3-17-94
E-8248

NASA Contractor Report 194440

Comparative M-H Characteristics of 1-5 and 2-17 Type Samarium-Cobalt Permanent Magnets to 300 C

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Prepared for
Lewis Research Center
Under Contract NAS3–25266

National Aeronautics and
Space Administration

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SUMMARY

Recent consideration of the use of permanent magnets in space power converters at heat rejection temperatures exceeding 250 C and in miniature high temperature actuators is supporting a search for permanent magnets resistant to demagnetizing forces at high temperature. The present paper investigates the short-term demagnetization resistance to applied bucking fields and at temperatures up to 300 C of $SmCo_5$ type magnets, in the form of 1-cm cubes, from several commercial sources. Quasistatic, 2nd quadrant M-H data taken at selected temperatures are the source of derived plots which are then compared to similar data for previously tested Sm_2Co_{17} type magnets. The 1-5 magnet remanence tends to be about 1.5 kG below that of the 2-17 magnets throughout the temperature range. However, the intrinsic coercivities and M-H curve 'knee-fields' seen in particular 1-5 magnets were considerably above those seen previously in the 2-17 magnets. This superior resistance to demagnetizing fields attainable in 1-5 magnets is also illustrated by safe operating area plots based on the knee-field, the magnetic induction swing and temperature. Comments are made on the possibility that a remanence versus knee-field tradeoff can make 1-5 material competitive with 2-17 in applications where a magnet has to withstand large bucking fields at high temperature.

INTRODUCTION

Temperatures exceeding 250 C are now being considered for the exciting magnets to be used in power converters for long-term space missions [1], where a high heat rejection temperature permits a great reduction in radiator size. Similarly high temperatures may be expected for magnets used in certain particle beam applications such as ion engines, traveling wave tubes and future miniaturized actuators. Whenever there is a need to minimize system mass and volume at high temperatures, samarium-cobalt permanent magnets become competitive with electrical coils because above 200 C the lack of thin and reliable wire insulation makes it difficult to construct compact coils that can deliver ampere-turns equivalent to a high energy permanent magnet. Moreover, the samarium-cobalt types are still the only magnets available that retain at 300 C a useful remanence (B_r ~ 0.9T) and an intrinsic coercivity ($_MH_c$) sufficiently high ($_MH_c \geq B_r$) to avoid self-demagnetization and to keep the induction (B) roughly linear with the applied field (H) in the 2nd quadrant [2].

M-H characteristics and short-term demagnetization resistance of anisotropic Sm_2Co_{17} type magnets have been previously reported to 300 C [3], [4]. This report presents similar data for $SmCo_5$ type magnets from several manufacturers and compares it to the 2-17 characteristics. Measured M-H characteristics are again given for selected temperatures to 300 C. From this basic data, plots versus temperature of the remanence (B_r), the $_MH_c$ and the knee-field $_MH_k$, at which the magnetic moment (M) is 10% below its remanence (M_r), are again derived and are superimposed on corresponding plots for selected 2-17 magnet samples. And as previously, the $_MH_k$ is invoked to create plots showing, at temperature, the margin of safety against irreversible loss of magnetization due to a given swing (ΔB) of B below B_r.

Although the 2-17 type magnets generally outperform the 1-5 type by some magnet performance criteria such as $(BH)_{max}$, these plots show instances where this is not so and they quantify the comparison versus temperature.

APPARATUS AND PROCEDURES

The quasistatic, 2nd quadrant M-H characteristics of the precisely sized 1-cm cubic magnet samples were measured by an electromagnet-driven hysteresigraph. This instrument is an improved, 300 C model of a temperature control oven and probe coil assembly for magnet testing that was originally developed at the University of Dayton [5]. Brief descriptions of this apparatus as well as the procedures used can be found in references [3], [4] and a diagram of the apparatus and further details of construction are given in reference [6].

