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OVEN REGULATED PERMANENT MAGNET HAVING THERMAL LAGGING BETWEEN THE OVEN AND THE MAGNET

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FIG. 1

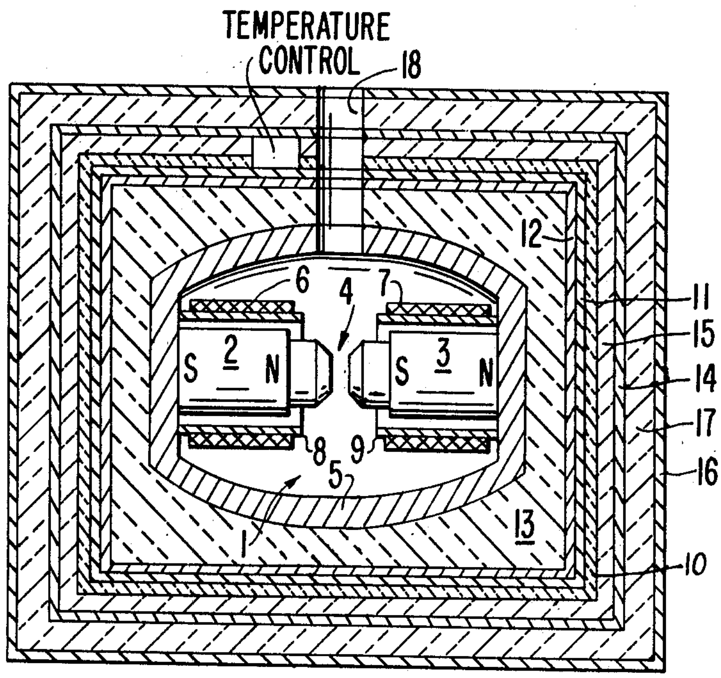


FIG. 2

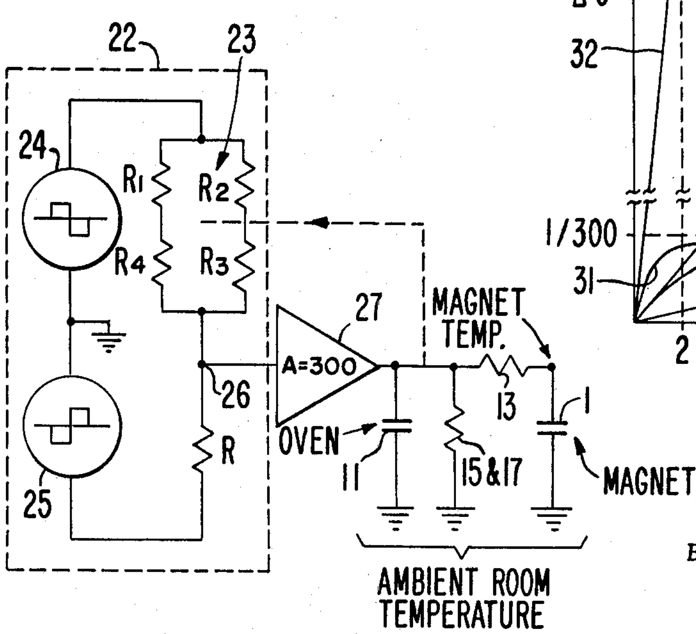
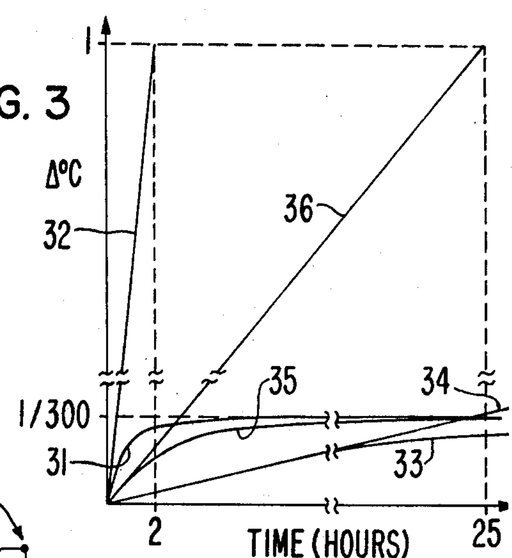


