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MILLIMETER-WAVE/MICROWAVE DEVICE APPLICATIONS OF RARE EARTH-COB--ETC(U)
AUG 78 F ROTHWARF, L J JASPER, H A LEUPOLD

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RESEARCH AND DEVELOPMENT TECHNICAL REPORT

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MILLIMETER-WAVE / MICROWAVE DEVICE APPLICATIONS OF RARE EARTH-COBALT MAGNETS

F. Rothwarf
L. J. Jasper, Jr.
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ELECTRONICS TECHNOLOGY & DEVICES LABORATORY

August 1978

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There is considerable military interest in the utilization of rare earth-cobalt permanent magnets to facilitate the currently contemplated extension of device operating frequencies into the millimeter-wave region and to enhance the efficiency of devices operating at presently employed frequencies. Specific examples of proposed devices (traveling-wave tubes (TWT's), crossed-field amplifiers, etc.) are discussed, and expected magnet property requirements which would make them viable are reviewed. Future military millimeter-wave/microwave

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ABSTRACT

There is considerable military interest in the utilization of rare earth (RE)-cobalt permanent magnets to facilitate the currently contemplated extension of device operating frequencies into the millimeter-wave region and to enhance the efficiency of devices operating at presently employed frequencies. Specific examples of proposed devices (traveling-wave tubes (TWT's), crossed-field amplifiers, etc.) are discussed, and expected magnet property requirements which would make them viable are reviewed. Future military millimeter-wave/microwave needs are presented and discussed in terms of magnet materials technology, and circuit design, and the requirement for improved quality control.

INTRODUCTION

The vagaries of the microwave tube field over the past 40 years were recently reviewed by Osepchuk.[1] The years during and after World War II saw extensive military development of microwave tubes. The Korean War ushered in the "golden" era of microwave tube R&D which lasted from 1950-1964. However, with the passing of the "golden" era for the design of microwave tubes, major innovations were not forthcoming until only recently. Osepchuk pointed out the many discarded concepts that never made it into production due to the lack of significant military interest and/or support. Thus, in recent years there has been a severe decline of research in this area with very few electrical engineering departments offering courses in microwave tube design. Even with the recent rapid growth in annual sales of magnetrons for microwave ovens little R&D effort has been needed, since previously developed technology was sufficient. In general, industry-supported R&D has been confined to

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quick-return projects and industry has shown little interest in supporting a sustained R&D effort in this field.[2] However, lately some of the discarded ideas have been resurrected - in particular, cyclotron-resonance devices such as the gyrotron[3,4] recently developed in the USSR. Such devices with their high power outputs in the millimeter-wave (tens of kilowatts) and microwave (megawatts) regions have stimulated renewed government interest in supporting research to develop a new millimeter-wave/microwave technology. In this report, we will briefly review the military and commercial applications that such a technology would yield. It is clear that the rare earth-cobalt magnets have an important contribution to make to this technology. Thus, we will also review some of the magnet material properties and unique magnetic circuit designs that will be needed to achieve suitable millimeter-wave/microwave devices.

ANTICIPATED APPLICATIONS

Today there are growing military and commercial motivations for developing the millimeter-wave spectrum covering the range 30-300 GHz.[5] One incentive is the crowded condition that exists in the microwave bands. For example, Bell Labs has already developed millimeter-wave trunks for future long-distance phone lines. However, the military's potential needs are providing the major impetus for the growing interest in this region of the spectrum.

A major proposed application is in military mapping employing entirely passive millimeter radiometers which are not easily jammed - an important asset for weapons systems. Such radiometers will be used in satellites for reconnaissance and in missiles such as the strategic cruise missile for terminal guidance. The Army is interested in compact and rugged cold-seeking radiometers which can be put into artillery shells that would then home in on large cold targets such as tanks or trucks that would stand out against warmer background vegetation. Since artillery shells have relatively small diameters, the receiving antenna would have to be small. To achieve sufficient sensitivity the Army is looking at 94 GHz as the frequency for this application, since a window exists there in the atmospheric attenuation vs frequency plot.

Active millimeter-wave target designators are also being considered for roles currently being played by laser designators. They have the advantage of being able to penetrate rain, snow, fog and enemy smoke screens, an important requirement for a standoff-weapons system. Thus, the development of high resolution radars at 35, 70, and 94 GHz, where atmospheric windows exist, are being considered for low-on-the-horizon tracking and airborne terrain avoidance applications.

For covert communications the Army at Fort Monmouth has already sponsored development of a millimeter line-of-sight radio by Hughes. The system uses 60 GHz where an attenuation peak occurs. Thus, secure communications can be achieved with limited risk of enemy monitoring. The Army envisions use of this system for short-range battlefield communcations, while the Navy is also interested for ship-to-ship contact. The 60-GHz frequency is also being considered for satellite-to-satellite communications. Greater range is attainable in space than on earth since there is no attenuation there. Such orbiting satellite links would be secure from earth monitoring or jamming because of high atmospheric attenuation.

Secure air-to-ground data links by use of spread-spectrum communications techniques are other applications being developed. Such methods consume enormous amounts of bandwidth so that there is no option but to use the available millimeter-wave frequencies.

The projected widespread use of this region of the spectrum opens up the eventual need for electronic countermeasures (ECM). While this aspect of the technology does not yet exist, the United States is already concerned with monitoring for the use of such frequencies by potential enemies. Thus, there is already a significant activity underway in the design of millimeter-wave receivers.

The commercial uses in addition to the Bell System telephone application and microwave cookers already mentioned involve high-power meat tempering and automotive braking systems. Raytheon is already producing a 75-kW bulk meat tempering system.[1] Studies are being sponsored by the Department of Transportation[6] to develop automatic radar braking systems that would prevent many rear-end and head-on crashes, or at least slow the involved vehicles to reduce the seriousness of accident injuries. Recent design studies at Bendix Communications Division[6] have shown that the small antennas and narrow beamwidths characteristic of millimeter-wave systems should reduce the false alarm rate of contemplated automotive radar braking systems. The Bendix work indicates that a frequency of 36 GHz would be reasonable for this application.

There is a lack of commercially available components with sufficient bandwidth and low enough insertion loss for these various applications. Many components both active and passive remain to be developed for these frequencies and for the power levels contemplated. The passive items include circulators, fast-acting cutoff switches, isolators, narrow- and wideband filters, dispersive filters and phase shifters. Such devices are based upon magnetic materials such as ferrites or yttrium iron garnet (YIG). Most of these devices require low biasing fields which could be supplied by rare earth-cobalt magnets to replace the ferrite and Alnico magnets employed in such components that exist at lower frequencies. The $SmCo_5$ magnets will most likely replace ferrite and Alnico materials in those systems applications where size and weight, not cost are the driving factors. Weight will be a major factor in those components where large biasing fields are needed such as in YIG-based tunable filters and active devices such as the various types of tubes that may be used in airborne systems. We will concentrate on these latter structures when we give examples of the problems that must be overcome before the rare earth-cobalt based magnets can fulfill their potential for significant contributions to the realization of the emerging millimeter/microwave technology.

In the following sections we address several areas with problems that are delaying or limiting the extensive use of the rare earth-cobalt magnets and for which R&D is recommended. These include: the need for lower reversible temperature coefficient materials; investigation of higher energy product (RE_2Co_{17}) compounds; quality control; and new design approaches. In the discussions that follow, some of these considerations will be interwoven. For example, when discussing zero temperature coefficient materials we will address the need, costs, quality control and material design aspects in the same section.

