MMPA STANDARD
No. 0100-00

STANDARD SPECIFICATIONS
FOR

PERMANENT MAGNET MATERIALS

MAGNETIC MATERIALS PRODUCERS ASSOCIATION

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FOREWORD

This publication represents standard practices in the United States relating to permanent magnet materials. This standard is a revision of "MMPA Standard OlOO-Standard Specifications for Permanent Magnet Materials" which was originally published in 1964, plus important information from the latest documents prepared by the International Electrotechnical Commission (IEC) Technical Committee 68.

IEC is the oldest continuously functioning standards organization in the world. In 1906, the IEC was given the responsibility of securing the cooperation of technical societies to consider the question of international electrical standardization. The membership of IEC consists of 41 national committees, one for each country. These committees represent the electrical interests of producers, users, government, educators and professional societies of each country. The MMPA is represented on the United States National Committee of IEC/TC68.

It is hoped that the data in this publication will serve as a guide to governmental and industrial purchasers so that they may be assured of uniform quality manufactured to commercial standards. These standard specifications were developed under the auspices of the Magnetic Materials Producers Association and were voluntarily established by mutual consent of those concerned. These specifications are advisory only and their use or adaptation is entirely voluntary. The users of the specification are wholly responsible for protecting themselves against all liabilities for patent infringement.

STANDARD SPECIFICATIONS FOR PERMANENT MAGNET MATERIALS

SECTION I

1.0 SCOPE & OBJECTIVE

1.1 Scope: This standard defines magnetic, thermal, physical and mechanical characteristics and properties of commercially available permanent magnet materials as listed in Table 1.

There are a large number of permanent magnet materials in use which are not described in this document. These materials generally fall into one of the following categories:

(a) Older materials that have been largely replaced by new materials.

(b) Materials made by only one company with a specialized and limited use.

(c) Materials evolving. from development status to production which at this time are not mature from a commercial viewpoint.

For reference purposes, the principal magnetic properties of the materials in the above categories are listed in Appendix A.

1.2 Objective: The objective of this standard is to establish criteria by which users of permanent magnet materials may be assured of magnets manufactured to present commercial standards.

2.0 DEFINITIONS & TERMS

2.1 Definitions: The following definitions characterize materials covered in this standard:

2.1.1 Permanent Magnet (Magnetically Hard) Material: A permanent magnet material, also designated as a magnetically hard material, has a coercive force gener-ally greater than 120 Oe.

2.1.2 Individual Magnet: The term individual *magnet* denotes a magnet purchased in a size and shape to be ready for direct incorporation into a magnetic circuit.

2.1.3 Bulk Magnet Material: The term bulk *magnet material* designates bar, rod, slab, strip, sheet, etc., from which the purchaser cuts, stamps or forms individual magnets.

2.1.4 Polarity of a Magnetized Magnet: The North Pole of a magnet is that pole which is attracted to the geographic North Pole. Therefore, the North Pole of a magnet will repel the north seeking pole of a magnetic compass.

2.1.5 Demagnetized Magnet: For the purposes of this standard, a magnet shall be considered demagnetized if, when any of its poles is dipped in soft iron powder (of -5, + 10 mesh), not more than 3 particles of powder adhere to it anywhere upon withdrawal.

2.2 Terms: A glossary of terms commonly used with permanent magnetic materials is given in Appendix B.

3.0 CONDITION

Unless otherwise specified, bulk magnet materials shall be furnished in the non heat-treated condition, as rolled, as forged, or as-cast condition as applicable. Individual magnets shall be furnished in a fully heat-treated and demagnetized condition.

4.0 CLASSIFICATION & DESIGNATION

4.1 Classification: The classification of permanent magnet materials covered by this standard is given in Table 1. Section numbers for the material classes covered in this standard as well as reference to the International Electrochemical Commission (IEC) material code numbers are also given in the table.

TABLE 1
MATERIAL CLASSIFICATION

Material	MMPA Section	IEC Code
Alnico	II	R1
Ceramic	III	S1
Rare-Earth	IV	R4, R5
Iron-Chromium-Cobalt	V	R2

4.2 Designation: Permanent magnet materials in this specification will be divided into separate sections by the MMPA Class. Each standard section will address the relevant properties, characteristics and specifications of each class of materials and the established sub-grades. In general, reference will be made to historically recognized subgrade descriptions (such as Alnico 1,2, etc., or Ceramic 5, 8, etc.) and to a system, referred to as the Brief Designation, that classifies each subgrade by typical normal energy product and typical intrinsic coercive force. In this system, for example, a material having maximum normal energy product of 5.0 megagauss-oersteds (MGO) and an intrinsic coercive force of 2000 oersteds (2.0 kOe) would be assigned a Brief Designa – tion of 5.01/2.0. When similar grades exist the nearest IEC Grade Code Number will also be listed for cross reference.

5.0 MAGNETIC PROPERTIES, THERMAL PROPERTIES & OTHER CHARACTERISTICS

The magnetic, thermal, surface and internal structure, and other physical characteristics are set forth in tables in each section for the different classes of magnetic materials. The figures in these tables are intended to be descriptions of each of the materials. The properties of the materials produced by individual manufacturers may differ somewhat from those shown. For information concerning properties of actual grades produced, refer to individual manufacturer's literature. The properties shown in the tables with each class shall not be used as inspection criteria of either individual magnets or bulk magnet materials.

5.1 Principal Magnetic Properties: Permanent magnet materials are identified by the following principal magnetic properties:

Maximum value of energy product	$(BH)_{max}$	MGO
Residual induction	B_r	gauss
Coercive force	H_c	oersteds

The measurement of the principal magnetic properties are made in a in closed magnetic circuit permeameter by commonly accepted procedures such as given in IEC Standard Publication *404-5 "Methods of Measurement of Magnetic Properties of Magnetically Hard* (Permanent Magnet) *Materials or* the *"MMPA Permanent Magnet Guidelines"* (current edition).They are accurate only for magnets having a straight magnet axis and produced with a constant cross section along the axis of magnetization. The minimum magnet volume of a sample used to measure these magnet properties shall be one cubic centimeter and the smallest dimension shall be at least 5mm. The' performance of a permanent magnet circuit is de-pendent on the dimensions of all components and the properties of the other components of the circuit, as well as the properties of the permanent magnet. It is recommended not to use unit properties of a material as the specification. These are generally recommended to be only used on prints or drawings to show a subgrade within a material group. Section 8.0 of the specification describes the proper means of specifying the acceptable properties of a permanent magnet component part.