FIG. 3



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OVEN REGULATED PERMANENT MAGNET HAVING THERMAL LAGGING BETWEEN THE OVEN AND THE MAGNET

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ABSTRACT OF THE DISCLOSURE

A permanent magnet apparatus which is temperature regulated to be especially suited for high resolution gyromagnetic resonance spectroscopy. The magnet apparatus includes a pair of permanent magnets axially extending toward each other to define a magnetic gap between their adjacent ends. The permanent magnets are enclosed by a yoke structure to magnetically shield the gap. A thermostated oven envelops the magnet and yoke structures for holding them at a predetermined temperature above ambient room temperature. A blanket of thermally insulative foam material enclosed the magnet and yoke structures physically supporting same from the oven. The foam serves to thermally lag the magnet relative to the oven such that the time rate of change of the magnet is much less than that of the oven. Also, the oven is thermally lagged by a similar blanket of insulative foam relative to ambient room temperature. Three separate concentric magnetic shields serve to add additional magnetic shielding for the gap.

Description of the prior art

Heretofore, temperature regulated permanent magnets have been used for high resolution nuclear resonance. One such magnet employed a thermostated oven which enclosed the magnet for holding same at a predetermined temperature above the ambient room temperature. The oven was thermally lagged by insulative foam from the ambient room temperature environment. However, the magnet was not thermally lagged with respect to the oven. Actually, hot air, which was heated by the oven, was circulated around the magnet inside the oven for causing the magnet to be essentially in good thermal contact with the oven. The problem with this arrangement is that the magnet temperature tends to follow relatively short term temperature changes of the oven. The time rate of change of temperature of the permanent magnet is very important for high resolution gyromagnetic resonance spectroscopy since the field intensity changes radically with changes in magnet temperature. Field changes produce unwanted drifts in the resonance spectra. Such drifts can be corrected by relatively complex and expensive field-frequency control circuitry but it is desired to reduce such temperature dependent drifts by less expensive means.

Summary of the present invention

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

One feature of the present invention is the provision, in a permanent magnet system temperature regulated by a thermostated oven, of a thermal lagging enclosure between the oven and the magnet, whereby the magnetic field produced by the magnet is stabilized against temperature fluctuations of the oven.

Another feature of the present invention is the same as the preceding feature wherein the thermal lagging between the oven and the magnet comprises an insulative foam structure enclosing the magnet and which also serves

to physically support the magnet within the oven structure, whereby the magnet support structure is simplified.

Another feature of the present invention is the same as any one or more of the preceding features wherein a magnetic shield encloses the magnet and yoke structure and is disposed adjacent the inside surface of the oven for holding the shield at a uniform temperature.

Another feature of the present invention is the provision of a thermally insulative foam structure enclosing the oven for thermally lagging the oven relative to ambient room temperature.

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 longitudinal sectional view of a magnet apparatus incorporating features of the present invention,

FIG. 2 is a schematic electrical equivalent circuit for the temperature control system employed with the magnet apparatus of FIG. 1, and

FIG. 3 is a plot of temperature change in degrees centigrade versus time in hours for various different magnet systems.

Description of the preferred embodiments

Referring now to FIG. 1, there is shown a temperature regulated magnet system incorporating features of the present invention. The magnet **1** includes a pair of axially extending permanent magnets **2** and **3** extending toward each other to define a magnetic gap **4** between their adjacent ends. The permanent magnets **2** and **3** are supported at their far ends from the ends of a generally egg-shaped magnetic yoke structure **5** which encloses the permanent magnets **2** and **3** and serves as a magnetic shield for shielding the gap **4** from external magnetic effects. A pair of magnetizing coils **6** and **7** are wound on coil forms **8** and **9** also carried from the ends of the yoke **5**. In addition, a heater coil may be wound in with the magnetizing coils **6** and **7** for initially heating the magnet **1** to its operating temperature. A sequence of high current pulses are fed through the magnetizing coils **6** and **7** for initially magnetizing the permanent magnets **2** and **3**.