LOW REVERSIBLE TEMPERATURE COEFFICIENT $RECo_5$-BASED MATERIALS

Many of the applications mentioned above require that air gap flux density be maintained constant over a wide temperature range. Since the magnetizations of Alnico, hard ferrites and rare earth-cobalt permanent magnets decrease with increasing temperature, one must compensate in some way for the magnetization changes. One method involves shunting the flux in the room temperature range by the addition of external shims attached to the magnets. The shim is made from an alloy, usually 30% Ni-Fe, which has a Curie temperature slightly above room temperature. Thus, as the temperature increases, less flux is shunted and the flux density in the gap is maintained constant. An example of the effects of such temperature compensation on intermodulation (IM) products is shown in Fig. 1. There the third-order IM product amplitude vs beam voltage characteristics of uncompensated and compensated versions of two prototype TWT's using $SmCo_5$ periodic permanent magnet stacks are shown for similar temperature ranges. It is clear that the temperature compensation significantly reduces the dB variation in IM product over the temperature ranges shown. However, the placement of the compensating shunts is an expensive, tedious, manual process. For the case of the prototype tubes discussed in Fig. 1, the addition of the shunt is a significant cost item amounting to more than 10% of the magnet cost itself.[7] Thus, there is a real need to develop and use intrinsically temperature stabilized rare earth-cobalt magnet materials. This need for zero temperature coefficient (ZTC) $RECo_5$ type alloys has been recognized by microwave tube manufacturers for some time. At the 1977 Intermag Conference Workshop on Permanent Magnets and Microwave Tubes there was general agreement[8] as to a requirement for a ZTC material for the range -50 C to 150 C with an energy product in excess of 15 MGOe.

For rare earth-cobalt permanent magnets intrinsic temperature stabilization can be achieved by suitable alloying, since the magnetic moment of the heavy rare earth atoms couple antiparallel to the cobalt sublattice while the light rare earth atoms couple parallel. Thus, heavy RECo compounds have ferrimagnetic behavior, while the light RECo compounds are ferromagnetic. These differences are apparent in Fig. 2 (from Bartholin[9]) which presents the magnetization vs temperature curves for some $RECo_5$ compounds. Thus, while the magnetization vs temperature curve of the commonly employed $SmCo_5$ has a negative slope, the $GdCo_5$ has a positive slope. Therefore, by adjusting the ratio of heavy to light rare earth atoms, it is possible to balance the negative temperature coefficient of the light rare earth compounds with the positive temperature coefficient of the heavy compounds. Benz, Laforce and Martin[10] were the first to demonstrate the feasibility of temperature compensation by such alloying with the $RECo_5$ compounds for the case of the $Sm_{1-x}Gd_xCo_5$ system. They demonstrated that the substitution of gadolinium for samarium can change the sign of the temperature coefficient α from negative to positive with $\alpha=0$ at a critical composition $x_c=0.41$. This behavior is shown in Fig. 3. Tokunaga and Yamakawa[11] and Jones and Tokunaga[12] demonstrated similar results for the $Sm_{1-x}Ho_xCo_5$, $Sm_{1-x}Tb_xCo_5$ and $Sm_{1-x}Er_xCo_5$ systems. For the Sm-Ho-Co system x_c was found to be 0.25. Shur, Shiryaeva, and Maikov[13] have reported a ZTC alloy for the quaternary composition $Sm_{0.68}Gd_{0.18}Er_{0.14}Co_{4.4}$.

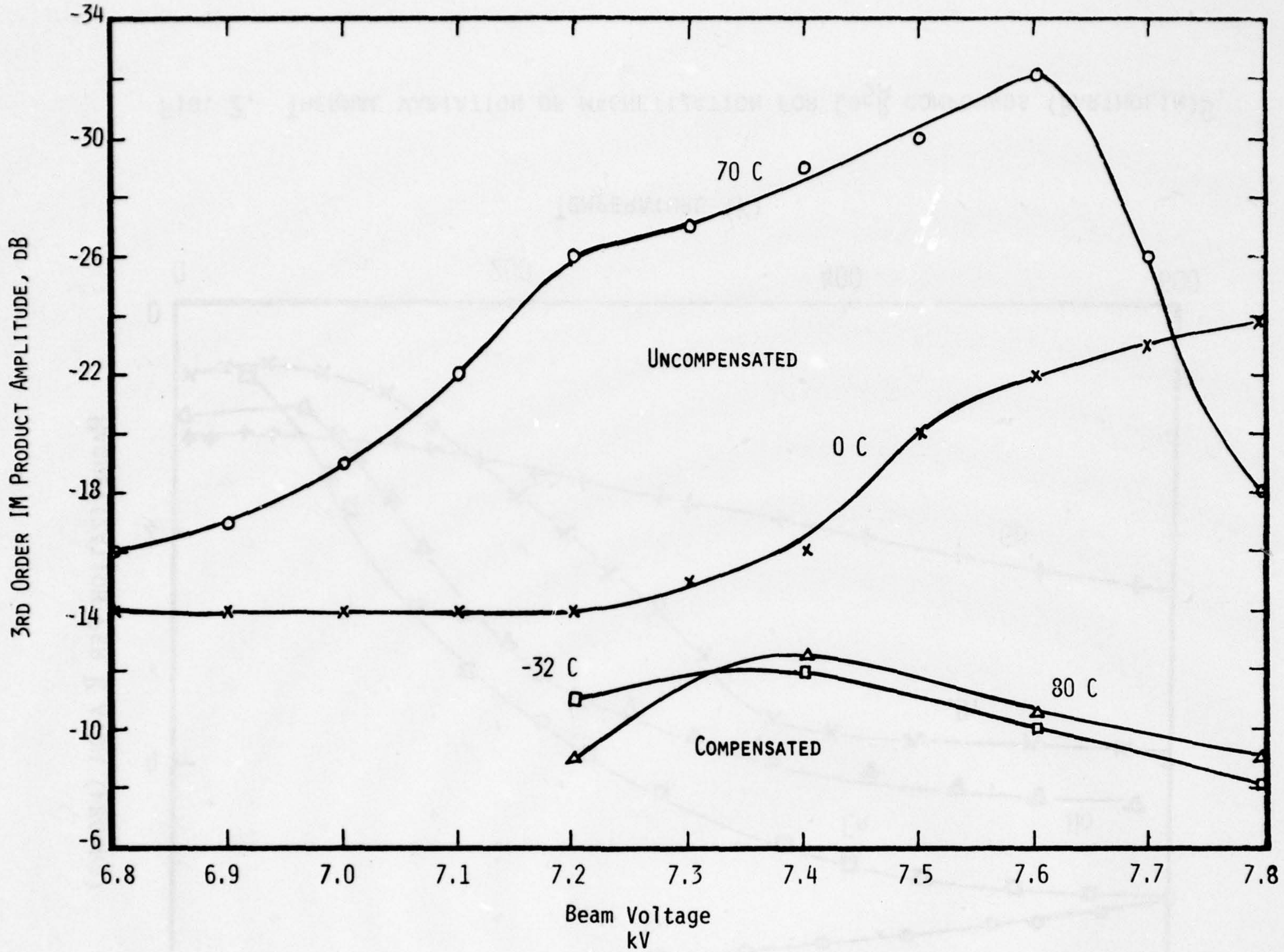


Fig. 1. The third order intermodulation product amplitude vs beam voltage for uncompensated and compensated versions of two prototype TWT's using $SmCo_5$ PPM's.

