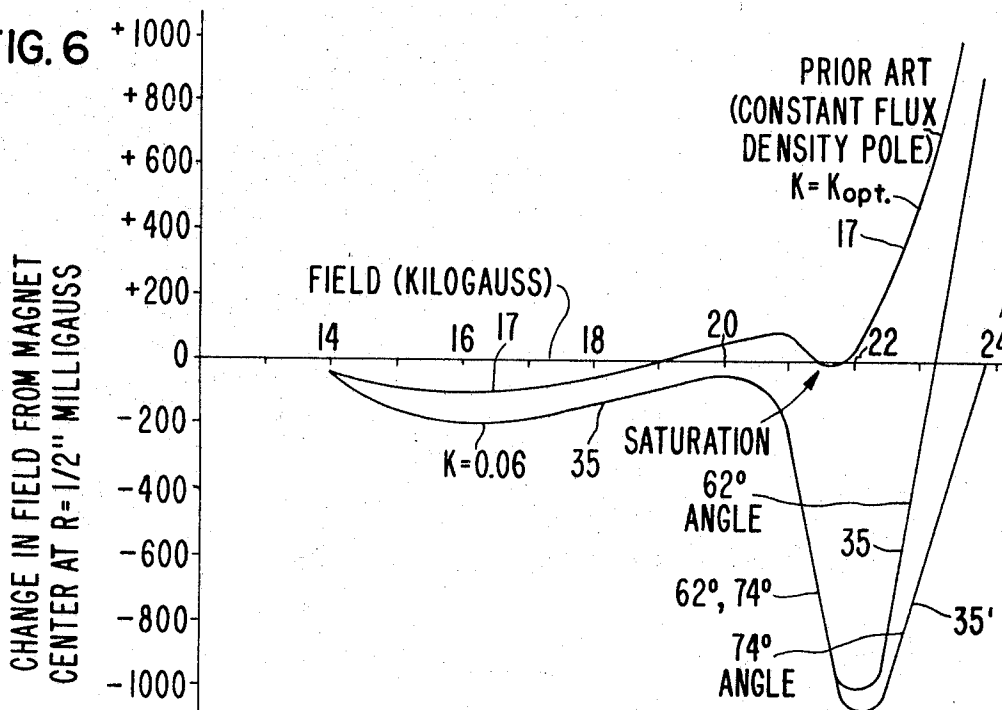


FIG. 6



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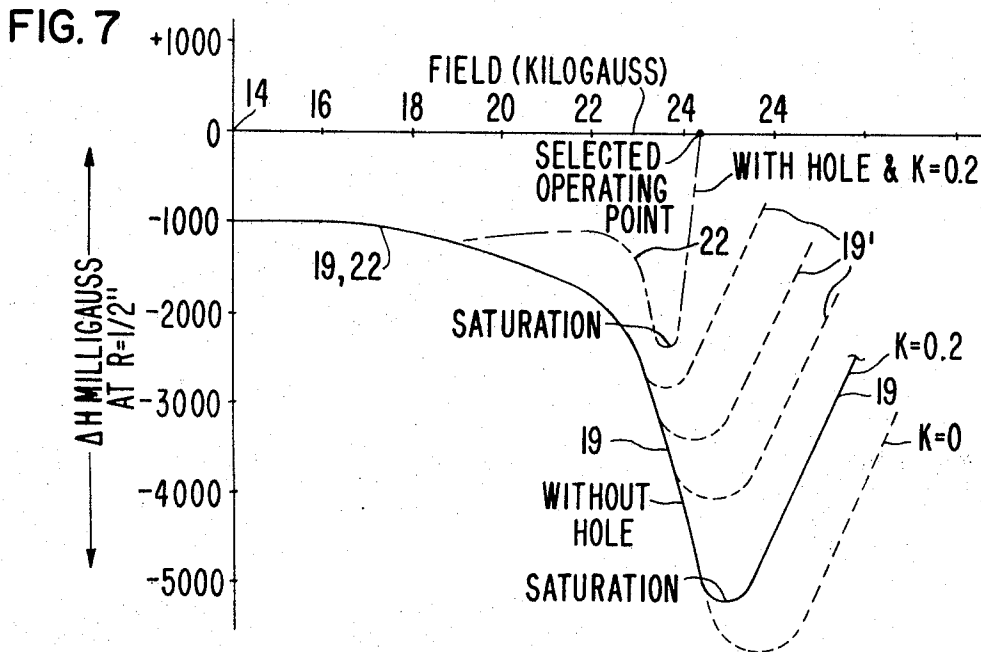