In a typical example, the magnets **2** and **3** are each formed by a stack of three disks of permanent magnet material such as Alnico V, each disk being 6" in diameter and 2.5" thick. The yoke **5** is, for example, a one inch thick shell of soft iron to provide a low reluctance flux return path around the magnets **2** and **3**. The magnets **2** and **3**, when fully energized, produce a field intensity of about 14.1 kg. in a 0.5" gap **4** which is approximately 3" in diameter. The magnet **1** is temperature compensated by Carpenter's steel shunting sleeves coaxially disposed around each of the magnets **2** and **3**, as described and claimed in copending U.S. patent applications 512,422, and 512,423, filed Dec. 8, 1965 and assigned to the same assignee as the present invention. As temperature compensated, field intensity of the magnet **1** has a temperature coefficient of about 30 parts per million per degree C.

A hollow cylindrical oven structure **11**, closed on its ends as of type 1100 aluminum having a wall thickness of 0.125", encloses the magnet **1**. Non-inductive printed circuit heating elements **10** are formed on the outside surface of the oven **11** for heating the oven **11** to a predetermined temperature such as 36±0.001° C., which is well above ambient room temperature. A hollow cylindrical mu-metal magnetic shield **12**, as of 0.050" wall thickness, is disposed adjacent the inside surface of the oven **11**. The magnetic shield **12** serves to additionally shield the gap **4** from external magnetic disturbances and effects. A thermally insulative foam structure **13** fills the space between the magnetic shield **12** and the enclosing magnetic yoke **5** for thermally logging the magnet **1** relative to the oven **11**. In a typical example, the foam **13** is Freon blown polyurethane. The enclosing foam structure **13** also serves to support the weight of the magnet **1** from the oven **11**. In a typical example, the foam **13** has a minimum thickness of 1 inch.

A second hollow cylindrical mu-metal magnetic shield **14** encloses the oven **11** for adding additional magnetic shielding for the gap **4**. In a typical example, the shield **14** has a wall thickness as of 0.030″. A second thermally insulative foam structure **15** fills the space between the second magnetic shield **14** and the oven **11**. The second foam structure **15** serves to support the oven **11** from the second shield **14**, is made of the same material as the inner foam structure **13**, and has a thickness of about 1 inch.

A third hollow cylindrical magnetic shield **16**, as of soft iron having a wall thickness of 0.090″, encloses the second magnetic shield **14**. The third shield **16** serves to shield the gap **4** from external magnetic effects. A third thermally insulative foam structure **17**, made of the aforecited foam material, as of 1 inch thick, fills the space between the outer shield **16** and the second magnetic shield **14**. The third foam enclosure **17** serves to support the second shield **14** from the outer shield **16**. The second and third foam enclosures, **15** and **17** respectively, provide thermal lagging for the oven **11** relative to the surrounding ambient room temperature environment. The outer shield **16** is supported within a cradle contained within a suitable cabinet, not shown. A bore **18**, as of 2″ in diameter, passes radially through the various shielding enclosures and magnetic yoke **5** to provide access to the magnet gap **4**. When the magnet is used with a gyromagnetic resonance spectrometer the sample probe, not shown, is inserted into the gap **4** through the access bore **18**.

Referring now to FIG. 2, there is shown an electrical equivalent circuit for the thermal system of the magnet and its surrounding oven and shields. In the equivalent circuit, voltage is equivalent to temperature, current is equivalent to heat, resistance is equivalent to thermal insulation, and capacity is equivalent to heat capacity. The thermostat circuit includes an electrical bridge **22** for sensing the difference between the temperature of the oven **11** and a reference temperature. The reference temperature is set by a reference resistor R placed in one arm of the bridge. The reference resistor R has a precise resistance to ±20 parts per million per degree centigrade. The temperature of the oven **11** is sensed by a resistive thermistor network **23** formed by four thermistors R_1, R_2, R_3, and R_4 connected in two parallel branches. The thermistors are affixed to the outside of the oven **11** at widely spaced points and connected such that temperature gradients are cancelled out to obtain an average temperature reading for the oven **11**. The bridge is excited by two reference signal generators **24** and **25**. The signal generators produce square wave outputs which are 180° out of phase relative to ground such that there will be no output signal at terminal **26** when the resistance of the thermistor network **23** is exactly equal to the resistance of reference resistor R. However, when the temperature of the oven **11** departs from the predetermined temperature, this will shift the resistance of the thermistor network and produce an output signal at terminal **26**. The output of the bridge **22** is fed to a power amplifier **27** and thence to the heating elements on the oven **11** for heating same sufficiently to balance the bridge **22**.

