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E. Hoyer, J.W.G. Chin, and D. Shuman

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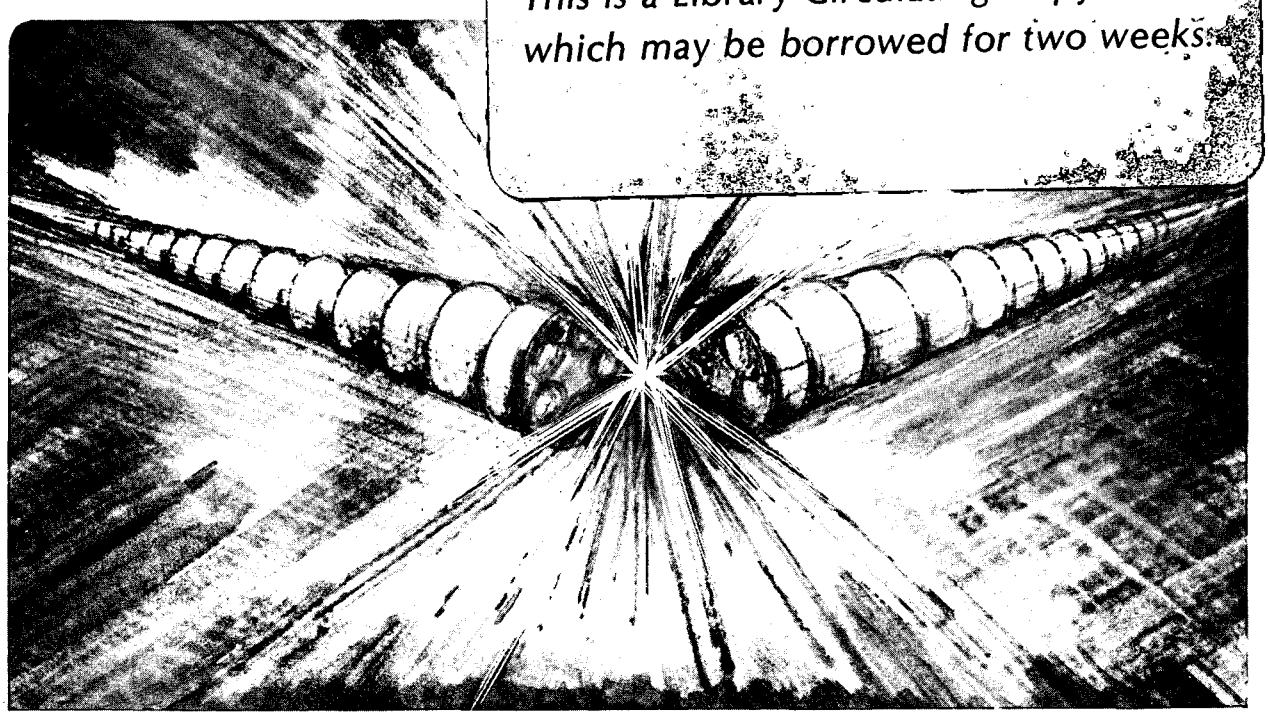

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REC and NdFe Magnetic Moment Irreversibility from Temperature Cycling*

E. Hoyer, J.W.G. Chin, D. Shuman

Lawrence Berkeley Laboratory, University of California
Berkeley, California 94720

Abstract

Presented are the results of thermal cycling tests carried out on REC and NdFe samples, to determine the irreversible losses in room temperature open circuit magnetic moment. A stabilization prescription was developed for a REC alloy that will allow two 4day/175°C temperature cycles, which simulate two UHV bakeouts, with only a 0.35% average loss and a 0.65% loss variation in the room temperature open circuit magnetic moment after stabilization.

Introduction

During the past five years rare earth permanent magnet (REPM) materials have found increasing application in short period wigglers and undulators[1]. Of the REPM materials available, alloys of rare-earth Cobalt (REC) have been used to date and Neodymium-Iron (NdFe) alloys are now being considered for new insertion devices[2].