FIG. 8

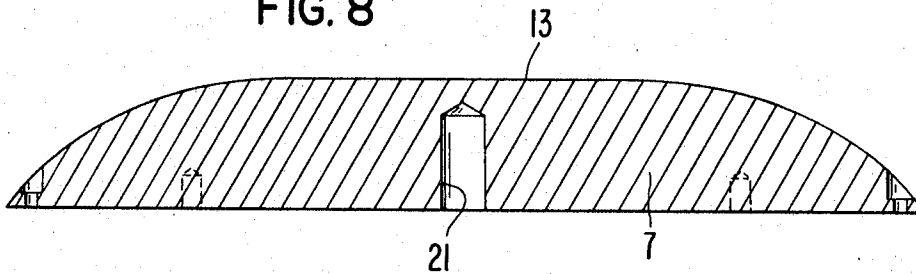
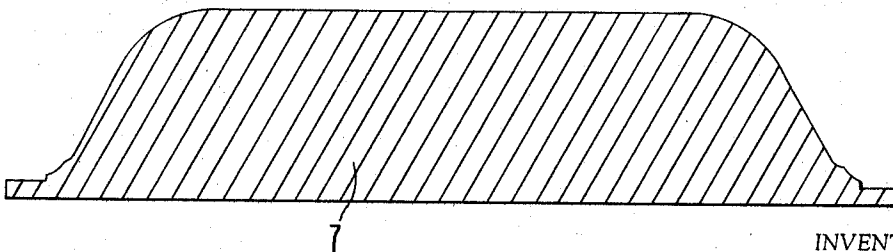


FIG. 9



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5 Claims

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ABSTRACT OF THE DISCLOSURE

Magnets for producing magnetic field intensities above saturation with extremely high homogeneity are disclosed. The magnets employ pole caps that have their opposed faces shaped to conform to the following equation with $0 < K < K_{opt}$:

$$R - R_1 = \frac{Z_0}{\pi - \tan^{-1} \frac{1}{K}} \ln \left(\frac{Z - Z_0}{Z_1 - Z_0} \right) - K(Z - Z_1)$$

where R is the radius of the pole cap from the axis of the gap, R_1 is the value of R where the curved face of the pole cap makes an angle of 2.1° with a plane perpendicular to the axis of the gap, Z is the axial distance from the midplane of the gap to the pole cap face in the curved region thereof, Z_1 is the value of Z at R_1 , Z_0 is the value of Z on the Z axis if the curved portion had been continued to the Z axis, K is an optional parameter having a negative value with an absolute magnitude greater than zero but less than K_{opt} , that value of K which yields a constant flux density pole cap for the ratio of gap diameter ($2R_1$) to gap length ($2Z_0$) of the magnet, and

$$\tan^{-1} \frac{1}{K}$$

lies between 0 and π .

By selecting $|K|$ greater than zero but less than $|K_{opt}|$ for the particular ratio of gap diameter to gap length a uniform field is produced at a certain value of field intensity above saturation, thereby permitting use at a higher field intensity than the prior constant flux density design which corresponds to use of K_{opt} . These smaller values of K also mean that the magnet pole diameters and required magnetomotive force are less than with the prior K_{opt} design. Moreover, even lower values of K and, thus, even smaller magnets may be used by boring the pole caps from the backsides thereof on the axis of the gap and/or by decreasing the taper of the side edges of the pole caps.