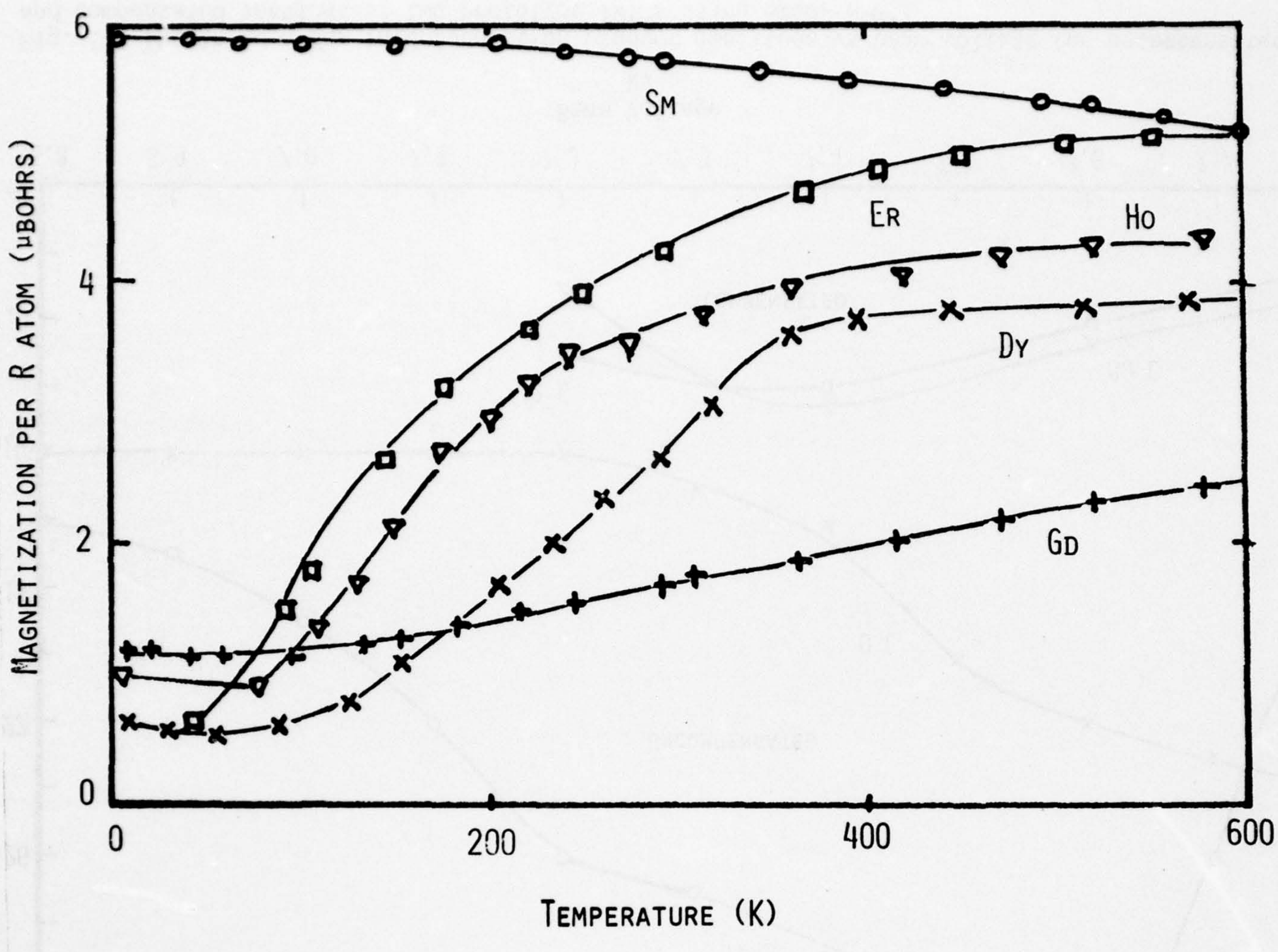


Fig. 2. Thermal variation of magnetization for Co_5R compounds (Bartholin)[9].

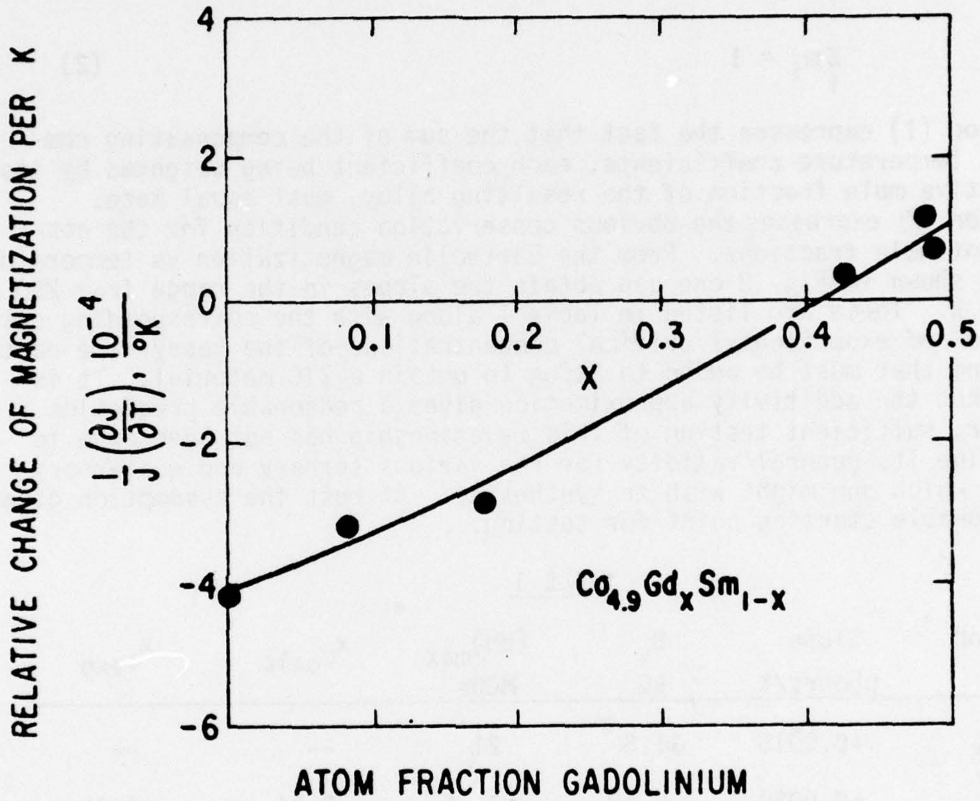


Fig. 3. Reversible temperature coefficient of magnetization (20 to 200 C) for a series of Co-Gd-Sm alloys (after Benz, Laforce and Martin[10]).

In general, one can design an alloy to have $\alpha \simeq 0$ for a finite temperature interval around some temperature T_0 which is usually chosen to be $\sim$ 300 K. Such a design depends upon knowing the M vs T curves for the various alloys such as those in Fig. 2. One usually assumes the additivity of the various mole fractions m_i of the different constituent alloys having positive or negative coefficients α_i over a given temperature interval. Thus, the design equations are given by

$$\sum_i m_i \alpha_i = 0 \qquad (1)$$

$$\sum_i m_i = 1 \qquad (2)$$

Equation (1) expresses the fact that the sum of the compensating component temperature coefficients, each coefficient being weighted by its respective mole fraction of the resulting alloy, must equal zero. Equation (2) expresses the obvious conservation condition for the constituent mole fractions. From the Bartholin magnetization vs temperature curves shown in Fig. 2 one can obtain the slopes in the range from 250 K to 350 K. These are listed in Table I along with the corresponding calculated and experimental critical concentrations of the heavy rare earth compound that must be added to $SmCo_5$ to obtain a ZTC material. It is seen that the additivity approximation gives a reasonable prediction. However, sufficient testing of this relationship has not been done to determine its general validity for the various ternary and quaternary alloys which one might wish to synthesize. At best the assumption gives a reasonable starting point for testing.