Performance of some REPM insertion devices have shown central vertical peak field variations of less than one percent at the highest fields[3,4]. Typically these small field variations are accomplished by accepting REPM blocks from a vendor with a ~5% variation in the magnetic moment and subsequently reducing this variation by either sorting or by changing the magnetic moment, thermally or magnetically, to obtain acceptable block to block variation. For example sorting has demonstrated that a variation of less than 0.1% can be achieved in the total magnetic moment per pole for an 8 block per pole system[4].

If the blocks are subjected to elevated temperature cycles, irreversible room temperature magnetic moment changes will occur. Unless suitable temperature stabilization of the material has been carried out, this may lead to degradation of field performance of the device. Elevated temperatures can occur during fabrication, for example bonding REPM blocks to an assembly with an epoxy adhesive requiring an elevated temperature cycle, or during preparation for operating, for example subjecting the assembly to an elevated temperature bake-out when ultra-high - vacuum is required, and possibly during operation when the storage ring temperature may rise during a warm period or because of equipment failure.

Irreversible losses of magnetization have been extensively reported in the literature and are dependent upon alloy composition, block size, manufacturing method, and block thermal history.[5,6,7] Reported here are irreversible room temperature magnetic moment changes in REC and NdFe due to elevated temperature cycling tests carried out on recent commercially manufactured, permanent magnet blocks. The motivation for these thermal tests was two fold; to understand the influence of temperature cycling of these REPM materials on the field performance of insertion devices and to investigate if it is possible to successfully stabilize REPM material for in-vacuum insertion devices that would be subjected to high temperature bakeouts.

Magnetic moment irreversibility due to thermal cycling

Tests to determine the irreversible changes in the room temperature open circuit magnetic moment were carried out with REC and NdFe with above room temperature thermal cycles.[8,9,10] The thermal cycling tests consisted of initially measuring the room temperature magnetic moments of a group of blocks, subjecting the blocks to an elevated temperature for a given period, allowing the blocks to cool to room temperature and then remeasuring the room temperature magnetic moment all in open circuit configuration.

REC Thermal cycling tests

Ten REC magnetic blocks per LBL Specification M636 from a 1036 block lot were tested.[11] Block size was 1.12 cm x 5.12 cm x 5.3 cm with the easy axis in the short dimension. Minimum coercive force was 9.0 kOe and the initial spread in the room temperature magnetic moment was 5.7% for the ten blocks. Blocks were manufactured by Vacuumschmelze, Hanau, West Germany. These blocks were heated in the open circuit condition for 1 hour periods at temperatures of 50°C, 100°C, 150°C, 175°C and 200°C. The irreversible room temperature magnetic moment changes were obtained by taking the differences between the room temperature open circuit magnetic moments recorded before and after each temperature cycle. A Helmholtz coil, integrator and digital voltmeter were used to measure the magnetic moments. When a significant

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change in magnetic moment occurred at a particular cycling temperature, the same REC blocks were recycled until only a very small change occurred which was then considered stabilized. Relative measurement errors were less than 0.2%.

Results of the REC block tests are shown in Figure 1 which shows average irreversible loss of room temperature magnetic moment from the initial magnetic moment prior to testing as a function of the number of 1 hour tests for various temperatures. The results show that as the test temperature increased, more 1 hour thermal cycles were required to obtain stabilization. Also, the largest loss in magnetic moment occurs during the first cycle at each test temperature. Figure 2 shows the cumulative average loss and associated variation in loss of the room temperature magnetic moment as a function of cycle temperature for REC. At 50°C a 0.23% average loss of magnetic moment with a 0.32% variation in loss is observed; at 100°C this increases to an average loss of 0.82% with a 1.32% variation, and at 200°C the average loss is 9.86% with a 24.5% variation. Further, these test blocks were subjected to subsequent cycles of 24 hrs and 96 hrs at 200°C with the average loss in magnetic moment increasing to 10.93% with a 25.9% variation. Somewhat disturbing is that the variation of loss of magnetic moment in the blocks is greater than the average loss.