5.2 Thermal Properties: Predicting magnet performance as a function of the magnet's temperature requires knowledge of the following thermal properties:

Reversible temperature coefficient of the residual induction	TC (B_r)	%/ºC
Reversible temperature coefficient of the intrinsic coercive force	TC (H_{ci})	%/ºC
Curie temperature	Tc	ºC
Maximum service temperature	T max	ºC

The values listed for each class of materials for thermal properties are typical values intended as design guide-lines only and are not to be used as a basis for accept-ance or rejection. Values for irreversible temperature characteristics are not listed because they depend on the magnet material, geometry and circuit in which the magnet is used.

5.3 Surface and Internal Structure Characteristics: Permanent magnet materials have been developed primarily for their magnetic properties. The magnetic properties of some materials are produced using manufacturing techniques which are not consistent with pro-ducking perfect physical specimens. Minor physical imperfections rarely impair the magnetic capabilities of a magnet or compromise its stability or ability to resist demagnetization. Imperfections commonly found in permanent magnet materials shall be judged acceptable if the following conditions are met:

(I) The magnet meets the magnetic performance criteria agreed upon between the magnet manufacturer and customer.

(2) The imperfections do not create loose particles that would interfere with proper assembly or functioning in the end use device. Unless otherwise agreed, visual imperfection guidelines listed in the individual material sections apply.

5.4 Other Physical Properties: Typical values for other physical properties important to a magnet user are listed in the tables in the sections for each class of permanent magnet material and are intended to be de-scrimptions of the material, not criteria for acceptance or rejection.

6.0 MECHANICAL CHARACTERISTICS

Most permanent magnet materials lack ductility and are inherently brittle. Such materials should not be utilized as structural components in a circuit. Measurement of properties such as hardness and tensile strength are not feasible on commercial materials with these inherent characteristics. Therefore, specifications of these properties are not acceptable. Measurements of mechanical properties shown in the tables were performed under very carefully controlled laboratory conditions. The values are shown only for reference and comparison to other classes of materials.

7.0 DIMENSIONS AND TOLERANCES

Dimensions and tolerances shall be as specified on the magnet drawing and must be agreed upon between the magnet manufacturer and user before an order is ac-cepted. Normally the magnet user furnishes a drawing to the manufacturer showing all dimensions and toler-ances. When no drawing is available from the user, the manufacturer may furnish a drawing to the user for his approval before manufacturing parts. The standard for drawing, drawing notation and tolerancing is that established in ANSI Y 14.5. Although individual manufacturers will each have their own capability to hold a given tolerance, standard tolerance tables applying to specific classes of these materials are listed in the individual sections.

8.0 PROCESS CONTROL

Most manufacturers use statistical process control to monitor key parameters at each process step.

9.0 INSPECTION &TESTING

Unless otherwise agreed upon, magnets will be inspected for all specified characteristics by the use of a statistically valid sampling plan. Such plans may be derived from, Quality Planning And Analysis: From Product Development Through Use, J.M. Juran and F. M. Gryna, 3rd Edition, McGraw Hill (1993), Chapter 19. ISBN 0-07-033183-9

9.1 Performance Testing Approach--Magnetic Characteristics: The principal characteristics--B_r, H_c, H_{ci}, and $(BH)_{max}$ of a magnetic material are used to identify a specific subgrade within a material class. Generally, individual manufacturers can hold unit magnetic property tolerances of ± 5% for residual flux density, B_r and ± 8% for coercive force, H_c. The range for the energy product, $(BH)_{max}$ is ± 10%. Intrinsic coercive force, H_{ci}, is generally specified as minimum value only.

The size and/or shape of the actual magnet to be produced may cause magnets to have propertie considerably different from these characteristics. Therefore, use of these characteristics in specifying acceptable properties for a given magnet shape is not recommended.The recommended means is to specify the minimum magnetic lines of flux at one or more load lines on the major or minor hysteresis loop. A magnet producer can assist in magnetic circuit analysis which will determine this actual operating flux. From the analysis, a method of test shall be chosen which will cause the magnet being tested to operate at levels which duplicate the performance in the final circuit. The magnet user and supplier shall agree upon a reference magnet to be used to calibrate the test equipment. The acceptance limits shall be agreeable to both manufacturer and user. The acceptability of a magnet shall be judged solely by a comparison with the reference magnet tested in an identical manner.

9.2 Visual Characteristics: The recommended procedure for establishing acceptable levels for visual characteristics is for manufacturer and user to prepare a mutually agreed upon set of go/no-go standards or sample boards. In the absence in such a set of standards or other descriptions of acceptable criteria, the guidelines set forth in each individual section apply.

SECTION II

ALNICO MAGNETS

1.0 CHEMICAL COMPOSITION

Alnico alloys basically consist of aluminum, nickel, cobalt, copper, iron and titanium. In some grades cobalt and/or titanium are omitted. Also these alloys may contain additions of silicon, columbium, zirconium or other elements which enhance heat treatment response of one of the magnetic characteristics.

2.0 MANUFACTURING METHODS

The Alnico alloys are formed by casting or powder metallurgical processes. The magnetic performance of most grades can be increased in a preferred direction by applying a magnetic field during heat treatment thus producing magnetic anisotropy. These alloy systems are hard and brittle and do not lend themselves to conventional machining. The best properties of cast Alnico magnets are achieved with columnar or single crystal structure with the direction of magnetization parallel to the columnar grain axis.