HIGH TEMPERATURE 1-5 DATA COMPARED TO 2-17: HIGH COERCIVITY IN 1-5

2nd quadrant M-H curves were taken for 5-sample groups of high $_MH_c$, anisotropic 1-5 type magnets from 3 manufacturers. As in the case of the previous 2-17s, a representative sample could again be selected from each group, since the variation of characteristics within each group was smaller than the variation between groups. Figures 1a-1c present the basic data taken at selected temperatures from room to 300 C and Figure 1d is included to review definitions and illustrate the relations between M and B and ΔB, in cgs units. All of the shown curves were repeatable, indicating no adverse metallurgical change during the measurements.

As temperature increases, the M-coercivity is seen to decrease much more rapidly than does the remanence, which is as usual for samarium-cobalt type magnets. The M-coercivity has also a greater manufacturer dependent scatter than does the remanence. Inspection of the presented curves shows that their squareness in the 2nd quadrant tends to increase with temperature. Thus these behaviors are qualitatively the same as observed for the 2-17 type magnets [4].

A significant strong point of some of the tested 1-5 samples is their relatively high $_MH_c$ and $_MH_k$, from room temperature to 300 C. At room temperature, their $_MH_c$ varies from about 23.8 kOe for the IG material to values exceeding the 32 kOe maximum field capability of the apparatus in the case of the Electron Energy (EE) and Recoma (Re) samples. At 300 C, the $_MH_c$ is down to 7.5 kOe for the IG, to 10 kOe for the EE and to 14 kOe for the Re samples. The $_MH_c$ comparison shown in Figure 2 is to the lowest coercivity, Shin-Etsu (SE), and to the highest coercivity, IGT, previously measured 2-17 type materials. It is clear that the $_MH_c$ of one of the 1-5 materials is significantly above that of the highest $_MH_c$, 2-17 material, although the relative variation among these 1-5 materials is quite large. The normalized rates $d(_MH_c / _MH_c(23\ C))/dT$ for the Re and EE 1-5 samples are about the same as for the IGT 2-17 sample, being -0.28%/C.

The point on the M-H characteristic in its 2nd quadrant where $M=0.9M_r$, or "knee point", is conventionally taken as the point of onset of rapid downslope. In case of a very square M-H characteristic, an immediate and great loss of magnetization will set in if an applied bucking field drives M below its knee value. Figure 3 clearly shows that the knee-field of the 1-5 test samples generally exceeds the highest 2-17 magnet (IGT) knee-fields observed up to 300 C. This further points out the fact that some 1-5 materials have been developed to achieve a superior resistance to short-term demagnetization by large bucking fields at high temperature.

A lower value of the remanence B_r ($=4\pi M_r$) in 1-5 materials as compared to the remanence of 2-17 types is a main weak point of the 1-5 materials. The B_r of the 1-5 magnets is shown by Figure 4 to be roughly 1.5 kG below the B_r of the 2-17 magnets over the temperature range covered. At 300 C, this amounts to a very substantial 30% or so loss in the energy product $(BH)_{max}$. On the other hand, in applications where a need to resist demagnetization imposes restrictions, it may be possible to trade off a reduced B_r for a higher $_MH_k$; more on this later.

SAFE OPERATING AREA

M-H Knee Point and Irreversible Demagnetization

The difference between the knee-field magnitude $|_MH_k|$ and the magnitude $|H_d|$ of the demagnetizing field needed to produce a desired induction swing ΔB below B_r is taken as a qualitative measure of the margin of safety against immediate, irreversible demagnetization and also possibly against long-term ageing losses.

All data necessary to prepare the safe operating area (SOA) plots shown in Figure 5 are derived from the basic data given in Figure 1. Thus, for a given material and temperature, Figure 1 specifies the constitutive relation $B=H+4\pi M(H)$, which together with $B=B_r-\Delta B$ then determines the bucking field H_d needed to give a specified ΔB. The SOA is the area below the $|_MH_k|$ curve. From the point of view of this ΔB-T SOA defined by the knee-field criterion, the Re 1-5 magnet is by far the most demagnetization resistant at 300 C, while being in this respect only slightly superior to the EE and IG samples at room temperature. Indeed, at 300 C this Re 1-5 magnet can tolerate a ΔB up to 11 kG, as compared to only 7.6 kG at 300 C for the most resistant 2-17 type magnet measured previously.