Description of the prior art

Heretofore, pole caps for magnets have been shaped to conform to the unique equipotential surface that yields a magnetic field in the pole cap material that is equal in magnitude and direction to the magnetic field in the center of the air gap between the two poles of the magnet. This unique surface shape is defined by a certain logarithmic equation employing a certain optimal parameter K which is a function of the diameter to gap length ratio of the gap of the magnet. The parameter K has been determined empirically in the prior art. Such a prior art magnet is described in an article titled, "On the Design of Wide Range Electromagnets of High Homogeneity," by A. Huber et al. appearing in the publication, "Nuclear Instruments and Methods," volume 33 (1965) at pp. 125-130, published by the North-Holland Publishing Co.

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While this prior art magnet design provides a highly uniform magnetic field from zero field to saturation of the pole caps, it does not produce uniform fields at fields higher than the saturation of the pole cap material, i.e., greater than 22 to 24 kg. Therefore, this prior art design leads to magnet designs which are not suitable for operation above saturation.

Summary of the present invention

The principal object of the present invention is the provision of an improved magnet.

One feature of the present invention is the provision of a magnet having pole caps shaped to conform approximately to a certain logarithmic curve with an optimal parameter K less than that which would yield a constant flux density design for the gap diameter to gap length ratio of the magnet, whereby a homogeneous magnetic field is produced above saturation.

Another feature of the present invention is the same as the preceding feature wherein the pole caps are modified by removing a portion of the pole cap material from the back of their central regions, as by boring, to permit use of smaller pole caps and magnet for operation at the homogeneous field above saturation.

Another feature of the present invention is the same as the first feature wherein the pole caps are tapered at their side edges with less taper to permit use of smaller pole caps and magnet for operation at the homogeneous field above saturation.

Another feature of the present invention is the same as any one or more of the preceding features wherein the logarithmic curve for the pole caps is approximated by a circular arc which coincides with the logarithmic curve near where the minimum radius of curvature occurs together with a transition curve which leads smoothly from the circular arc to the flat area of the pole face and including a linear taper on the outside of the circular arc which taper makes an angle of more than 45° with the central flat surface of the pole cap.

Other features and advantages of the present invention will become apparent upon a perusal of the following specification taken in connection with the accompanying drawings wherein:

Brief description of the drawings

FIG. 1 is a sectional view of a magnet incorporating features of the present invention,

FIG. 2 is a sectional view of the structure of FIG. 1 taken along line 2-2 in the direction of the arrows,

FIG. 3 is a sectional view of a portion of the pole cap structure of FIGS. 1 and 2,

FIG. 4 is an enlarged view of an alternative pole cap structure to that delineated by line 4-4 of FIG. 3,

FIG. 5 is a plot of optimal parameter K versus diameter to gap ratio for magnets employing the property of constant flux density pole caps and including a hatched area containing values of K according to the present invention.

FIGS. 6 and 7 are plots of change in magnetic field from the center at radius equal to 0.5" versus magnetic field at the center of the gap for various different pole cap configurations, and

FIGS. 8 and 9 are sectional views of alternative pole cap shapes incorporating features of the present invention.

Description of the preferred embodiments

Referring now to FIGS. 1 and 2, there is shown a magnet incorporating features of the present invention. The magnet 1 includes a rectangular yoke 2, as of soft iron, having a pair of cylindrical pole pieces 3 and 4, as of

soft iron. The pole pieces 3 and 4 are coaxially aligned and are spaced apart at their mutually opposed ends to define a magnetic gap 5 therebetween. The opposed end portions of the pole pieces are capped by a pair of pole caps 6 and 7, as of soft iron or an iron-cobalt alloy. The ends of the pole pieces 3 and 4 are tapered at 8 and 9. A pair of electric coils 11 and 12 are coaxially disposed of the pole pieces 3 and 4 for energizing the magnet 1 to produce a magnetic field in the gap 5 which may be varied from 0 to 24 kg. Typical gaps 5 vary from 0.750" to 2.00" in length and the pole caps 6 and 7 typically vary from 8" to 12" in diameter and from 1.00 to 2" in thickness.