3.0 MAGNETIC PROPERTIES

Typical magnetic properties and chemical compositions of the various commercial grades of Alnico are given in Table II-l.

4.0 DIMENSIONS AND TOLERANCES

Allowable tolerances for cast and sintered Alnico are given in Tables II-2 and II-3.

5.0 MECHANICAL CHARACTERISTICS

The following general specifications are for mechanical characteristics and visual imperfections.

5.1 Surface Conditions

51.1 All magnet surfaces shall be free of foreign materials which would tend to hold or collect extraneous particles on the magnet surface in the unmagnetized condition.

5.2 Chips and Burrs

5.2.1 Magnets shall be free of loose chips and burrs. They shall be free of imperfections which will result in loose chips or particles under normal conditions of handling and service.

5.2.2 A chipped edge or surface shall be acceptable if no more than 10 percent of the surface is removed, provided no loose particles remain and further provided the magnet under examination meets the agreed upon magnetic specification.

5.3 Other Physical Imperfections

5.3.1 Any of the common imperfections found in cast or sintered Alnico magnets: cracks, porosity, voids, cold flow, shrinkage, pipe and others, shall be acceptable if the following conditions are met:

5.3.1.1 The magnet meets the minimum magnetic performance criteria agreed upon.

5.3.1.2 The imperfections do not create loose particles or other conditions which will interfere with proper functioning of the end use device.

5.3.1.3 These visual imperfections do not extend more than 50% through any cross-section. However, this does not apply to the columnar materials (Alnico 5-7 and Alnico 9) which are particularly crack-prone due to their columnar grain. Magnets made of these materials shall be judged acceptable if they maintain their physical integrity satisfactorily for the application.

5.4 Other Conditions

5.4.1 Inspection methods such as the use of penetrants, microscopic inspection, magnetic particle analysis, spin tests, ultrasonics, or x-ray shall not be acceptable methods for judging the quality of cast or sintered Alnico magnets except as provided in 5.4.2 below.

5.4.2 In cases where the magnet is expected to with stand abnormal conditions or stresses, such conditions must be previously specified and a mutually acceptable service test devised to assure that the magnet shall not fail under the specified service conditions. Such tests should duplicate service conditions with appropriate safety factors.

6.0 PHYSICAL PROPERTIES

Typical physical properties for Alnico magnets are given in Table II-4.

7.0 THERMAL PROPERTIES

Typical thermal properties for Alnico magnets are listed in Table II-5.

8.0 INSPECTION SAMPLING PLANS

Unless otherwise agreed upon, magnets will be inspected for all specified characteristics by the use of a statistically valid sampling plan. Such plans may be derived from, Quality Planning and Analysis: From Product Development Through Use, J. M. Juran and F. M. Gryna, 3rd Edition McGraw Hill (1993), Chapter 19. ISBN-0-07-033183-9.

TABLE II-1
TYPICAL MAGNETIC PROPERTIES AND CHEMICAL COMPOSITION OF ALNICO MATERIALS

MMPA Brief Designation	Original MMPA Class	IEC Code Reference	Chemical Composition*					Magnetic Properties							
			Al	Ni	Co	Cu	Ti	Max. Energy Product $(BH)_{max}$ (MGOe)	(kJ/m^3)	Residual Induction B_r (gauss)	(mT)	Coercive Force H_c (oersteds)	(kA/m)	Intrinsic Coercive Force H_{ci} (oersteds)	(kA/m)
ISOTROPIC CAST ALNICO															
1.4/0.48	Alnico 1	R1-0-1	12	21	5	3	-	1.4	11.1	7200	720	470	37	480	38
1.7/0.58	Alnico 2	R1-0-4	10	19	13	3	-	1.7	13.5	7500	750	560	45	580	46
1.35/0.50	Alnico 3	R1-0-2	12	25	-	3	-	1.35	10.7	7000	700	480	38	500	40
ANISOTROPIC CAST ALNICO															
5.5/0.64	Alnico 5	R1-1-1	8	14	24	3	-	5.5	43.8	12800	1280	640	51	640	51
6.5/0.67	Alnico 5DG	R1-1-2	8	14	24	3	-	6.5	57.7	13300	1330	670	53	670	53
7.5/0.74	Alnico5-7	R1-1-3	8	14	24	3	-	7.5	59.7	13500	1350	740	59	740	59
3.9/0.80	Alnico 6	R1-1-4	8	16	24	3	1	3.9	31.0	10500	1050	780	62	800	64
5.3/1.9	Alnico 8	R1-1-5	7	15	35	4	5	5.3	42.2	8200	820	1650	131	1860	148
5.0/2.2	Alnico 8HC	R1-1-7	8	14	38	3	8	5.0	39.8	7200	720	1900	151	2170	173
9.0/1.5	Alnico 9	R1-1-6	7	15	35	4	5	9.0	71.6	10600	1060	1500	119	1500	119
ISOTROPIC SINTERED ALNICO															
1.5/0.57	Alnico 2	R1-0-4	10	19	13	3	-	1.5	11.9	7100	710	550	44	570	45
ANISOTROPIC SINTERED ALNICO															
3.9/0.63	Alnico 5	R1-1-10	8	14	24	3	-	3.9	31.0	10900	1090	620	49	630	50
2.9/0.82	Alnico 6	R1-1-11	8	15	24	3	1	2.9	23.1	9400	940	790	63	820	65
4.0/1.7	Alnico 8	R1-1-12	7	15	35	4	5	4.0	31.8	7400	740	1500	119	1690	134
4.5/2.0	Alnico 8HC	R1-1-13	7	14	38	3	8	4.5	35.8	6700	670	1800	143	2020	161