Comment on Remanence-Coercivity Tradeoffs

To avoid the risk of magnet demagnetization inherent in too close an operation to the knee point, the restriction on maximum allowed ΔB may be sufficient to preclude operation at some optimum point, such as minimum magnet volume. In such cases, it may be possible to substitute a magnet material of lower B_r, but of higher $_MH_k$, without a volume penalty. To illustrate a B_r versus $_MH_k$ tradeoff, consider the idealized magnet operating line $B=\mu H+B_r$, for $H>{_MH_k}$, and the problem of smallest magnet to give a specified field in a specified gap volume. In this case, the inverse magnet volume is proportional to [7] $-BH=-H(\mu H+B_r)=\mu^{-1}\Delta B(B_r-\Delta B)$, where $_MH_k<H<0$ and $\Delta B=-\mu H$. As a function of B_r and ΔB in the first quadrant, the (-BH) is a saddle-shaped surface that intercepts the (B_r, ΔB) plane along the lines $\Delta B=B_r$ and $\Delta B=0$. Along cuts of constant B_r, this surface attains a peak height of $(-BH)_{max}=B_r^2/(4\mu)$ at $\Delta B=B_r/2$; note, however, that the line of steepest ascent from (or descent to) the origin is $\Delta B=(\sqrt{2}-1)B_r$, and not the locus $\Delta B=B_r/2$. Thus a magnet material restricted by demagnetization considerations is being operated off-peak with respect to the constant B_r cuts and can possibly be replaced to advantage by another, lower B_r, but higher $_MH_k$, material. A similar example is the linear alternator output power per unit volume of its exciting magnets, given approximately by $\frac{1}{4}(\omega/\mu)\Delta B B_r[1-(1+K_1)^2(\Delta B/B_r)^2]^{1/2}$, [8]. Along cuts of constant B_r, this function attains its peak value $\omega B_r^2/[8(1+K_1)\mu]$ at $\Delta B=B_r/[(1+K_1)\sqrt{2}]$. Using such geometric visualizations, it is straight forward to write algebraic criteria for feasible magnet substitutions. Since this becomes a matter of case studies, it will not be pursued further.

SUMMARY OF RESULTS AND CONCLUSIONS

M-H characteristics were obtained from room temperature to 300 C for 5-sample groups of high coercive, $SmCo_5$ type magnets from 3 manufacturers. A representative sample was chosen from each group and its 2nd quadrant M-H curves at selected temperatures to 300 C are presented in Figure 1. For these 1-5 type samples, the remanence B_r varied, by manufacturer, from 8.9 kG to 9.2 kG at room temperature and from 7.6 kG to 8.0 kG at 300 C. And the variations, by source, of the intrinsic coercivity were from 23.6 kOe to over 32 kOe at room temperature, and from 7.42 kOe to 14.2 kOe at 300 C. The rate of loss of B_r with temperature was about the same as for the reported [4] Sm_2Co_{17} type magnets, but the 1-5 magnet B_r was consistently about 1.5 kG below the 2-17 magnet B_r over the temperature range. However, the intrinsic coercivity of one of the 1-5 magnets was observed, from room temperature to 300 C, to be at least 5 kOe above the highest coercivity measured for a 2-17 type magnet. Especially the knee-field, defined as the applied bucking field at which the magnetization is reduced to $0.9B_r$, of the 1-5 magnets was found to be significantly and consistently above that of the 2-17 magnets. This data shows that certain commercial 1-5 type magnets have been developed to provide coercivities significantly exceeding those of the 2-17 types at temperatures up to 300 C.

An estimate of the margin of safety against immediate demagnetization due to too large an applied bucking field is based on the criterion that safe operation must be above the knee point of the M-H characteristic, for a given induction swing at temperature. Safe operating area plots have been presented that illustrate the superior demagnetization resistance to 300 C of particular 1-5 type magnets as compared to the previously tested 2-17 type magnets.

The data taken has shown that in cases where resistance to high demagnetizing fields at high temperatures is important, the use of certain $SmCo_5$ type magnets, instead of the higher B_r, Sm_2Co_{17} types, may permit a greater magnetic induction swing ΔB. And as remarked, both B_r and ΔB commonly enter into measures of magnet performance in various applications. Therefore in certain magnetically stressful applications, some of the 1-5 type magnets may offer competitive performance, in spite of their lower B_r.