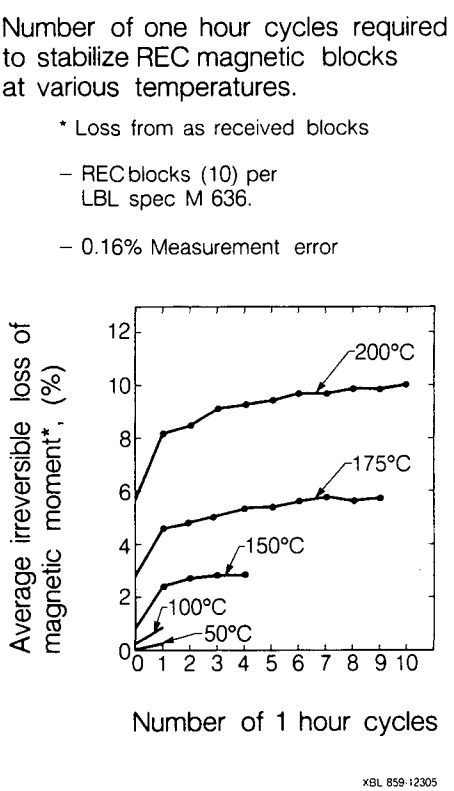


Figure 1.

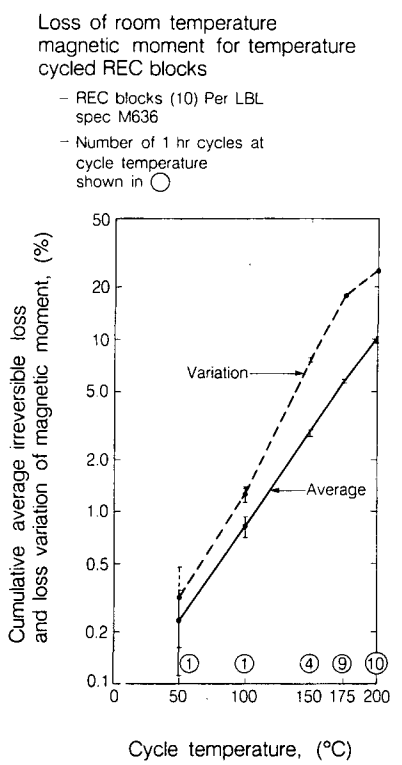


Figure 2.

Clearly, as the temperature of the cycle is increased the irreversible loss increases. Small changes in field performance of an insertion device fabricated from this material, would probably become noticeable with temperature excursions of 100°C or greater even with multiple block pole configurations.

NdFe Thermal Cycling

Similar thermal cycling tests were carried out on NdFe magnetic blocks. Three different grades of magnetized NdFe blocks were tested; the grade, coercive force, block size and number of blocks tested are tabulated in Table 1.

Table 1

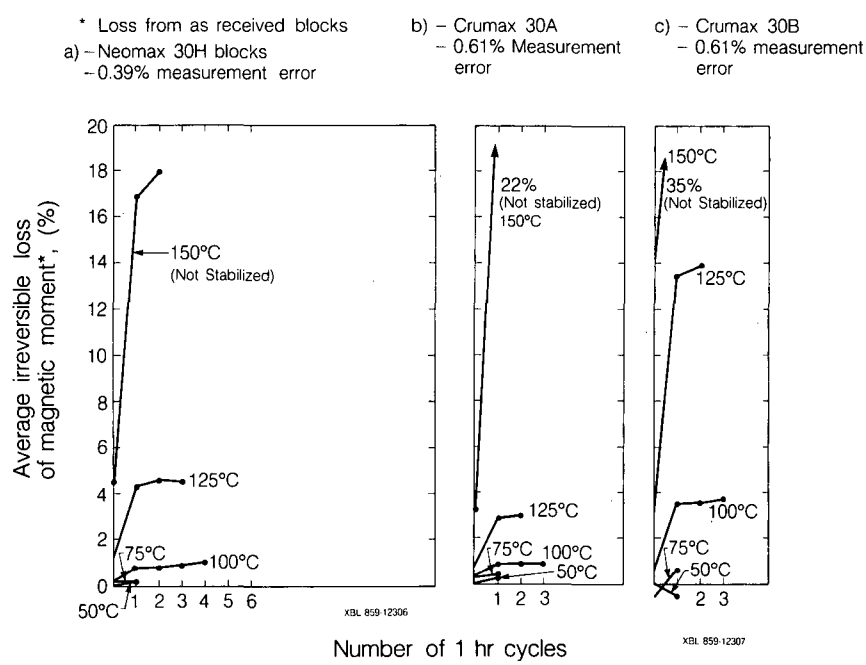
Test NdFe Magnetic Block Information

Grade+	Coercive Force (H_c) (kOe)	Block Size (cm x cm x cm)	Number of blocks tested
Crumax 30A	10.67	3.30 x 2.29 x 0.95*	4
Crumax 30B	10.51	3.30 x 2.29 x 0.95*	4
Neomax 30H	10.78	5.08 x 2.13 x 1.12*	13
Neomax 30H	10.78	4.17 x 2.13 x 1.12*	6