Note: Balance iron for all alloys

TABLE II-2
TOLERANCES, CAST ALNICO MAGNETS

	Dimensions		Tolerances	
	(Inches)	(Millimeters)	(Inches)	(Millimeters)
Size:				
Unfinished surfaces: (including draft)	0-1	0-25	±0.016	±0.4
	1-2	25-50	±0.031	±0.8
	2-3	50-75	±0.031	±0.8
	3-4	75-100	±0.047	±1.2
	4-5	100-125	±0.047	±1.2
	5-6	125-150	±0.062	±1.6
	6-7	150-175	±0.062	±1.6
	7-8	175-200	±0.078	±2.0
	8-9	200-225	±0.078	±2.0
	9-10	225-250	±0.094	±2.4
	10-12	250-275	±0.094	±2.4
Finished surfaces: any plane ground dimension			±0.005	±0.1
Center or centerless ground:				
0 to 1.5 Inches OD (0 to 38 mm)			±0.004	±0.1
Over 1.5 Inches OD (over 38 mm)			±0.008	±0.2
Parallelism:				
Finished surfaces			½ total tolerance between surfaces	
Angles, including squareness:				
Between two unfinished surfaces			± 1½°	
Between one finished & one unfinished surface			± 1½°	
Between two finished surfaces			±0.005 (± 0.1 mm) from true angle as measured on the shorter of the two surfaces in question or ± ½°, which-ever is greater	
Concentricity between inside and outside surfaces:				
Unfinished surfaces				
Hole diameter > its length			0.032 TIR	0.8 TIR
Hole diameter < its length			1.5 x Total OD TOL. TIR	
Finished surfaces			0.007 TIR	0.2 TIR
Surface roughness:				
Unfinished surfaces			No surface roughness specification	
Finished surfaces			63 microinches (1.6 µm) over at least 95% of the surface	

TABLE II-3
TOLERANCES, SINTERED ALNICO MAGNETS

	Dimensions		Tolerances	
	(Inches)	(Millimeters)	(Inches)	(Millimeters)
Size:				
Unfinished surfaces: (including draft)	0 to 0.125	0 to 3.2	±0.005	±0.1
	over 0.125 to 0.625	3.2 to 16	±0.010	±0.2
	over 0.625 to 1.25	16 to 32	±0.015	±0.4
Finished surfaces:				
Plane ground	any		±0.005	±0.1
Center or centerless ground:	0 to1.5	0 to 38	±0.002	±0.05
	over 1.5	over 38	±0.005	±0.1
Parallelism:				
Finished parallel surfaces			½ total tolerance between surfaces	
Angles, including squareness:				
Between two unfinished surfaces			± 1°*	
Between one finished & one unfinished surface			± 1°*	
Between two finished surfaces			±0.005 (±0.1) from true angle as measured on the shorter of the two surfaces in question or ± ½°, whichever is greater	
Concentricity between inside and outside surfaces:				
Unfinished surfaces	0 to 0.5 OD	0 to 13	0.005 TIR	0.1 TIR
	over 0.5 to 1 OD	13 to 25	0.010 TIR	0.2 TIR
	over 1 to 1.5 OD	25 to 38	0.015 TIR	0.4 TIR
Finished surfaces	any		0.003 TIR	0.8 TIR
Surface roughness:				
Unfinished surfaces			No surface roughness specification	
Finished surfaces			63 microinches (1.6 µm) over at least 95% of the surface	

*Tolerances may be greater for special shapes

TABLE II-4
PHYSICAL PROPERTIES OF ALNICO MATERIALS

MMPA Brief Designation	Original MMPA Class	IEC Code Reference	Density		Tensile Strength		Transverse Modulus of Rupture		Hardness (Rockwell C)	Coefficient of Thermal Expansion 10^{-6} per °C	Electrical Resistivity Ohm-cm x 10^{-6} (at 20°C)
			lbs/in^3	g/cm^3	psi	Pa x 10^6	psi	Pa x 10^6			
1.4/0.48	Alnico 1	R1-0-1	0.249	6.9	4,000	28	14,000	97	45	12.6	75
1.7/0.58	Alnico 2	R1-0-4	0.256	7.1	3,000	21	7,000	48	45	12.4	65
1.35/0.50	Alnico 3	R1-0-2	0.249	6.9	12,000	83	23,000	158	45	13.0	60
5.5/0.64	Alnico 5	R1-1-1	0.264	7.3	5,400	37	10,500	72	50	11.4	47
6.5/0.67	Alnico 5 DG	R1-1-2	0.264	7.3	5,200	36	9,000	62	50	11.4	47
7.5/0.74	Alnico5-7	R1-1-3	0.264	7.3	5,000	34	8,000	55	50	11.4	47
3.9/0.80	Alnico 6	R1-1-4	0.265	7.3	23,000	158	45,000	310	50	11.4	50
5.3/1.9	Alnico 8	R1-1-5	0.262	7.3	10,000	69	30,000	207	55	11.0	53
5.0/2.2	Alnico 8HC	R1-1-7	0.262	7.3	10,000	69	30,000	207	55	11.0	54
9.0/1.5	Alnico 9	R1-1-6	0.262	7.3	7,000	48	8,000	55	55	11.0	53
1.5/0.57	Alnico 2	R1-0-4	0.246	6.8	65,000	448	70,000	483	45	12.4	68
3.9/0.63	Alnico 5	R1-1-10	0.250	6.9	50,000	345	55,000	379	45	11.3	50
2.9/0.82	Alnico 6	R1-1-11	0.250	6.9	55,000	379	100,000	689	45	11.4	54
4.0/1.7	Alnico 8	R1-1-12	0.252	7.0	50,000	345	55,000	379	45	11.0	54
4.5/2.0	Alnico 8HC	R1-1-13	0.252	7.0			55,000	379	45	11.0	54

NOTE: Alnico permanent magnet materials lack ductility, and are inherently extremely brittle. They should not be designed for use as structural components. Measurement of properties such as hardness and tensile strength is not appropriate or feasible on commercial materials but values are shown above for comparison. This data, determined experimentally under controlled laboratory conditions, is a composite of information available from industry and research sources.