In a typical example, the oven **11** has a heat capacity of 1° C. per 2 watt-hours, the foam insulators **15** and **17** for the oven have an insulation of 1 watt/° C., the thermal insulation **13** for the magnet **1** has an insulation of 1 watt/° C., and the magnet **1** has a heat capacity of 1° C. per 25 watt-hours. The amplifier has a gain of 300.

Referring now to FIG. 3, the operation of temperature control system for the magnet **1** will be described. It is assumed for the sake of explanation that the ambient room temperature is suddenly increased by 1° C. in the manner of a step function increase. The oven **11** with its external thermal lagging has a time constant of about 2 hours. The sensor **23** will sense the change in temperature and correct the temperature of the oven **11** as indicated by line **31** such that the total temperature rise of the oven **11** is only $+1/300$° C. However, the thermostat changes the temperature of the oven **11** with an initial time rate of change equal to the slope of 1° C./2 hours, as indicated by line **32**. However, due to the thermal lagging of the internal foam structure **13** and due to the large heat capacity of the magnet **1**, the time constant of the magnet **1** is 25 hours. Thus, the magnet **1** changes its temperature by $+1/300$° C., as shown by curve **33**, with an initial maximum time rate of change in temperature of $+1/300$° C./25 hours corresponding to line **34**. During a six minute period, the magnet **1** changes temperature less than $1/75{,}000$° C. for a 1° C. step change in the ambient.

If it were not for the internal thermal lagging produced by insulative structure **13** and if the magnet **1** was thermally connected to the oven **11**, as in the prior art circulating air scheme, the magnet temperature would follow curve **35** and would have an initial time rate of change of 1° C./25 hours, as indicated by line **36**. Thus, the thermal lagging **13** reduces the time rate of change of the magnet **1** by the gain of the amplifier **27**. In the example cited, this is a factor of 300 reduction as compared to the prior art scheme.

Since many changes could be made in the above construction and many apparently widely different embodiments of this invention could 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 permanent magnet apparatus, means forming a pair of permanent magnets axially extending toward each other to define a magnetic gap in the space between their adjacent ends, means forming a magnetic yoke structure interconnecting said pair of magnets to provide a flux return path around said pair of magnets, means forming an oven structure having a thermally conductive metallic wall enclosing said permanent magnets and said yoke structure, means including a heating element disposed externally of said metallic wall of said oven in heat exchanging relation therewith for heating and controlling the temperature of said oven to a predetermined temperature substantially above ambient room temperature, the improvement comprising; means forming a thermally insulative structure substantially completely enclosing said permanent magnet and yoke structures, said thermally insulative structure being disposed between and substantially filling the space between said thermally conductive wall of said oven and said magnet and yoke structures for thermally lagging said magnet and yoke structures relative to said enclosing oven structure, an access opening through said oven wall and communicating with the magnetic gap of the magnet.

2. The apparatus of claim 1 wherein said yoke structure substantially encloses said pair of permanent magnets and the gap therebetween for magnetically shielding said magnets and gap from external magnetic effects, and wherein said enclosing thermally insulative structure includes a thermally insulative foam structure serving to physically support said magnet and yoke structures within said oven structure.

3. The apparatus of claim 1 including means forming a magnetic shield structure enclosing said magnet and yoke structures and disposed inside of said oven structure

for additionally shielding said gap from external magnetic effects.

4. The apparatus of claim 1 including a second thermally insulative structure enclosing said oven structure for thermally lagging said oven relative to changes in the temperature of the ambient room temperature.

5. The apparatus of claim 4 wherein said second thermally insulative structure includes a thermally insulative foam structure serving to physically support said oven therewithin.

6. The apparatus of claim 4 including means forming a second magnetic shield structure enclosing said second thermally insulative structure for additionally shielding the magnetic gap from external magnetic effects.

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219—201, 510; 324—.5