Referring now to FIG. 3, there is shown the pole cap structure 7 of FIG. 1. Pole caps 6 and 7 have mutually opposed flat face portions 13 which are equally spaced along the axis of the magnetic gap 5 (Z axis) from a midplane 14 (Z=O plane) of the gap 5. At a predetermined radius R_1 from the axis of the gap 5 (Z axis), the pole caps 6 and 7 follow a certain logarithmic curve. The logarithmic curve is defined by the following equation:

$$R - R_1 = \frac{Z_0}{\pi - \tan^{-1} \frac{1}{K}} \ln \left(\frac{Z - Z_0}{Z_1 - Z_0} \right) - K(Z - Z_1) \quad (1)$$

where R is the radius from the axis of the gap (Z axis), R_1 is the value of R where the curved side edge of the pole cap makes an angle of 2.1° with the midplane 14, Z is the axial distance from the midplane 14 to the pole cap face in the curved region, Z_1 is the value of Z at R_1 , Z_0 is the value of Z on the Z axis if the curved portion had been continued to the Z axis as indicated by the dotted line, K is an optional parameter having a negative value with an absolute magnitude greater than zero but less than that value of K (K_{opt}) which will define a magnetic equipotential surface for the pole cap face that gives rise to a constant flux density pole piece for the ratio of gap diameter ($2R_1$) to gap length ($2Z_0$) of the magnet 1, and

$$\tan^{-1} \frac{1}{K}$$

lies between 0 and π . LN is the logarithm to the base e.

In the prior art constant flux density pole cap design, the caps have a logarithmic curved surface defined by Equation 1 except that K was empirically determined to yield the cap surface defining the constant flux density equipotential for a given gap diameter to gap length ratio of the magnet. Curve 16 of FIG. 5 is a plot of K for the prior art pole caps. The prior art pole caps provided a region of uniform magnetic field as shown by curve 17 of FIG. 6. As can be seen from curve 17, the field is extremely uniform up to a magnetic field intensity at which the pole cap material saturates.

Above saturation, the field becomes quite inhomogeneous, thus, limiting its use to field intensities below saturation.

These prior art pole caps, i.e. K_{opt} , are relatively large in diameter and, therefore, require the use of relatively large electric coils with relatively large pole diameters. Designs based on K_{opt} provide relatively large diameter regions of homogeneous (uniform) magnetic fields, e.g., 4" diameter regions of magnetic field for a 12" diameter pole piece. Many applications for intense uniform magnetic fields do not require such a large diameter of the uniform magnetic field region. In these latter cases, a smaller pole face diameter is selected, i.e., a gap diameter to gap length ratio less than 6. A choice for K is found from FIG. 5 which is less than K of the prior art curve 16 but greater than $K=0$. For example, K and the diameter to gap length ratio are selected from the cross hatched area of FIG. 5. Such a selection of K yields a smaller

region of uniform magnetic field and leads to a substantially smaller and, thus, less expensive magnet 1.

For example, a pole cap design with a gap diameter to gap length ratio of 2.4 and a K of -0.2 corresponds to the selection identified as point 18 in FIG. 5. The resultant magnetic field curve is shown at 19 in FIG. 7. The field is fairly uniform up to 20 kg. at which point the pole caps begin to saturate and the field uniformity drops off substantially with increased field intensity.