TABLE II-5
THERMAL PROPERTIES OF ALNICO MATERIALS

Brief Designation	Original MMPA Class	IEC Code Reference	Reversible Temperature Coefficient % Change per °C			Curie Temperature		Max. Service Temperature	
			Near B_r	Near Max. Energy Prod.	Near H_c	°C	°F	°C	°F
1.5/0.57	Alnico 2	R1-0-4	-0.03	-0.02	-0.02	810	1490	450	840
5.5/0.64	Alnico 5	R1-1-1	-0.02	-0.015	+0.01	860	1580	525	975
3.9/0.80	Alnico 6	R1-1-4	-0.02	-0.015	+0.03	860	1580	525	975
5.3/1.9	Alnico 8	R1-1-5	-0.025	-0.01	+0.01	860	1580	550	1020
5.0/2.2	Alnico 8HC	R1-1-7	-0.025	-0.01	+0.01	860	1580	550	1020
9.0/1.5	Alnico 9	R1-1-6	-0.025	-0.01	+0.01	860	1580	550	1020

NOTE: The above data is a composite of information available from industry and research sources.

SECTION III

CERAMIC MAGNETS

1.0 CHEMICAL COMPOSITION

The general formula $MO{\cdot}6Fe_2O_3$ describes the chemical composition of ferrite (ceramic) permanent magnets, where M generally represents barium or strontium or any combination of the two.

2.0 MANUFACTURING METHOD

Ceramic magnets are generally formed by a compression or extrusion molding technique which is then followed by sintering. Finish grinding or shaping, when necessary for better control of dimensions, is normally done by using diamond grinding wheels. The material to be molded can be in either a dry powder or wet slurry form. Magnetic performance can be increased in a preferred direction by applying a magnetic field in that direction during the molding process.

3.0 MAGNETIC PROPERTIES

The magnetic properties of the various commercial grades of ceramic permanent magnet materials are given in Table III-l. This data is compiled from information submitted by ceramic magnet manufacturers. Characteristics of each grade obtained from individual manufacturers may vary from the standard listing.

4.0 OTHER CHARACTERISTICS

4.1 Mechanical Characteristics: Ceramic magnets are used for their magnetic capability, not for their mechanical properties. It is recommended that they not be used for structural purposes since they are low in tensile and flexural strength.

4.2 Visual Characteristics: Imperfections such as cracks, porosity, voids, surface finish, etc., all of the type commonly found in sintered ceramic magnets. shall not constitute reason for rejection. They shall be judged acceptable if the following conditions are met:

1. The magnet meets the minimum magnetic performance criteria agreed upon.
2. The imperfections do not create loose particles or other conditions which will interfere with proper assembly or mechanical functioning of the end use device.

Mutually agreed upon acceptance criteria in the form of written descriptions, pictorial drawings or actual part sample boards can be especially useful for judging visual acceptability. In the absence of an agreed upon standard, the follo\ving visual inspection guidelines apply:

1. Magnets shall be free from loose chips and surface residue which will interfere with proper assembly.
2. Chips shall be acceptable if no more than 5% of any surface identified as a magnetic pole surface is removed.
3. Cracks shall be acceptable provided they do not extend across more than 50% of any surface identified as a magnetic pole surface.

In cases where the magnet is expected to withstand abnormal conditions such as chemical corrosion, thermal shock or mechanical stresses, such conditions must be previously specified. A mutually acceptable service test should be devised to evaluate the acceptability of the magnets. Such tests should duplicate service conditions with appropriate safety factors. Inspection methods such as the use of penetrants, magnetic particle analysis, ultrasonics, or x-ray shall not be acceptable methods for judging quality of sintered ceramic magnets.

4.3 Dimensions and Tolerances: Recommended tolerances for ceramic magnets are given in Table III-2. Functional gaging and dimensioning of ground arc shape segments is given in Table III-3.

6.0 PHYSICAL PROPERTIES

Typical physical properties for ceramic magnets are listed in Table 111-4.

6.0 THERMAL PROPERTIES

Typical parameters that relate to temperature changes for ceramic magnets are listed in Table III-5.

7.0 PROCESS CONTROL

Most manufacturers use statistical process control to monitor key parameters at each process step. Control plans are individually negotiated with customers to meet specific quality requirements.

8.0 INSPECTION & TESTING

In the absence of a control plan, ceramic magnets will be inspected for all specified characteristics using a statistically valid sampling plan. Refer to Section I, paragraph 9.0 on page 5 for additional information.

TABLE III-1
TYPICAL MAGNETIC PROPERTIES AND CHEMICAL COMPOSITION OF CERAMIC MAGNET MATERIALS

MMPA Brief Designation	Original MMPA Class	IEC Code Reference	Chemical Composition (M represents Barium, Strontium or combination of the two.)	Magnetic Properties							
				Max. Energy Product $(BH)_{max}$		Residual Induction B_r		Coercive Force H_c		Intrinsic Coercive Force H_{cj}	
				(MGOe)	(kJ/m^3)	(gauss)	(mT)	(oersteds)	(kA/m)	(oersteds)	(kA/m)
1.0/3.3	Ceramic 1	S1-0-1	MO • $6Fe_2O_3$	1.05	8.35	2300	230	1860	150	3250	260
3.4/2.5	Ceramic 5	SI-1-6	MO • $6Fe_2O_3$	3.40	27.1	3800	380	2400	190	2500	200
2.7/4.0	Ceramic 7	SI-1-2	MO • $6Fe_2O_3$	2.75	21.9	3400	340	3250	260	4000	320
3.5/3.1	Ceramic 8	SI-1-5	MO • $6Fe_2O_3$	3.50	27.8	3850	385	2950	235	3050	245
3.4/3.9	-		MO • $6Fe_2O_3$	3.40	27.1	3800	380	3400	270	3900	310
4.0/2.9	-		MO • $6Fe_2O_3$	4.00	31.8	4100	410	2800	225	2900	230
3.2/4.8	-		MO • $6Fe_2O_3$	3.20	25.5	3700	370	3500	280	4800	380
3.8/4.0	-		MO • $6Fe_2O_3$	3.80	30.2	4000	400	3650	290	4000	320

NOTE FOR ALL MATERIALS:

Recoil Permeability Range --1.05 to 1.2
To achieve the properties shown in this table, care must be taken to magnetize to Saturation (typically 10,000 to 15,000 oersteds minimum depending on material grade).