ACKNOWLEDGMENTS

This work was sponsored by the NASA Lewis Research Center under contract NAS3-25266, with G.E. Schwarze as the Project Manager.

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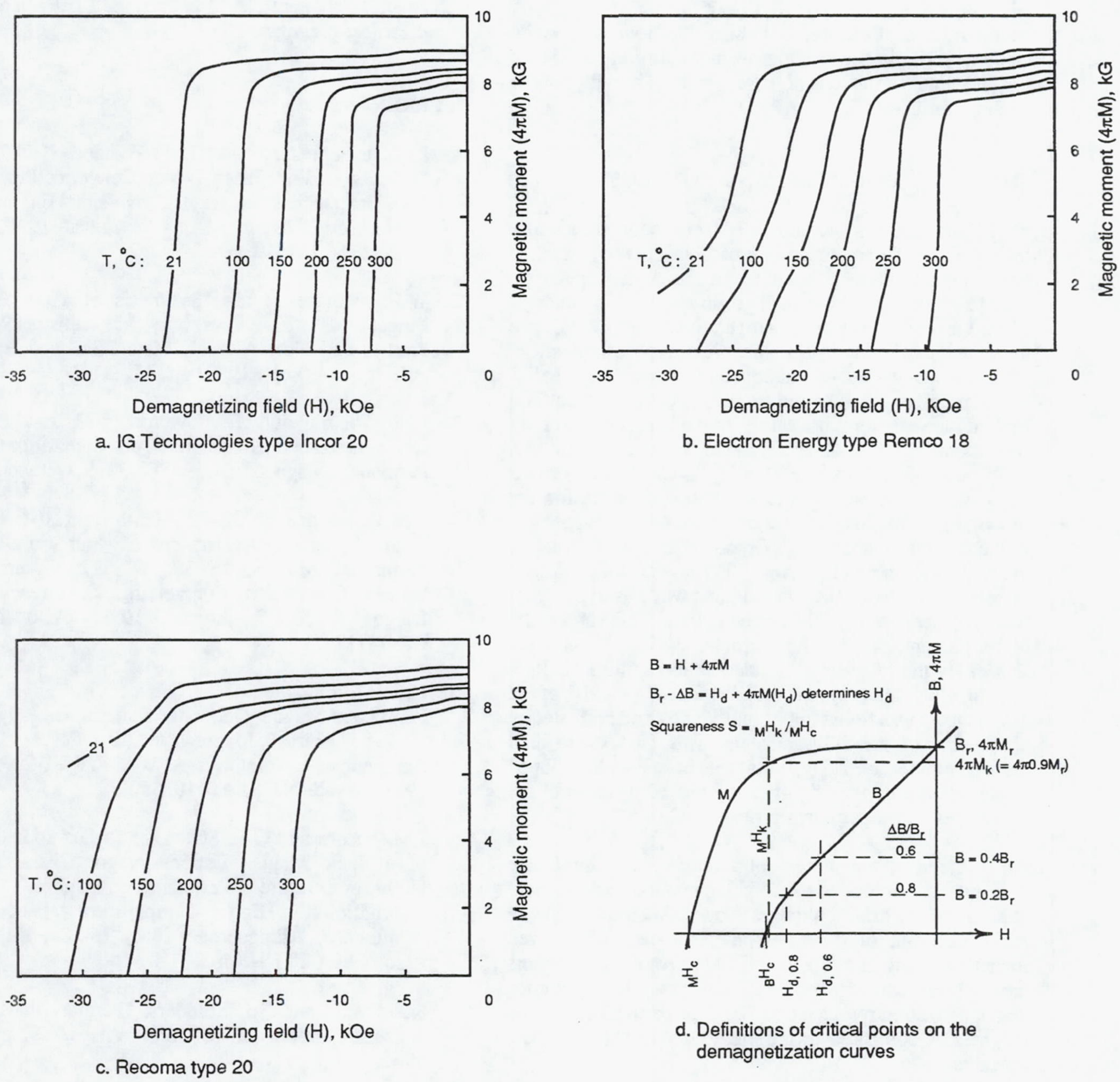


Figure 1. Demagnetization characteristics of commercial 1-5 type samarium-cobalt magnets at selected temperatures to 300 °C, with illustration of definitions.