If curve 19 were extrapolated to the $\Delta H=0$ line (corresponding to a homogeneous field) it would cross at about 30 kg. However, due to saturation of the pole pieces 3 and 4 and the limited size of the electric coils 11 and 12, the operating point at 30 kg. is not obtainable. As is seen from FIG. 7, there is a whole family of curves 19', for the given pole cap diameter to gap length ratio, one for each value of K. As |K| is increased from zero to K_{opt} , the $\Delta H=0$ operating point moves lower in field intensity until at some value of field with a K less than K_{opt} there will be an operating point $\Delta H=0$ above saturation that can be obtained with the given sized pole pieces 3 and 4 and magnet windings 11 and 12.

Referring now to FIG. 8, an effective increase in K is obtained without actually increasing K by boring a 0.5 inch diameter hole 21 in the back faces of the pole caps 6 and 7. The hole 21 terminates within 0.250" of the pole face 13. The hole 21 alters the characteristics of the magnetic field for an actual $K=-0.2$ from curve 19 to that as shown by curve 22 of FIG. 7. The hole 21 extends the field intensity for fairly uniform field up to 22.5 kg. from 20 kg. It further permits operation of the magnet 1 at a value of field above saturation (24.5 kg.) while providing a substantial region of very uniform magnetic field $\Delta H=0$. The field remains fairly uniform below 20 kg. for both designs, as indicated by curves 19 and 22.

In the pole cap of FIG. 8, the flat area 13 has a diameter of 4.001", an outside diameter of 9.926", a thickness of 1.509" and is made of an iron-cobalt alloy having 65% iron and 35% cobalt.

Referring now to FIG. 4, there is shown a curved pole cap surface which approximates the logarithmic curve of Equation 1. The composite logarithmic curve is made up of three sections. A first section 28 is a section of circular arc located to coincide with a point 29 of minimum radius of curvature R_{min} of the logarithmic curve to be approximated. The point 29 of minimum radius of curvature is given by:

$$R_{min} = 1.653Z_0(1 - 2.0508K + 2.316K^2) \quad (2)$$

For |K| less than 0.4

For a pole cap design having a gap diameter to gap length ratio of 5.16 and a K of -0.06 , an R_{min} occurs at a radius of 3.313" and a Z which is 0.286" in from the face 13. This pole cap design is also shown in FIG. 9 and corresponds to point 30 of FIG. 5. The region of circular arc 28 is connected smoothly to the flat surface 13 by means of a transition curve 31 forming the second section of the composite surface. The third section of the composite surface 32 is formed by a linear taper which is brought into the arc at a point 33 tangent to the outside of the circular arc section 28 at an angle greater than 45° with the flat face 13 of the pole cap 7. In the cap 7 of FIGS. 4 and 9, the angle of the linear taper section is 62 degrees to the face 13.

In the pole cap design of FIG. 9, the cap 7 has a thickness of 1.925" and an outside diameter of 9.005" and is made of pure soft iron. The gap length is 0.895". The flat surface 13 has a radius R, of 1.956". The point 29 of minimum radius R_{min} occurs at a radius of 3.313" and the point 33 at which the linear taper section 32 meets the circular arc 28 has a radius of 3.605".

The pole cap 7 of FIG. 9 has a field uniformity versus versus field intensity characteristic as shown by curve 35 of FIG. 6. Curve 35 shows substantial saturation near 22 kg. but uniform field ($\Delta H=0$) is obtained above saturation at 23.5 kg. Small variations in the field strength at which the field becomes uniform above saturation are produced by changing the point 33 where the linear taper 32 begins and the circular arc 28 ends. For example, increasing the angle of the taper 32 to 74° moves point 33 out to a larger radius and increases the field intensity above saturation at which the field becomes uniform ($\Delta H=0$) as shown by curve 35'. Decreasing the angle toward 45° moves point 33 into a smaller radius and decreases the field intensity above saturation at which the field becomes uniform, $\Delta H=0$.