TABLE III-2
TOLERANCES, SINTERED CERAMIC MAGNETS
(See Table III-3 for arc segment dimensions)

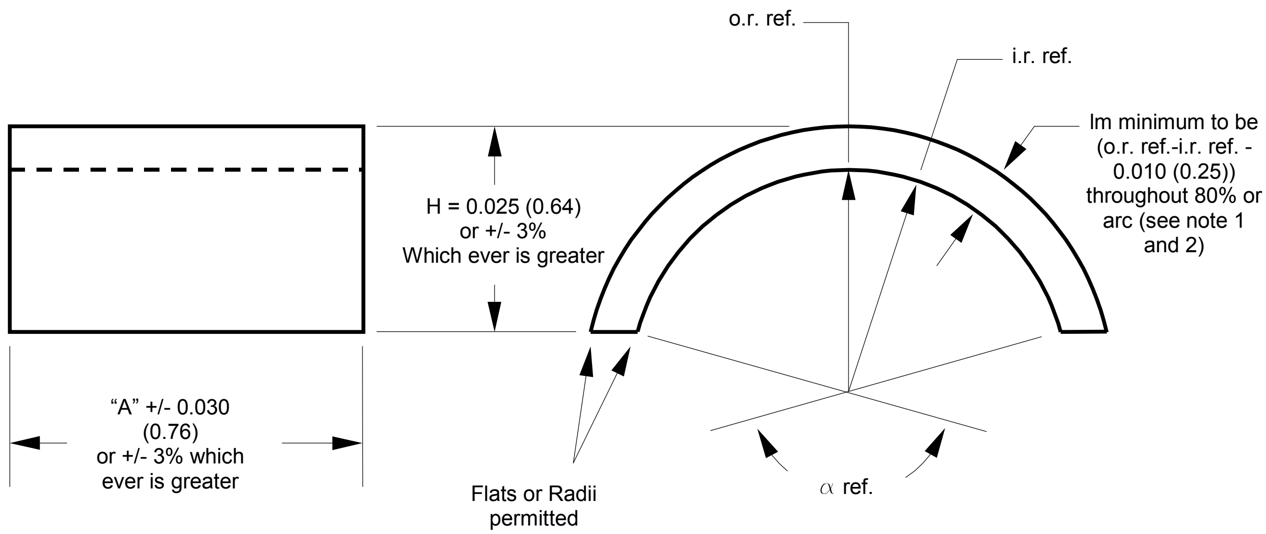
	DIMENSIONS		TOLERANCES	
	inches	mm	inches	mm
Size:				
Unfinished surfaces:				
Dimensions perpendicular to pressing: die formed)	any	any	2% or ±0.025, whichever is greater	2% or ±0.64, whichever is greater
Dimensions parallel to pressing (1): (punch formed)	0 to 0.4 0.4 to 0.8 Over 0.8	0 to 10 10 to 20 over 20	± 0.016 ±0.025 ±3%	±0.41 ±0.64 ±3%
Cut dimensions:	any	any	±3% or ± 0.025, whichever is greater	3% or ± 0.64, whichever is greater
Finished surfaces:				
Plane ground:	any	any	±0.005	±0.13
Center or centerless ground:	0 to 1.0 over 1.0	0 to 25 over 25	±0.003 ±0.005	±0.08 ±0.13
Squareness:				
Between two unfinished surfaces:			900 ± 1º	900 ± 1º
Between one finished, one unfinished surface:			900 ± 1º	900 ± 1º
Between two finished surfaces:			900 ± 30'	900 ± 30'
Parallelism:				
Finished parallel surfaces:			% total tolerance between surfaces	% total tolerance between surfaces
Surface Roughness:				
Unfinished surface:			Within standard dimensional tolerance	Within standard dimensional tolerance
Finished surface: (over at least 80% of the ground surface)			125×10^{-6}	3.2×10^{-3}
Warp:				
Maximum allowable warp:			.011 inches per inch	0.011 mm/mm
Rings and Rounds:				
Out of round:			Within standard dimensional tolerance Greater of ± 1½% or	Within standard dimensional tolerance Greater of ± 1½% or
Wall thickness:			±0.010	± 0.25

(1) Wet compacted ceramic magnets are ground on the magnetic pole surfaces in most cases.

TABLE III-3

FUNCTIONAL GAGING AND DIMENSIONING OF GROUND ARC SEGMENTS

Inches (millimeters)



Gage Note:

Part must pass through a gage having an outside radius of o.r. ref. + 0.006 (0.15) and an inside radius of i.r. ref. - 0.006 (0.15). Minimum axial length of gage to be "A".

Notes:

1) When dimension "A" exceeds two inches (51 mm), subtract an additional 0.003 (0.076) from Im minimum for each additional one half inch (13 mm).

2) Remaining 20% of arc to be no less than 0.9 x Im minimum

TABLE III-4
PHYSICAL PROPERTIES OF CERAMIC MAGNETS

Property	Typical Value	
Density	0.177 lbs/in^3	4.9 g/cm^3
Coefficient of thermal expansion (250C to 450'C)		
Perpendicular to orientation	$6X1\ 0^{-6}$ Inch/inch • ºF	$1OX1\ 0^{-6}$ cm/cm • ºC
Parallel to orientation	$8X10^{-6}$ Inch/inch • ºF	$14X1\ 0^{-6}$ cm/cm • ºC
Thermal conductivity	0.018 cal/inch•sec•ºC	0.029 W/cm•ºC
Electrical resistivity	10^6 ohm•cm	10^6 ohm•cm
Porosity	5%	5%
Modulus of elasticity	$2.6X1\ 0^7$ psi	$1.8X10^{11}$Pa
Poisson ratio	0.28	0.28
Compressive strength	130,000 psi	$895X1\ 0^6$ Pa
Tensile strength	5000 psi	$34X1\ 0^6$ Pa
Flexural strength	9000 psi	62X1 0 Pa
Hardness (Mohs)	7	7

TABLE III-5
THERMAL PROPERTIES OF CERAMIC MAGNETS

Property	Typical Value*	
Reversible temperature coefficient of residual Induction	-0.11% / ºF	-0.2% / ºC
Reversible temperature coefficient of intrinsic coercive force	0.11 to 0.28% / ºF	0.2 to 0.5% / ºC
Curie temperature	840 ºF	450ºC
Maximum service temperature*	1470ºF	800ºC

* Maximum temperature without structural change. Temperatures greater than 450º C will require remagnetization.