*Easy axis direction

Test cycle temperatures were 50°C, 75°C, 100°C, 125°C, 150°C. Relative measurement errors are 0.4% for the Neomax 30H blocks and 0.6% for the Crumax 30A & 30B blocks.

Figures 3a, 3b and 3c (similar to Figure 1 but for NdFe material), shows the irreversible average loss of room temperature magnetic moment as a function of the number of 1 hour tests for the three materials tested for various test temperatures. When comparing the NdFe test data to the REC test data, the losses are generally comparable up to 100°C cycle temperatures and greater for higher temperatures than 100°C, which is expected since the Curie temperature for NdFe alloys is lower than for REC. The large loss in the first cycle at a given test temperature, characteristic of the REC data, is also noted in the NdFe test data. Tests were terminated at 150°C for the NdFe because the average loss in room temperature magnetic moments were large, 18 to 35 percent.

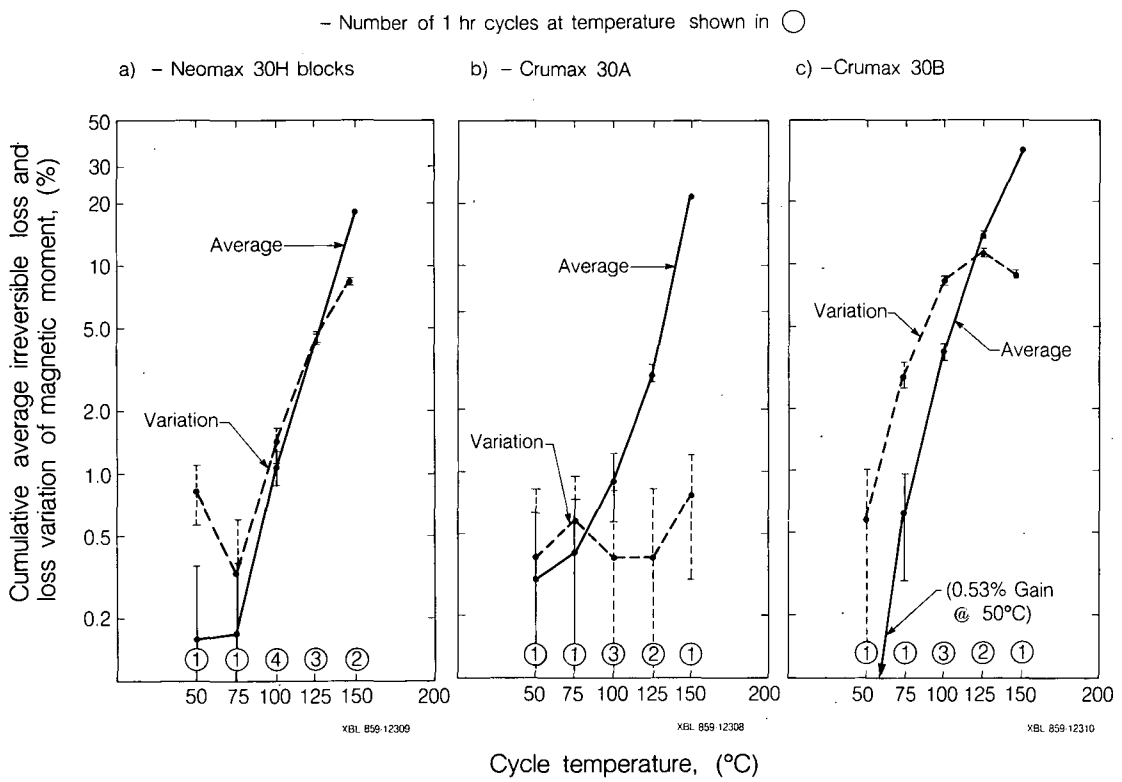


Number of one hour cycles required to stabilize NdFe blocks at various temperatures

Figure 3.