TABLE I

Compound	Slope μbohrs/K	B_s kG	$(BH)_{max}$ MGOe	$x_{c_{calc}}$	$x_{c_{exp}}$
$SmCo_5$	-0.0015	11.5	21	--	--
$GdCo_5$	+0.0029	8.48	11.5	0.34	0.41
$HoCo_5$	+0.0040	9.77	15.3	0.28	0.25
$ErCo_6$	+0.0065	10.5	17.5	0.19	--

Another major factor that must be considered is the energy product that will be available in the resulting ZTC compound. A glance at Fig. 2 shows that the heavier 1:5 compounds have lower saturation inductions than $SmCo_5$. Thus, one can anticipate lower energy products for the ternary ZTC compounds than for $SmCo_5$ itself. An estimate of the saturation moment for the ZTC material formed from a given heavy substituent compound can be obtained by a linear interpolation between the saturation value for $SmCo_5$ (11.5 kG) and that for the substituent compound.

Some typical saturation moments for the ZTC concentrations at 300 K are also shown in Table I. These values were taken from Velge and Buschow[14] whose measurements were made on aligned powder samples. The remanence B_r typically obtained in commercial magnets is $\sim 0.8\ B_s$. The $(BH)_{max}$ to be expected in practice is often estimated[8] to be $(B_r^2/4)$. Thus, $(BH)_{max} = (0.64\ B_s^2/4)$. Some of these estimates at the critical ZTC concentrations are also given in Table I.

It is of interest to note that the ZTC alloy in the SmGdErCo system reported by Shur et al[13] had an energy product of 15 MGOe, the highest value yet reported for an intrinsically compensated $RECo_5$ permanent magnet material. Martin[8] has indicated that the energy product limit for ZTC $RECo_5$-based alloys employing the heavy lanthanides is approximately 17 to 18 MGOe. Any attempt to achieve still higher energy products would have to be based on other Co-rich RECo alloys which have higher saturation moments. The design of such alloys would also be based upon the additivity assumption expressed in Eqs. (1) and (2).

So far the need for ZTC materials has been emphasized. However, in considering a certain device design, it may be important to be able to specify a magnet alloy with a particular positive or negative coefficient over a given temperature range. Thus, the device designer would have the option of compensating for the changes in other device components with temperature. Such flexibility is not readily possible with the present method of externally shunting the magnets with a compensating material. Thus, it is important to accumulate temperature coefficient data for compositions on either side of the ZTC composition.

HIGH ENERGY PRODUCT MATERIALS

There are many desired permanent magnet applications for military devices which are presently not viable because of stringent performance requirements coupled with severe restrictions on weight, bulk and mechanical fragility. An example of such an application is illustrated in Fig. 4. Figure 4 shows the maximum permissible dimensions of a magnetic circuit for an E-F band crossed-field amplifier which requires from 2.0 to 2.5 kOe in a gap of 0.75 inches. These requirements can be marginally fulfilled with the best of commercial $SmCo_5$ magnets with $B_r \cong 9$ kG and for which the design calculations show an expected gap field of 2.2 kOe. The word marginal is used here because experience in this laboratory has shown that many commercial magnets with a nominal remanence of 9 kG actually show values closer to 7 kG or even less. A magnet with a remanence of 7 kG would produce a gap field of only 1.7 kOe; about 25% less than the minimum field required.

Also needed is a slight modification of this circuit for operation in the I-J band where a gap field of 5 kOe in a 0.5-inch gap is required. In this case, insertion of a magnet with a remanence of 9 kG yields only 4.2 kOe in the gap. To attain the required 5 kOe a B_r of 11 kG would be needed for marginal performance and 12 kG for operation with a comfortable margin of safety against possible shortcomings in the quality control of mass produced commercial material.