NOTE: The above data is a composite of information from industry and research sources.

SECTION IV

RARE EARTH MAGNETS

1.0 CHEMICAL COMPOSITION

Rare earth magnet materials currently fall into three families of materials. They are rare-earth cobalt 5, the rare earth 2 transition metal 17 group and rare earth iron alloys.

1.1 l-5 Alloys (Rare-Earth Cobalt 5): These alloys are usually binary or ternary alloys with the approximate atomic ratio of one rare earth atom to five cobalt atoms. The rare earth element is most commonly samarium but can also be other light rare earth such as, but not limited to, praseodymium, cerium, neodymium or a combination, or a mixture known as misch metal. Heavy rare earths such as gadolinium, dysprosium and erbium can substitute for the light rare earth elements to give the magnetic material a lower temperature coefficient of remanence. The rare earth elements typically are 34 to 39 weight percent of the alloy.

1.2 2-17 Alloys (Rare-Earth 2 Transition Element 17): These alloys are an age hardening type with a com- position ratio of 2 rare earth atoms to 13-17 atoms of transition metals. The rare earth atoms can be any of those found in the l-5 alloys. The transition metal (TM) content is a cobalt rich combination of cobalt, iron and copper. Small amounts of zirconium, hafnium or other elements are added to enhance the heat treatment response. The rare earth content of 2-17 materials is typically 23 to 28 weight percent of the alloy.

1.3 Rare Earth Iron Alloys: These alloys have a com- position of two rare earth atoms to 14 iron atoms with one boron atom. There may be a substitution of other rare earth and/or minor additions of other elements. Cobalt is substituted for the iron at 3 to 15 % to improve high temperature performance. The rare earth content of RE-Fe magnet alloys is typically 30 to 35 weight percent.

2.0 MANUFACTURING METHODS

The rare earth magnet alloys are usually formed by powder metallurgical processes. The magnetic per formance of all grades is optimized by applying a mag netic field during the pressing operation, thus produc- ing a preferred direction of magnetization. Pressing and aligning techniques can substantially vary the degree of orientation and the residual induction (Br) of the finished magnet.

The direction of the magnetic field during die pressing can be either parallel or perpendicular to the pressing direction. Magnets can also be formed by isostatic pressing. After pressing, the magnets are sintered, heat treated and ground to the final dimensions. Rare earth magnets are inherently brittle and cannot be machined with con-ventional metal cutting processes such as drilling, turning or milling. The magnets can be readily ground with abrasive wheels if liberal amounts of coolant are used. The coolant serves to minimize heat cracking, chipping and also eliminates the risk of fires caused by sparks contacting the easily oxidized grinding dust.

3.0 MAGNETIC PROPERTIES

The magnetic properties and chemical compositions of the commercial grades of rare earth magnet materials are given in Table IV-l. Since many combinations of elements and orientations are possible, many additional grades are available from various producers.

4.0 DIMENSIONS AND TOLERANCES

Allowable tolerances for sintered rare earth magnets are given in Table IV-2.

5.0 MECHANICAL CHARACTERISTICS

The following general specifications are for mechanical characteristics and visual imperfections.

5.1 Surface Conditions

5.1 .1 All magnet surfaces shall be free of foreign materials which would tend to hold or collect extraneous particles on the magnet surface in the unmagnetized condition.

5.2 Chips

5.2.1 Magnets shall be free of loose chips. They shall be free of imperfections which will result in loose chips or particles under normal conditions of handling, shipping, assembly and service.

5.2.2 A chipped edge or surface shall be acceptable if no more than 10 percent of the surface is removed, provided that no loose particles remain at the edge or surface, and further provided the magnet under examination meets the magnetic specification agreed upon between the producer and user.

5.3 Other Physical Imperfections

5.3.1 Imperfections such as minor hairline cracks, porosity, voids, and others, all of the type commonly found in sintered metallic magnets, shall be judged acceptable if the following conditions are met:

5.3.1.1 The magnet meets the minimum magnetic performance criteria agreed upon.

5.3.1.2 The imperfections do not create loose particles or other conditions which will interfere with proper functioning of the end device.

5.3.1.3 Cracks shall be acceptable provided they do not extend across more than 50 percent of any pole surface.

5.4 Other Conditions

5.4.1 Non-destructive inspection methods such as the use of penetrants, microscopy, magnetic particle analysis, ultrasonic inspection, or x-ray shall not be acceptable able methods for judging the quality of sintered rare earth magnets except as provided in Section 5.4.2.

5.4.2 In cases where the magnet is expected to withstand abnormal conditions or stresses, such conditions must be previously specified and a mutually acceptable service test devised to assure that the magnet shall not fail under the specified service conditions. Such tests should duplicate service conditions with appropriate safety factors.

6.0 PHYSICAL AND THERMAL PROPERTIES

Typical physical and thermal properties for rare earth magnets are given in Table IV-3.

7.0 PROCESS CONTROL

Most manufacturers use statistical process control to monitor key parameters at each process step. Control plans are individually negotiated with customers to meet specific quality requirements.