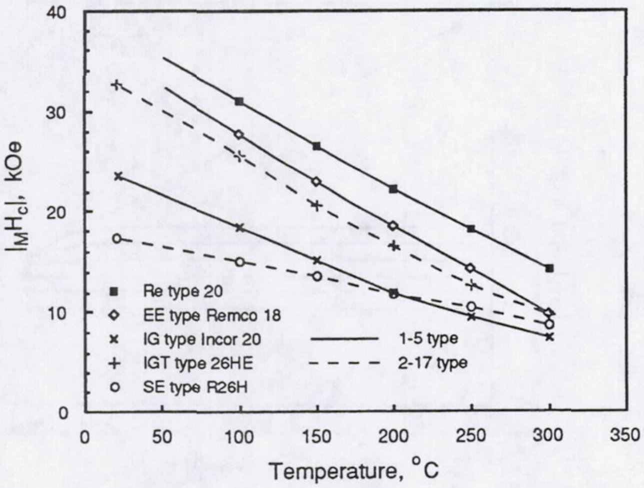


Figure 2. Temperature dependence of the intrinsic coercivity $|_M H_c|$ for 1-5 and 2-17 magnets compared. The IGT type 26HE was the highest $|_M H_c|$, 2-17 type magnet tested.

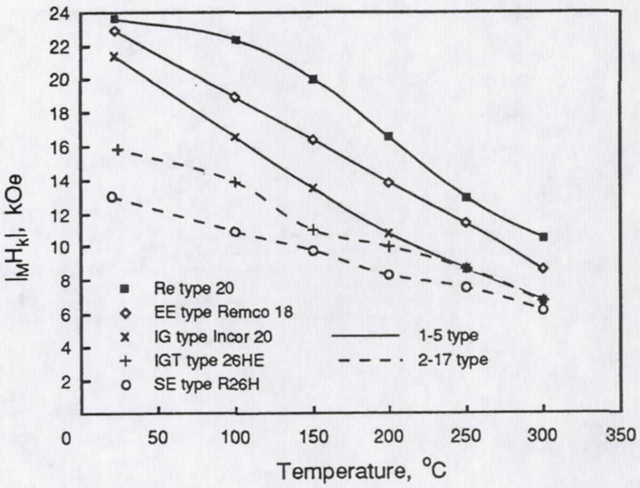


Figure 3. Temperature dependence of the knee-field $|_M H_k|$ for 1-5 and 2-17 magnets compared, showing nearly no overlap in this property among the 2 different types of magnets.

