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

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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, 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 SmCo7 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 (Br ~ 0.9T) and an intrinsic coercivity (Hc) sufficiently high (Hc > Br) 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 SmCo7 type magnets have been previously reported to 300 C [3], [4]. This report presents similar data for SmCo5 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 (Br), the Hc, and the knee-field, Bk, at which the magnetic moment (M) is 10% below its remanence (Mr), are again derived and are superimposed on corresponding plots for selected 2-17 magnet samples. And as previously, the Hc 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 Br.

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 Hc, 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
Figures la-Ic present the basic between M and B and \(\Delta B\), in cgs units. All of the shown included to review definitions and illustrate the relations between the Re coma (Re) samples. At 300 C, the MHe is down to 7.5 which is as usual for samarium-cobalt type magnets. The temperatures from room to 300 C and Figure 1d is 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 \(\mu H\) is down to 7.5 kOe for the IG, to 10 kOe for the EE and to 14 kOe for the Re samples. The \(\mu H\) 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.

A significant strong point of some of the tested 1-5 samples is their relatively high \(\mu H\) and \(\mu H_k\) from room temperature to 300 C. At room temperature, their \(\mu H\) 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 \(\mu H\) is down to 7.5 kOe for the IG, to 10 kOe for the EE and to 14 kOe for the Re samples. The \(\mu H\) 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.

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].

SAFE OPERATING AREA

M-H Knee Point and Irreversible Demagnetization

The difference between the knee-field magnitude \(|\mu H_k|\) and the magnitude \(|H_k|\) of the demagnetizing field needed to produce a desired induction swing \(\Delta B\) 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 \(B=H+\pi M(H)\), which together with \(B=H-\Delta B\) then determines the bucking field \(H_d\) needed to give a specified \(\Delta B\). The SOA is the area below the \(|\mu H|\) curve. From the point of view of this \(\Delta B-T\) 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 \(\Delta B\) 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 \(\Delta B\) 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 \(\mu H\), without a volume penalty. To illustrate a \(B_r\) versus \(\mu H\) tradeoff, consider the idealized magnet operating line \(B=\mu H+B_r\) for \(H>\mu H\) 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] \(-BH=-H(\mu H+B_r)=\mu^4\Delta B(B_r-\Delta B)\), where \(\mu H_r<\mu H<0\) and \(\Delta B=\mu H\). As a function of \(B_r\) and \(\Delta B\) in the first quadrant, the \((-BH)\) is a saddle-shaped surface that intercepts the \((B_r, \Delta B)\) 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 \((-BH)_{max}=B_r/(4\mu)\) 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 \(\mu H\), material. A similar example is the linear alternator output power per unit volume of its
exciting magnets, given approximately by 
\[ \frac{1}{4}(a/p)\Delta B B [1-(1+K)(\Delta B/B)^2]^{1/2}, \] [8]. Along cuts of constant B, this function attains its peak value \\
\[ \omega B/(B(1+K))^{1/2}. \] Using such geometric visualizations, it is straightforward to write 
the 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, SmCo5
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, 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, with temperature was about the same as for the
reported [4] SmCo5 type magnets, but the 1-5 magnet B,
was consistently about 1.5 kG below the 2-17 magnet B,
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, 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 SmCo5 type magnets, instead
of the higher B, Sm2Co17 types, may permit a greater
magnetic induction swing AB. And as remarked, both B,
and AB 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,.

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REFERENCES


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 $|H_{c1}|$ for 1-5 and 2-17 magnets compared. The IGT type 26HE was the highest $|H_{c1}|$, 2-17 type magnet tested.

Figure 3. Temperature dependence of the knee-field $|H_{k1}|$ 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.
Figure 5. Temperature variation of the knee-field ($M_{H_k}$) and the demagnetizing field ($H_d$) for selected induction swings ($\Delta B$) of 1-5 type samarium-cobalt magnets. The safe operating area (SOA) is below the $M_{H_k}$ curve.
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**Subject Terms**
Permanent magnets; Samarium-cobalt magnets; Demagnetization; High coercivity; High temperature; Magnet trade-off

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