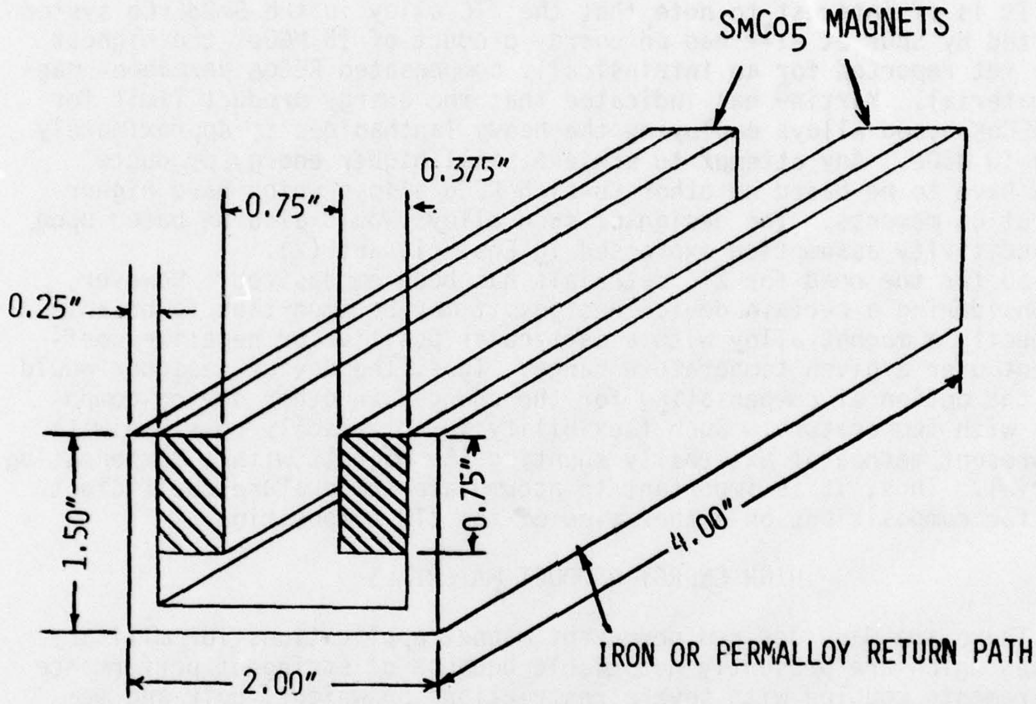


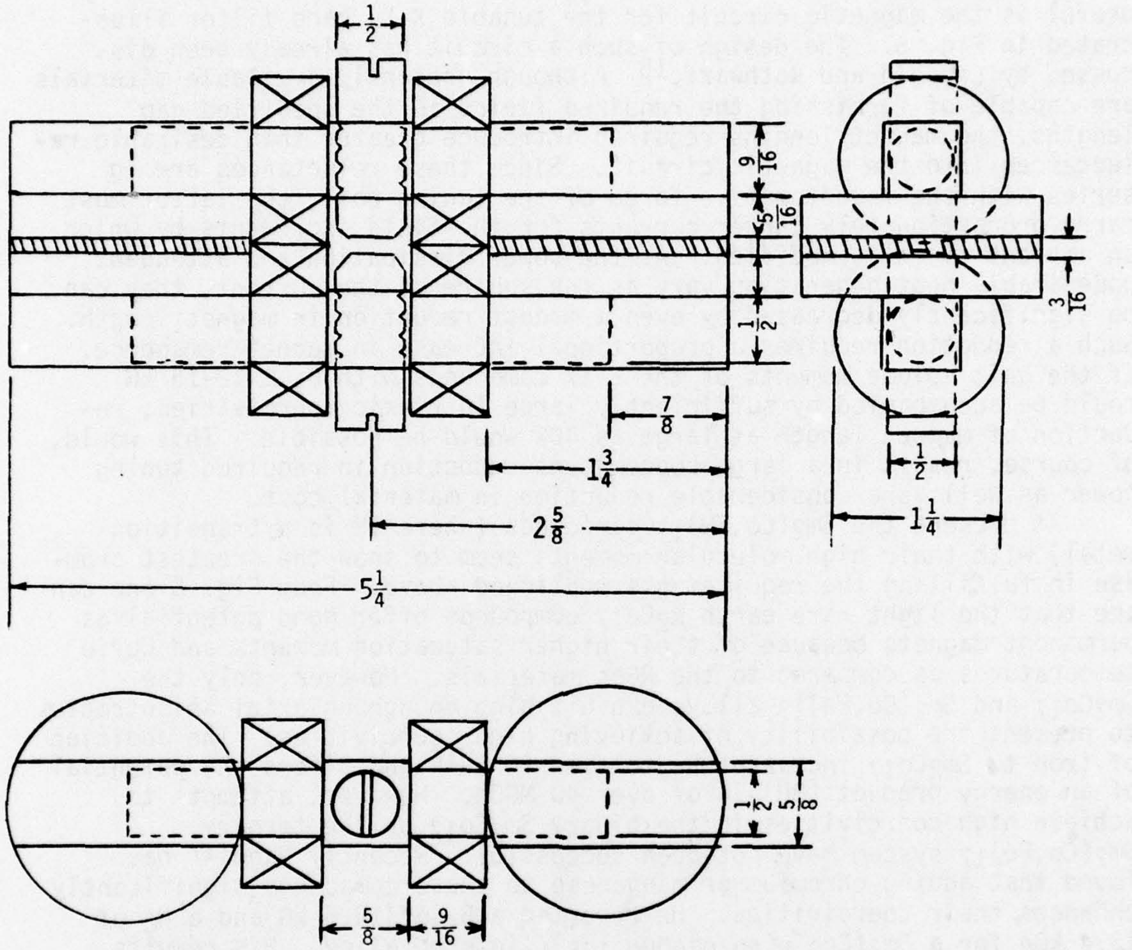
FIG. 4. MAXIMUM ALLOWABLE DIMENSIONS FOR THE E-F BAND crossed-field AMPLIFIER. THE WIDTH AND HEIGHT RESTRICTIONS ARE REMOVED FOR THE I-J BAND DEVICE BUT THE OVERALL LENGTH IS LIMITED TO THREE INCHES.

Another application in which higher remanences would be extremely useful is the magnetic circuit for the tunable K-Ka band filter illustrated in Fig. 5. The design of such a circuit has already been discussed by Leupold and Rothwarf.[15] Although presently available materials are capable of furnishing the required fields in the specified gap lengths, the magnet lengths required introduce greater than desirable reluctances into the magnetic circuit. Since these reluctances are in series with the magnetomotive force of the tuning coil, the latter must carry proportionately larger currents for the field increments by which an ambient field is modified. As the power dissipation and attendant undesirable heat generation vary as the square of the current, they can be significantly decreased by even a modest reduction in magnet length. Such a reduction requires a proportional increase in magnet remanence. If the unit volume moments of the 2-17 compounds with $B_s \simeq 12\text{-}15$ kG could be accompanied by sufficiently large intrinsic coercivities, reduction of magnet length as large as 40% would be possible. This would, of course, result in a large concomitant reduction in required tuning power as well as a considerable reduction in material cost.

At present the $Sm_2(Co,TM)_{17}$ compounds (where TM is a transition metal) with their high molecular moments seem to show the greatest promise in fulfilling the requirements mentioned above. From Fig. 6 one can see that the light rare earth R_2Co_{17} compounds offer good potential as permanent magnets because of their higher saturation moments and Curie temperatures as compared to the RCo_5 materials. However, only the Sm_2Co_{17} and $Sm_2(Co,Fe)_{17}$ alloys exhibit high enough uniaxial anisotropies to present the possibility of achieving high coercivities. The addition of iron to Sm_2Co_{17} increases B_s to over 16 kG[16] and offers the potential of an energy product $(BH)_{max}$ of over 40 MGOe. However, attempts to achieve high coercivities in the binary Sm_2Co_{17} or the ternary $Sm_2(Co,Fe)_{17}$ system have not been successful. Recently Nagel[17] has found that adding chromium or manganese to these compounds significantly enhances their coercivities. He reported a B_r of 10.6 kG and a H_c of 13.4 kOe for a $Sm_2(Co_{0.8}Fe_{0.075}Mn_{0.125})$ sintered alloy. His results were consistent with a just reported study by Leupold et al[18] of the anisotropy fields in the systems $Sm_2(Co,Fe)_{17}$ and $Sm_2Mn(Co,Fe)_{16}$. They found that the presence of Mn in the latter system raised the anisotropy fields (H_A) by as much as 55% over those measured for the corresponding compounds in the ternary system. The augmentation of anisotropy was accompanied by a slight decline in $4\pi M_s$ of approximately 5% for materials of highest H_A. Furthermore, the values of $4\pi M_s$ for the quaternary compounds showed better temperature stability, increasing by about 5% in going from 300 K to 4.2 K as compared to 15% for the ternary system.

Still further substitutions to form five-component compounds have been made by Ojima et al[19] who have studied the system $Sm_2(Co,Cu,Fe,M)_{17}$, where M represents the elements Nb, V, Ta and Zr. The alloys containing zirconium or niobium showed good permanent magnet properties with $Sm_2(Co,Cu,Fe,Nb)_{17}$ magnets yielding energy products up to 28 MGOe while $Sm_2(Co,Cu,Fe,Zr)_{17}$ alloys attained 30 MGOe by a step tempering process. The best results were obtained for the alloys containing zirconium.

Other compositions of the RECo alloys have also been studied. These are the 1:7 and 1:8 types.[20,21] For example, the alloy



ALL DIMENSIONS ARE IN INCHES.
CROSS HATCHED SECTIONS ARE $SmCo_5$ MAGNETS.
X'D BOXES ARE TUNING COIL SECTIONS.

FIG. 5. TUNABLE MAGNET FOR K-KA BAND FILTER.

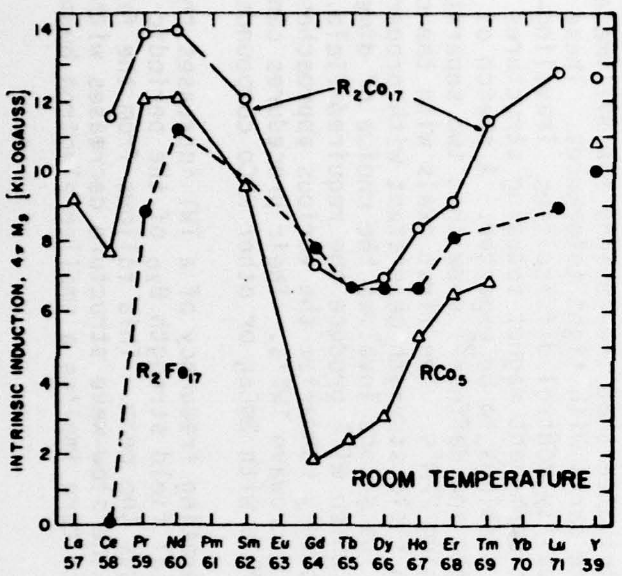


Fig. 6a. Saturation values of the phases R_2Co_{17} and R_2Fe_{17} compared with those of RCo_5.