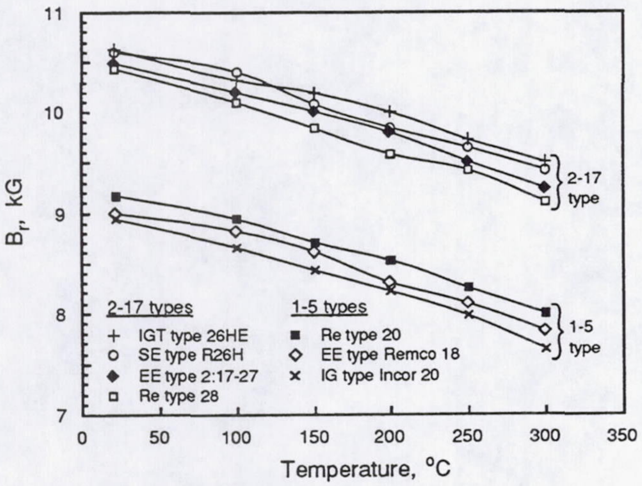
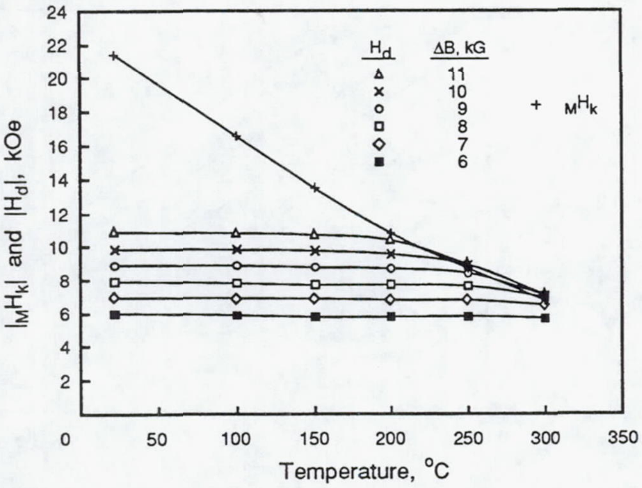
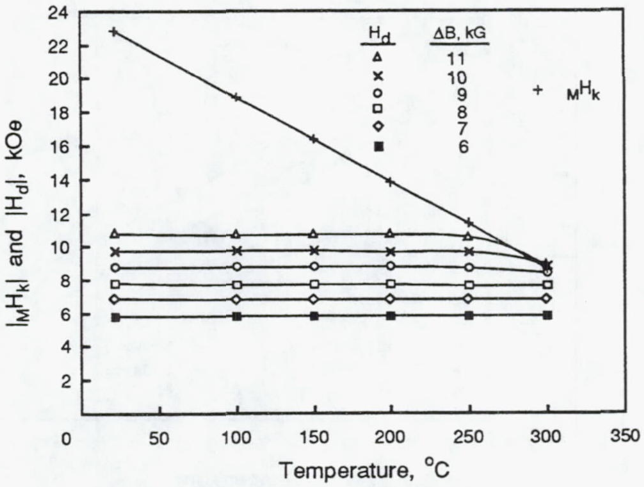


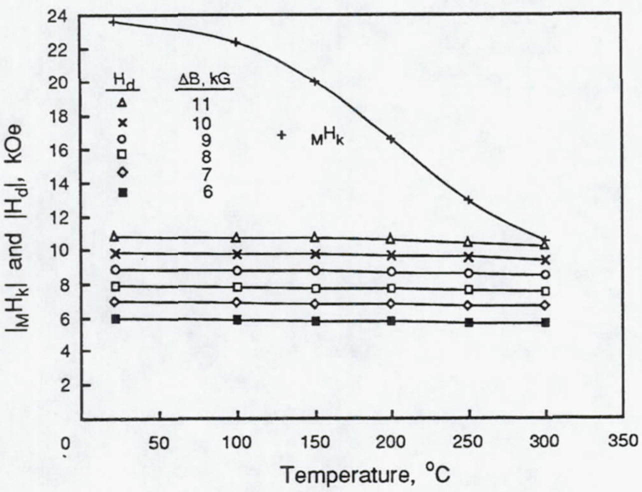
Figure 4. Temperature dependence of the remanence B_r for 1-5 and 2-17 magnets compared, showing an approximately 1.5 kG difference in B_r between the magnet types.



a. SOA for a typical IG Incor 20 sample



b. SOA for a typical Electron Energy Remco 18 sample



c. SOA for a typical Recoma 20 sample

Figure 5. Temperature variation of the knee-field ($_MH_k$) and the demagnetizing field (H_d) for selected induction swings (ΔB) of 1-5 type samarium-cobalt magnets. The safe operating area (SOA) is below the $_MH_k$ curve.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE
March 1994

3. REPORT TYPE AND DATES COVERED
Final Contractor Report

4. TITLE AND SUBTITLE
Comparative M-H Characteristics of 1-5 and 2-17 Type Samarium-Cobalt Permanent Magnets to 300 C

5. FUNDING NUMBERS
WU–583–02–21
C–NAS3–25266

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER
E–8298

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135–3191

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA CR–194440

11. SUPPLEMENTARY NOTES
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12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category 33

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

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14. SUBJECT TERMS
Permanent magnets; Samarium-cobalt magnets; Demagnetization; High coercivity; High temperature; Magnet trade-off

15. NUMBER OF PAGES
8

16. PRICE CODE
A02

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	