+Crumax is a Colt Industries Trademark
Neomax is a Sumitomo Trademark

Figures 4a, 4b and 4c, similar to Figure 2, show the cumulative average loss and associated variation in the loss of the room temperature magnetic moment as a function of cycle temperature for the different grades of NdFe. For example, at 75°C, varieties 30H, 30A and 30B show irreversible losses of 0.13%, 0.40% and 0.63% respectively with corresponding loss variations of 0.33%, 0.58% and 2.90%. When comparing these materials, though they have comparable coercive forces (H_c), irreversible magnetic moment and variation in loss are quite different. These results may be somewhat biased in that only four 30A and four 30B samples were tested and that the 30H samples were used in model tests prior to temperature cycling after which they suffered a slight loss of magnetic moment. Nevertheless, the results suggest that if elevated temperature changes are anticipated in the life of the device, magnetic moment thermal cycling tests should be carried out on a representative sample of the material of choice.



Loss of room temperature magnetic moment for temperature cycled NdFe blocks

Figure 4.

General conclusions can probably only be drawn from the 30H material results since there was a reasonable statistical sample (19 blocks). Here, small changes in field performance of an insertion device, if fabricated from this material, would probably be noticeable for temperature excursions of 100°C or greater even with multiple block pole configurations. Because the losses were large at 150°C, higher temperature (>150°C) stabilization was not attempted for the NdFe alloys.

REC Stabilization Tests

The objective was to see if REC could be stabilized at 200°C and then subsequently be subjected to two 4 day/175°C temperature cycles (to simulate 2 UHV bakeouts at 175°C) to see if a variation of ~0.5% in the irreversible losses of the magnetic moment could be obtained.

A total of 30 magnetized REC blocks were tested from the same 1036 block lot previously described. Ten blocks were stabilized for 2 hours at 200°C, another ten blocks were stabilized for 8 hours and the third ten were stabilized for 96 hours. After stabilization all the blocks were subjected to two 4 day (96 hours)/175°C temperature cycles. Magnetic moments were measured before and after each cycle. The relative measurement errors in the magnetic moment measurements were less than 0.2%. Results of the initial 200°C stabilization are shown in Table 2.

Table 2

200°C Magnetized REC Block Stabilization
(10 blocks in each group)

Irreversible loss of room temperature magnet moment

200°C stabilization period (hrs)	Average loss (%)	Minimum loss (%)	Maximum loss (%)
2	8.03	2.88	21.37
8	5.30	1.35	21.52
96	6.78	1.99	28.11

The correlation between average loss of magnetic moment and duration of stabilization in this case probably has to do with blocks having large losses. The 2 hour stabilization group had the largest average loss of magnetic moment which was probably due to the fact that the group had 4 blocks with losses greater than 10% and the other groups had only 1 each. For all the blocks, the initial average room temperature magnetic moment variation was 6.5% and after stabilization the average loss of room temperature magnetic moment was 6.7% with a resulting maximum variation of 26.8%. It is clear from the table that material can be manufactured, and processed through this stabilization, only loosing 1.35% in magnetic moment.

Irreversible losses of room temperature magnetic moment with stabilization after the two 96 hour/175°C cycles are shown on Figure 5. From the curve, average loss and variation decreases with an increased period of stabilization. The 96 hour stabilization cycle, though long, produces an acceptable loss 0.35%, with a maximum variation in the irreversible loss of o.43%.