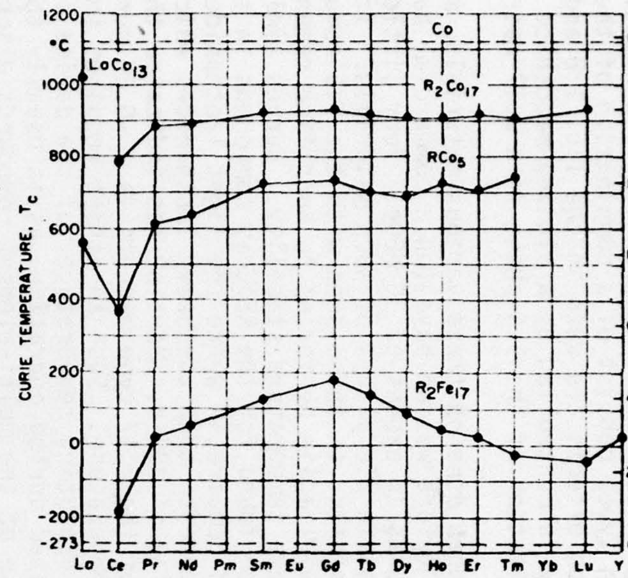


Fig. 6b. Curie temperature of the phases R_2Co_{17} and R_2Fe_{17} compared to those of RCo_5 and cobalt.

$Sm(Co_{0.76}Fe_{0.10}Cu_{0.14})_{6.8}$ had a B_r of 10.4 kG, H_{ci} of 6.2 kOe and $(BH)_{max}$ of 26.4 MGOe. Another alloy of the 8:1 composition type $Sm(Co_{0.85}Fe_{0.05}Cu_{0.10})_z$ with $8.0 \leq z \leq 8.25$ had properties close to the 1:7 alloys but somewhat higher $4\pi M_s$ due to higher cobalt content.[22] The 1:7 and 1:8 composition types consist of a combination of the 1:5 and 2:17 phases. Nucleation effects are seen in the 1:5, 1:8 and 2:17 types, while the coercivity is controlled by a pinning mechanism in the 1:7 type due to precipitation of the 1:5 phase in a 2:17 matrix or vice versa.[22-26]

Though much work has been done on these various materials, much clearly remains to be done before we can have (on a commercial basis) compounds with energy products in excess of 30 MGOe. Very little or nothing has been done to obtain ZTC alloys of such materials. It is anticipated that problems similar to those seen with the 1:5 compounds will be encountered. One will again be forced to sacrifice remanence and energy product to achieve temperature stability. Curves similar to those shown in Fig. 2 can be found for the RE_2Co_{17} compounds in studies by Miller and D'Silva[27] and Lemaire,[28] where the light lanthanides are ferromagnetic with higher moments than the heavy lanthanides which are ferrimagnetic in the vicinity of 300 K. Martin[8] has indicated that an important disadvantage of the 2:17 type magnets is a -0.6% per C change of H_{ci} above room temperature. Such an effect requires the use of longer magnets when the operating temperature of the device is expected to be somewhat elevated during operation, as is usually the case with TWT's. Whether the use of the multi-element compounds discussed above can minimize or reduce this effect remains to be determined by further R&D.

MILLIMETER-WAVE TUBE DESIGN PROBLEMS

In the design of microwave tubes as a general rule it is found that when the operating frequency increases, the size of the tube components decrease. Thus, it is anticipated that the designs for millimeter-wave tubes will require miniature parts with tight tolerances. These in turn will present severe quality control difficulties. Traveling-wave tubes which employ periodic permanent magnet focusing structures (PPM's) can illustrate some of the problems to be expected. A sketch of a PPM is shown in Fig. 7. Sterrett and Heffner[29] show that two separate problems are involved in designing PPM's. The first deals with the choice of periodicity and magnetic field strength consistent with proper focusing of the electron beam. The second involves the choice of dimensions of magnets and pole pieces which will produce the required field. Sterrett and Heffner effectively summarize the various approaches to solving these problems for microwave TWT's. Their procedures can readily be extended to designing PPM's with $SmCo_5$ or other RECo compounds for millimeter-wave tubes.

In general, as the operating frequency of a TWT increases there is an increase in the peak axial field strength B_{zo} of the periodic magnetic field required to focus the beam. This follows from the fact that the helix diameter of the slow-wave structure decreases with increasing frequency. This in turn implies a smaller electron beam

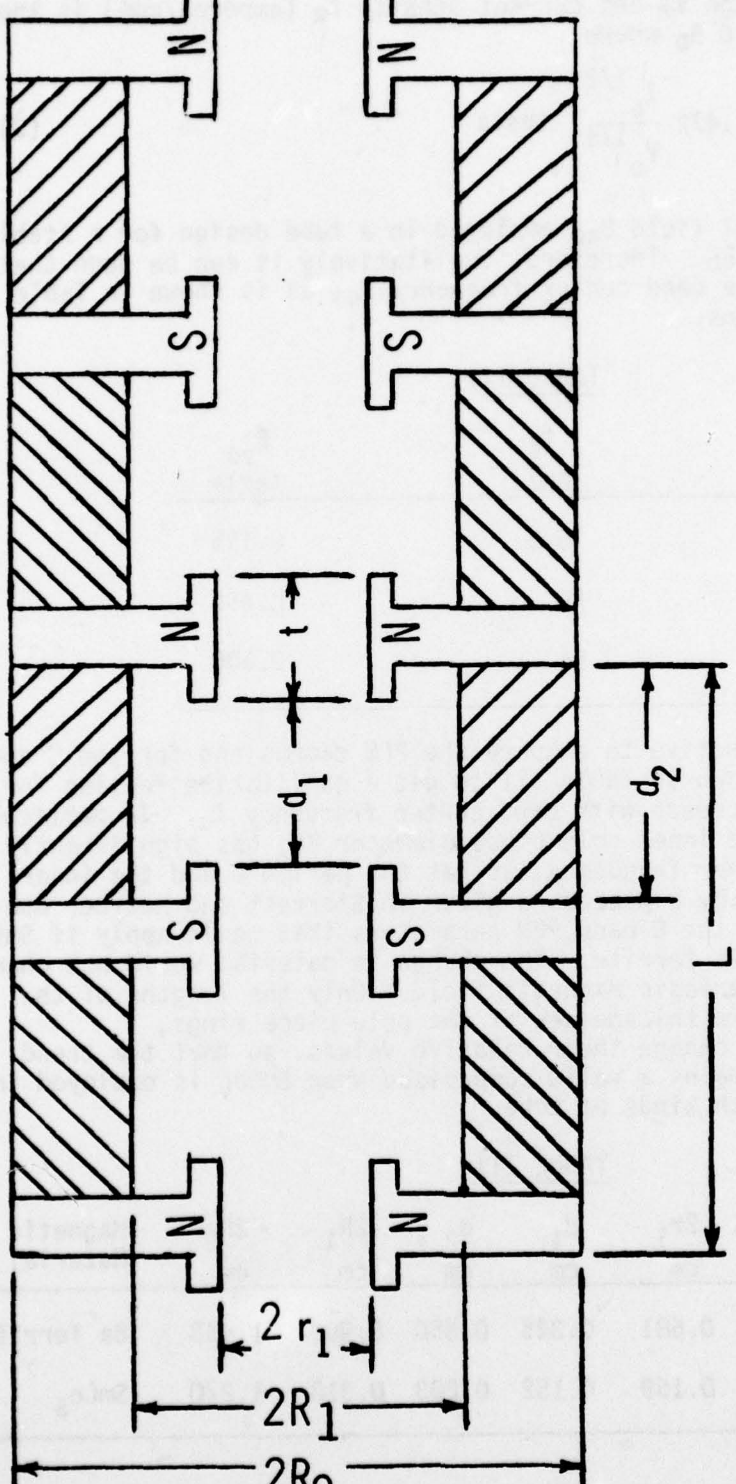


Fig. 7. Periodic permanent magnet focusing structure.

diameter and thus an increased current density I_0 for a given current. The minimum magnetic field which will focus a particular electron beam at a given beam voltage V_0 and current density I_0 (amperes/cm^2) is known as the Brillouin field B_b where

$$B_b = 0.1472 \frac{I_o^{1/2}}{V_o^{1/4}} \text{ tesla} \quad (3)$$

Usually the peak axial field B_{zo} employed in a tube design for a stable beam is 2 to 4 times B_b. Therefore, qualitatively it can be seen that B_{zo} increases with the band center frequency f_0, as is shown in Table II, for some kW TWT designs.