Referring now to FIG. 3, the pole caps 6 and 7 are affixed to the poles 3 and 4 via spacer plates 37, as of iron. The caps 6 and 7 are drilled and tapped at 38 from the backside at 90° intervals of arc around the pole cap and screwed via screws 39 to the plate 37. The pole caps 6 and 7 together with their plates 37 are drilled at 41. Holes are drilled and tapped in the pole pieces 3 and 4 at 42 to receive screws 43 which hold the pole caps 6 and 7 and spacer plates 37 to the poles 3 and 4.

The principal advantage of the modified logarithmic curved pole caps 6 and 7 of the present invention, which employ a K less than that for a constant flux density design, is that they permit operation at a certain field value above saturation. Another advantage is that they provide substantial regions of uniform field at and below saturation with smaller sized magnet coils and pole pieces than required for K_{opt} pole caps. This greatly reduces the cost of a magnet for operation up to and in saturation. For example, a 9" pole diameter magnet employing pole caps of FIG. 9 provides a sufficiently large region of uniform magnetic field at 23.5 kg. to be used with a high resolution nuclear resonance spectrometer at 100 mc. The prior magnet to produce this same operation would have been a substantially more costly 12" pole diameter magnet.

Since many changes could be made in the above construction and many apparently widely different embodiments of this invention can be made without departing from the scope thereof it is intended that all matter contained in the above description or shown in the accompanying drawings shall be interpreted as illustrative and not in a limiting sense.

What is claimed is:

1. In a magnet apparatus, means forming a magnetic circuit having a pair of magnetic poles spaced apart to define a magnetic gap therebetween, means forming a pair of magnetic permeable pole cap portions forming the opposed ends of said gap defining magnetic poles for shaping the magnetic field in the gap, said pole caps having mutually opposed curved face surfaces approximately conforming to the shape defined by the logarithmic expression

$$R - R_1 - \frac{Z_0}{\pi - \tan^{-1} \frac{1}{K}} \ln \left(\frac{Z - Z_0}{Z_1 - Z_0} \right) - K(Z - Z_1)$$

where R is the radius from the axis of the gap, R_1 is the value of R where the curved face of the pole cap makes an angle of 2.1 degrees with the plane perpendicular to the axis of the gap, Z is the axial distance from the midplane of the gap to the pole cap face in the curved region thereof, Z_1 is the value of Z at R_1 , Z_0 is the value of Z on the Z axis if the curved portion had been continued to the Z axis, K is an optimal parameter dependent upon the ratio of gap diameter to gap length, and

$$\tan^{-1} \frac{1}{K}$$

lies between 0 and π , the improvement wherein, K is negative and selected to have an absolute value greater than zero but less than that value, K_{opt} , which will define a magnetic equipotential that gives rise to a constant flux density pole for the ratio of gap diameter to gap length of the magnet, whereby the magnet will provide a homogeneous region of field above saturation.

2. The apparatus of claim 1 wherein said pole caps have portions of their magnetic permeable material recessed on their axes and on the sides thereof remote from their mutually opposed faces to reduce the size of the magnet for producing the homogeneous region of field above saturation.

3. The apparatus of claim 1 wherein each of said approximate logarithmic curved surfaces of said pole caps are formed by a composite of first, second and third surface portions, said first surface portion being a section of a circular arc which coincides with the logarithmic curve approximately where the minimum radius of curvature occurs, said second surface portion being a transition curve which leads smoothly from said first section of circular arc to a flat surface of the pole face of said pole cap, and said third portion of said surface being a linear taper section leading smoothly into said circular arc section on the outside thereof and making more than a 45 degree angle with the flat surfaces of said pole cap.

4. The apparatus of claim 1 wherein K and the diameter to gap ratio fall within the cross hatched area of FIG. 5.

5. The apparatus of claim 3 wherein said section of circular arc is shortened from the outside toward the axis of the gap as compared the length of such circular arc for the certain selected value of K to decrease the field intensity of the operating point above saturation at which the magnetic field is homogeneous.

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