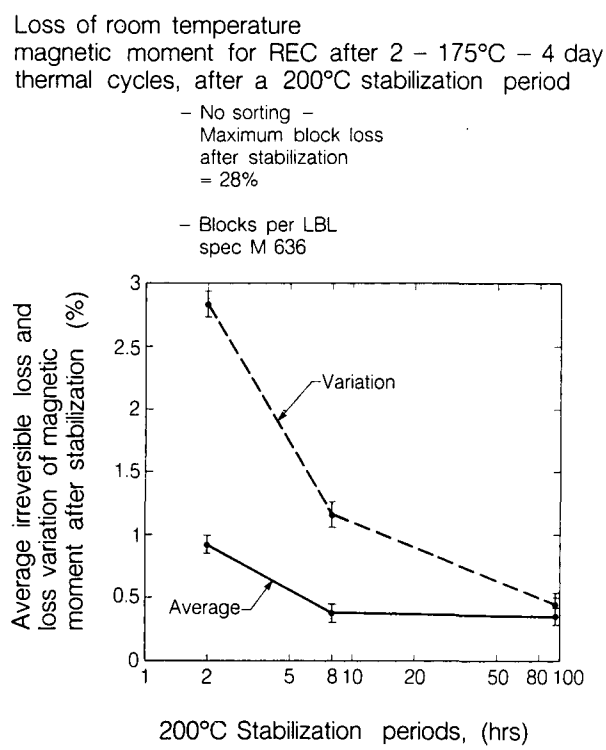


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Figure 5.

If the blocks with losses in excess of 10% after stabilization are eliminated; then 20% of the blocks would not be used. As shown in Figure 6, for this sorted case after the two 96 hour/175°C cycles the irreversible losses in room temperature magnetic moment are less, 0.22% to 0.34%; all the stabilization cycles are able to show low variations in the irreversible losses, the largest is 0.65% maximum. If blocks with losses of less than 5% are only considered after stabilization, 37% of the blocks would be eliminated. Figure 7 shows the irreversible losses in room temperature magnetic moment, for blocks that have had no more than a 5% loss of magnetization during stabilization, after the two 96 hour/175°C cycles. There is only a very small improvement in average loss and variation for the stabilized blocks with a 5% variation when compared with those with a 10% variation.

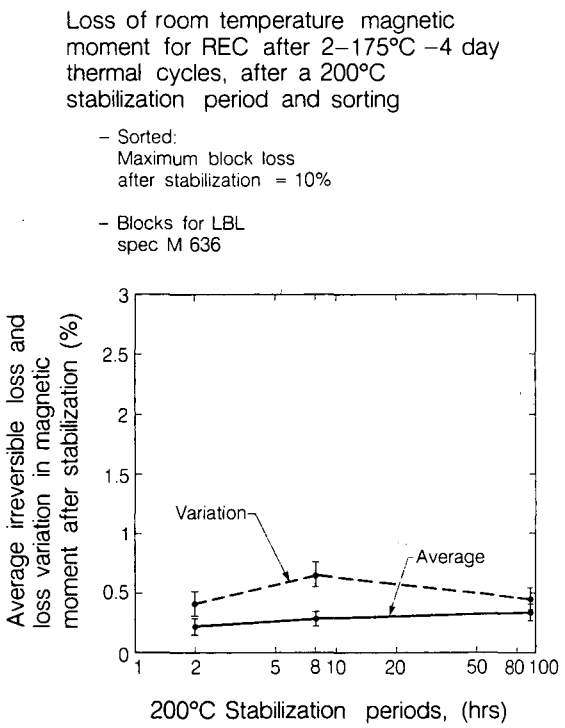

Figure 6.

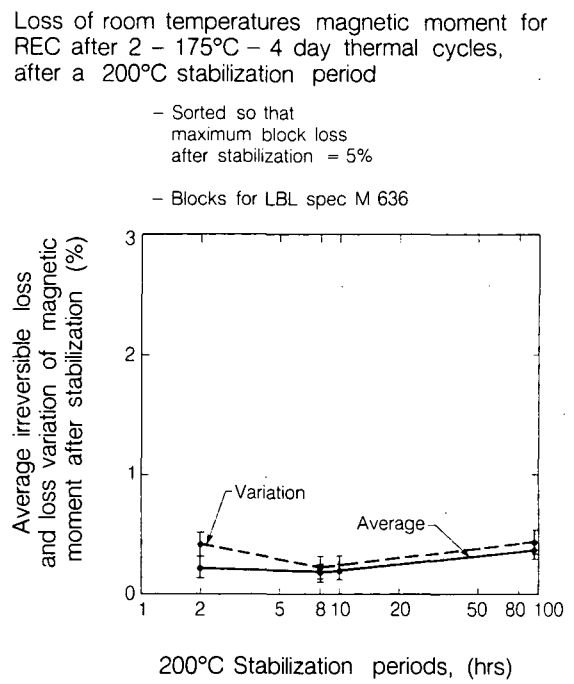

Figure 7.