TABLE II

Band	f_o GHz	B_{zo} tesla
C	5.5	0.155
Ka	35	0.450
E	94	0.600

It is also instructive to compare the PPM dimensions for the C and Ka band 1 kW TWT's shown in Table III to get a qualitative feeling for how the part sizes decrease with band center frequency f_0. In particular, it is notable that the inner pole piece diameter $2r_1$ has significantly decreased for the higher frequency, as has the period L and the inner magnet diameter $2R_1$. By a procedure given in Sterrett and Heffner one can readily calculate the C-band PPM parameters that would apply if $SmCo_5$ were used instead of Ba ferrite. The change in material would not change the period L of the periodic magnetic field. Only the lengths of the magnet rings d_2 and the thicknesses of the pole piece rings, $t = (L-2d_2)/2$, would change their relative values, so that the trend shown in Table III remains a valid comparison when $SmCo_5$ is employed in the PPM stacks for both kinds of tube.

TABLE III

Band	f_o GHz	L cm	$2r_1$ cm	d_1 cm	d_2 cm	$2R_1$ cm	$2R_2$ cm	Magnetic Material
C	5.5	1.626	0.681	0.325	0.650	0.909	1.453	Ba ferrite
Ka	35	0.610	0.159	0.152	0.203	0.318	1.270	$SmCo_5$

Another consideration in designing TWT's involves minimizing the ripple of the magnetic field that is inherent in the PPM field geometry. The ripple can be made smaller by reducing the period L. However, when this is done a problem arises in supplying enough permanent magnet material to give the required axial field. The compromise solution results in thin rings (small d_2) which have poor aspect ratios. This condition coupled with the demagnetizing effect of the various rings being stacked in magnetic opposition to one another results in the requirement for materials with reversible demagnetization curves and with high coercivities. The RECo materials, in general, have these properties and have begun to make a significant impact on the design of microwave TWT's It remains to be seen whether materials and electrical engineering ingenuity will be able to achieve similar success with the millimeter tubes that are now needed.

NEW CIRCUIT DESIGNS

To meet the demands for higher fields with given gap size, volume and weight constraints, innovative designs will be required. One such approach that might be quite useful is based upon the very high coercive forces, high anisotropies and great resistance to demagnetization of the RECo magnet materials. In a recent patent, Neugebauer[30] of the General Electric Company disclosed a unique low leakage magnetic circuit design concept. This idea employs the high anisotropy of $SmCo_5$ to minimize the leakage flux and significantly enhance the field and homogeneity that one can obtain in a given circuit. This idea is illustrated in Fig. 8a. A conventional high flux density magnet structure suitable for high-power, voltage-tunable magnetrons is shown in the bottom of the figure. Above this are shown two other designs which achieve higher flux densities in the gap. The first design (center of figure) consists of a $SmCo_5$ - Alnico IX composite core surrounded by radially magnetized $SmCo_5$ flux-bucking segments. This idea for cladding is a novel method of reducing or eliminating leakage flux and should be applicable to a wide range of magnetic circuits. The second magnet design (top figure) involved two radially magnetized hemispheres of $SmCo_5$, two short radially magnetized cylindrical sections, two Vanadium Permendur pole pieces, and an iron return shell. This oriented material design gives significantly higher flux densities than either of the other designs while still maintaining the same package dimensions. Flux densities of 1 tesla can be achieved. A comparison of the respective flux profiles within the gap is shown in Fig.8b. It is evident that the oriented magnet design has almost three times the usable flux density as the conventional design with the same outer dimensions. The range of operation of the $SmCo_5$ on its demagnetization curve was such that all the material was used near the point of maximum energy product. The material near the Vanadium Permendur plugs carries the highest flux density, while that near the iron return shell carries the lowest flux density.

The General Electric Microwave Tube Operation demonstrated the cladding principle by designing a single reversal magnet structure, for a high power klystron (see Fig. 9) under development for airborne radars by the US Air Force. This magnet structure weighed 143 kg of which the $SmCo_5$ material weighed 123 kg. It replaced the klystron solenoid which

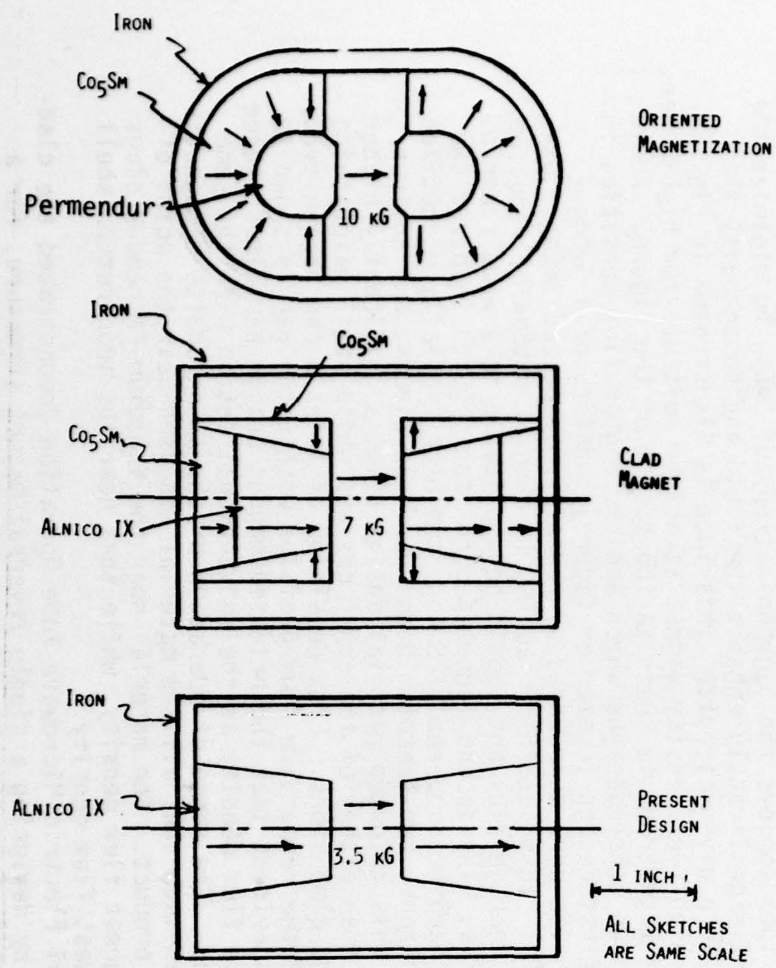


Fig. 8a. High flux density magnet structure for voltage-tunable magnetrons: bottom - conventional design, middle - clad magnet design, top - oriented magnet design (Neugebauer[30]).