From these REC stabilization tests, to meet the ~0.5% variation in the loss of magnetic moment criteria, it appears that stabilization is successful, with a resulting loss of ~7% in magnetization, if the 200°C stabilization cycle is ~ 4 days long. If the high loss blocks (>10%) are eliminated after stabilization, a 2 hour stabilization cycle will be satisfactory. Further, in actual design where there are multiple REPM blocks per pole, the effect of the variation in the irreversible loss will be reduced by at least the inverse of the square root of two times the number of blocks used per pole assembly. In an actual device it is recommended that the bakeout be done at least 50°C below the stabilization temperature because of the possibility of non-uniform heating and thermal overshoot. Attention should be given to overall distortion of the precision magnetic structure due to thermal cycling.

Conclusions

Irreversible losses in the room temperature magnetic moment do occur when REC or NdFe alloys are subjected to elevated temperature cycles when the materials have not been previously thermally stabilized. Irreversible losses are dependent on the type of alloy, block size, the method of manufacture, and its previous thermal history. Losses increase with increased temperature excursion.

Thermal stabilization results in an initial lower magnetization of the REPM material because of the stabilization, but reduces the irreversible losses of magnetic moment due to subsequent thermal cycling at temperatures below the stabilization temperature.

A successful stabilization prescription was worked out for an REC alloy so that the material can be subjected to two 4 day/175°C cycles (150°C maximum temperature recommended) and experience a maximum irreversible room temperature magnetic moment average loss of only 0.35% and a loss variation of only 0.65%. The stabilization resulted in a ~7% average per block loss of irreversible room temperature

magnetic moment. The technique involves subjecting the REC blocks to either a 4 day/200°C temperature cycle or a 2 hour/200°C temperature cycle and sorting the blocks such that the blocks with irreversible losses in excess of 10% are eliminated.

In conclusion, during the design phase, to minimize irreversible loss of magnetic moment effects in REPM insertion device, the following guidelines should be considered:

- Anticipate the probable thermal history of the device.
- Verify if the irreversible losses in magnetic moment for the selected unstabilized material being considered will be within an acceptable range.
- If the irreversible magnetic moment losses fall outside an acceptable range, develop an appropriate stabilization/sorting method to bring the losses within an acceptable range.

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References

1. K. Halbach, Physical and Optical Properties of REC Magnets, LBL 11393, 1980

2. K.G. Tirsell et al, Development of a NdFe - Steel Hybrid Wiggler for SSRL, SPIE - Vol 582, 1985.

3. K. Halbach, et al, A Permanent Magnet Undulator for Spear, IEEE Transactions, Nuclear Science, NS-28, 3136 1981

4. E. Hoyer, et al, The Beam Line VI REC - Steel Hybrid Wiggler for SSRL, IEEE Transactions, Nuclear Science, NS-30, 3118, 1983

5. H.F. Mildrum, M.F. Hastings, K.J. Strnat, Thermal Stability and Temperature Coefficients of Sintered Samarium - Cobalt Magnets, AIP Conf. Proc. No. 18, Part 2, 1163-7, 1974

6. S.T. Mildrum, et al, An investigation of the aging of Thermally Prestabilized Sintered Samarium - Cobalt Magnet IEEE-Vol. Mag-10, No.3, 723-5, 1974

7. S.T. Trout, Improving the Distribution of Magnetic Properties In Rare Earth - Cobalt Magnets by the use of Thermal Stabilization, IEEE, Vol Mag-19, No. 5, 2047-9, 1983

8. J.W.G. Chin, E. Hoyer, Magnetic Moment Changes of REC Blocks with Elevated Temperature Cycling, LBID 896, 1984

9. D. Shuman, Measured Magnetic Properties of Neodymium-Iron, LBL Engineering Note, M6350A, 1985

10. D. Shuman, Temperature Stability of Neodymium-Iron, LBL Engineering Note, M6405A, 1985

11. E. Hoyer, Magnetized Rare Earth Cobalt Blocks, LBL Specification M636, 1982.

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