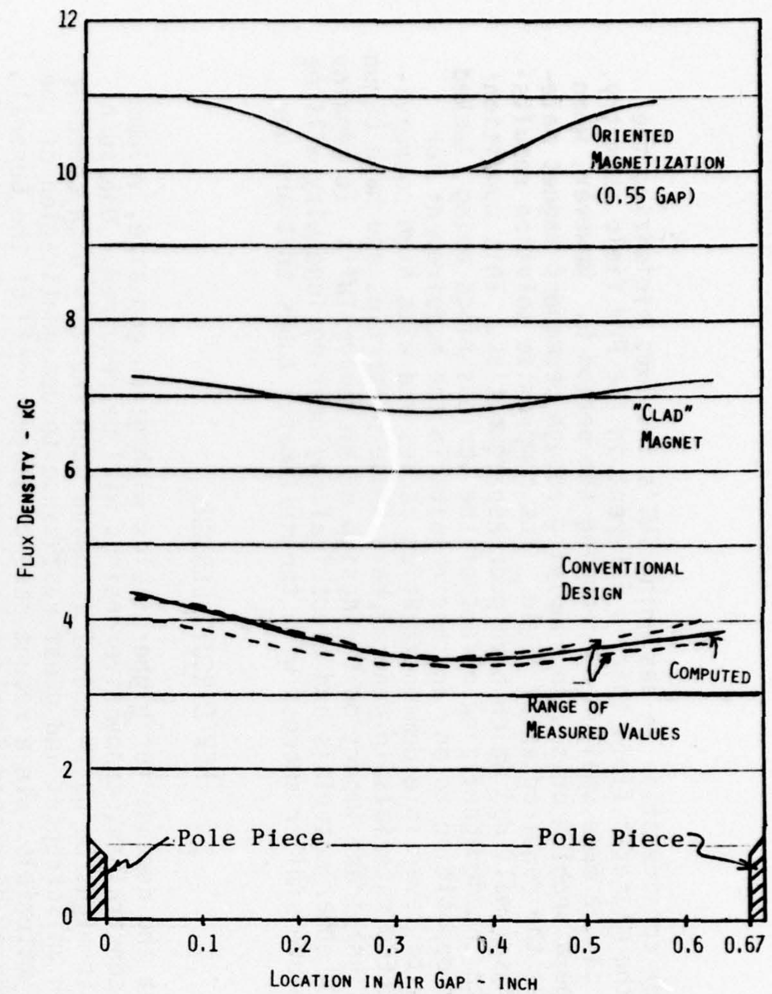


Fig. 8b. Comparison of flux profiles within the gaps of the different magnet designs all having the same outside dimensions (Neugebauer[31]).

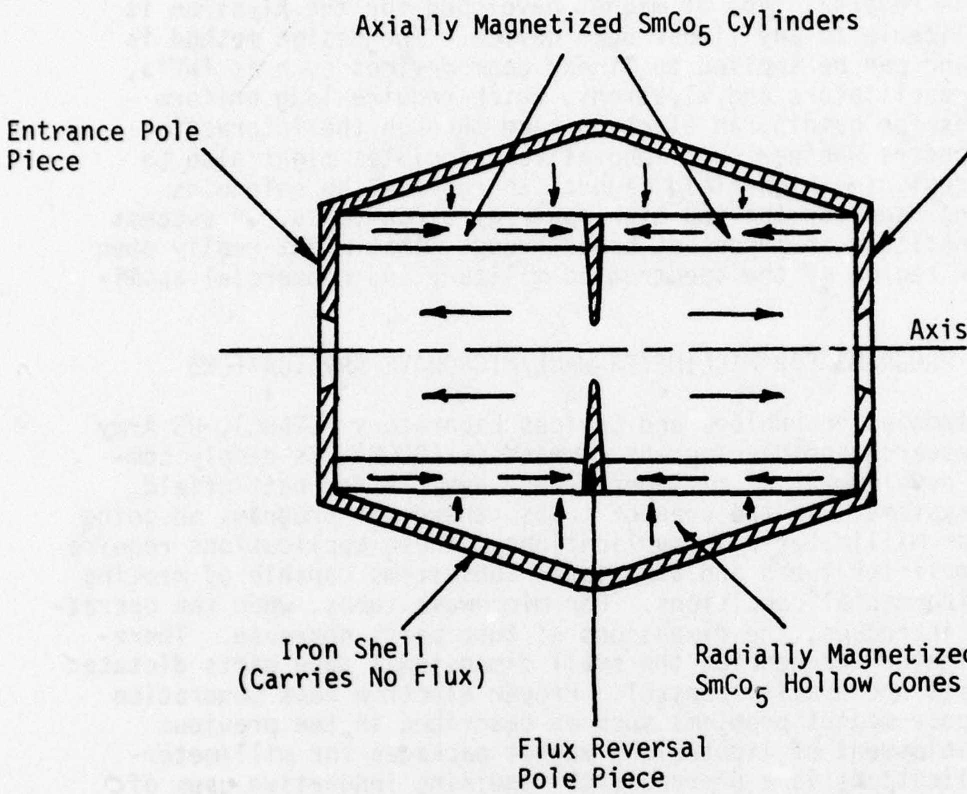


Fig. 9. Single reversal magnetic circuit (Neugebauer[30]).

weighed 308 kg and consumed 3 kW of power. The permanent magnet therefore represented a significant saving in both weight and power. The cladding method also insured that the magnetic circuit had no external leakage fields. This meant that the tubes could be operated near magnetically sensitive instruments without any serious problems. Furthermore, such magnetic circuits can be handled without the hazard of uncontrolled attraction of other ferromagnetic objects which might become dangerous to personnel. The almost total suppression of leakage flux by means of cladding segments prevents such difficulties.

The single reversal type of magnet developed for the klystron is generally applicable to any linear beam device. The design method is quite simple and can be applied to linear beam devices such as TWT's, backward wave oscillators and klystrons, which require long uniform magnetic fields for guiding an electron beam through the interaction space. One wonders whether such innovative principles might also be suitable for designing high field magnets to replace the solenoids currently being used for the new high power gyrotron tubes. A success here would constitute an important breakthrough, that might really open the millimeter region of the spectrum to military and commercial application.

ARMY TUBE PROGRAMS FOR MILLIMETER-WAVE/MICROWAVE APPLICATIONS

The Electronics Technology and Devices Laboratory (ET&DL), US Army Electronics Research and Development Command (ERADCOM), is deeply committed to the development of millimeter-wave devices for battlefield and airborne systems. In the area of tubes, there are programs on-going and planned for millimeter-wave applications. These applications require lightweight amplifier tubes and associated subsystems capable of meeting stringent environmental conditions. For microwave tubes, when the operating frequency increases, the dimensions of tube parts decrease. Therefore, at millimeter frequencies the small dimensional tube parts dictate tight tolerances and quality control. Proper electron beam generation and focusing pose magnet problems such as described in the previous sections. Development of lightweight magnet packages for millimeter-wave tube applications is a prerequisite requiring innovative uses of magnetic materials and magnetic circuit designs and constructions. The technical barriers and pacing problems are recognized. ET&DL has extensive exploratory and advanced development millimeter-wave tube programs under its assigned mission. These programs are aimed at developing tubes for applications in smoke penetration, high resolution air defense, beam-riders, remotely piloted vehicles (RPV's) and tank borne radar systems. The Army expects that the innovative use of rare earth-cobalt materials will make significant contributions to the realization of the various, needed systems.

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