8.0 INSPECTION & TESTING

In the absence of a control plan, rare earth magnets will be inspected for all specific characteristics using a statistically valid sampling plan. Such plans may be derived from, Quality Planning And Analysis: From Product Development Through Use, J.M. Juran and F. M. Gryna, 3rd Edition, McGraw Hill (1993), Chapter 19. ISBN 0-07-033183-9.

TABLE IV-1
TYPICAL MAGNETIC PROPERTIES--CHEMICAL COMPOSITION OF RARE EARTH MAGNETS

MMPA Brief Designation	IEC Code Reference	Chemical Composition		Magnetic Properties *							
		Alloys	Possible Elements	Max. Energy Product $(BH)_{max}$		Residual Induction B_r		Coercive Force H_c		Intrinsic Coercive Force H_{ci}	
				(MGOe)	(kJ/m^3)	(gauss)	(mT)	(oersteds)	(kA/m)	(oersteds)	(kA/m)
16/19	R4-1	RE Co_5	RE = Sm	16	130	8300	830	7500	600	19000	1510
18/30	R4-1	RE Co_5	RE = Sm	18	140	8700	870	8500	680	30000	2390
20/16	R4-1	RE Co_5	RE = Sm, Pr	20	160	9000	900	8500	680	16000	1270
20/30	R4-1	RE Co_5	RE = Sm, Pr	20	160	9000	900	8800	700	30000	2390
22/16	R4-1	RE Co_5	RE = Sm, Pr	22	180	9500	950	9000	720	16000	1270
24/7	R4-1	RE_2TM_{17}	RE = Sm, TM = Fe,Cu,Co,Zr,Hf	24	190	10000	1000	6000	480	7000	560
24/26	R4-1	RE_2TM_{17}	RE = Sm, TM = Fe,Cu,Co,Zr,Hf	24	190	10000	1000	9300	740	26000	2070
26/10	R4-1	RE_2TM_{17}	RE = Sm, TM = Fe,Cu,Co,Zr,Hf	26	210	10500	1050	9000	720	10000	800
26/26	R4-1	RE_2TM_{17}	RE = Sm, TM = Fe,Cu,Co,Zr,Hf	26	210	10700	1070	9750	780	26000	2070
28/7	R4-1	RE_2TM_{17}	RE = Sm, TM = Fe,Cu,Co,Zr,Hf	28	220	10900	1090	6500	520	7000	560
28/26	R4-1	RE_2TM_{17}	RE = Sm, TM = Fe,Cu,Co,Zr,Hf	28	220	11000	1100	10300	820	26000	2070
30/24	R4-1	RE_2TM_{17}	RE = Sm, TM = Fe,Cu,Co,Zr,Hf	30	240	11600	1160	10600	840	24000	1910
24/41	R5-1	$RE_2TM_{14}B$	RE = Nd,Pr,Dy TM = Fe,Co	24	190	10000	1000	9600	760	41000	3260
26/32	R5-1	$RE_2TM_{14}B$	RE = Nd,Pr,Dy TM = Fe,Co	26	210	10500	1050	10090	800	31500	2510
28/23	R5-1	$RE_2TM_{14}B$	RE = Nd,Pr,Dy TM = Fe,Co	28	220	10800	1080	10300	820	23000	1830
28/32	R5-1	$RE_2TM_{14}B$	RE = Nd,Pr,Dy TM = Fe,Co	28	220	10730	1073	10490	830	31500	2510
30/19	R5-1	$RE_2TM_{14}B$	RE = Nd,Pr,Dy TM = Fe,Co	30	240	11300	1130	10800	860	19000	1510
30/27	R5-1	$RE_2TM_{14}B$	RE = Nd,Pr,Dy TM = Fe,Co	30	240	11300	1130	10800	860	27000	2150
32/16	R5-1	$RE_2TM_{14}B$	RE = Nd,Pr,Dy TM = Fe,Co	32	260	11800	1180	11200	890	16000	1270
32/31	R5-1	$RE_2TM_{14}B$	RE = Nd,Pr,Dy TM = Fe,Co	32	260	11600	1160	11100	880	31000	2470
34/22	R5-1	$RE_2TM_{14}B$	RE = Nd,Pr,Dy TM = Fe,Co	34	270	11960	1196	11500	920	22250	1770
36/19	R5-1	$RE_2TM_{14}B$	RE = Nd,Pr,Dy TM = Fe,Co	36	290	12310	1231	11520	920	19140	1520
36/26	R5-1	$RE_2TM_{14}B$	RE = Nd,Pr,Dy TM = Fe,Co	36	290	12200	1220	11700	930	26000	2070
38/15	R5-1	$RE_2TM_{14}B$	RE = Nd,Pr,Dy TM = Fe,Co	38	300	12500	1250	12000	950	15000	1190
38/23	R5-1	$RE_2TM_{14}B$	RE = Nd,Pr,Dy TM = Fe,Co	38	300	12400	1240	12000	950	23000	1830
40/15	R5-1	$RE_2TM_{14}B$	RE = Nd,Pr,Dy TM = Fe,Co	40	320	12800	1280	12000	950	15000	1190
40/23	R5-1	$RE_2TM_{14}B$	RE = Nd,Pr,Dy TM = Fe,Co	40	320	12900	1290	12400	990	23000	1830
42/15	R5-1	$RE_2TM_{14}B$	RE = Nd,Pr,Dy TM = Fe,Co	42	340	13100	1310	12700	1010	15000	1190
44/15	R5-1	$RE_2TM_{14}B$	RE = Nd,Pr,Dy TM = Fe,Co	44	350	13500	1350	13000	1030	15000	1190
48/11	R5-1	$RE_2TM_{14}B$	RE = Nd,Pr,Dy TM = Fe,Co	48	380	13750	1375	10300	820	11000	880
50/11	R5-1	$RE_2TM_{14}B$	RE = Nd,Pr,Dy TM = Fe,Co	50	400	14100	1410	10300	820	11000	880

* To achieve the properties shown in this table, care must be taken to magnetize to saturation.

TABLE IV-2
TOLERANCES
SINTERED RARE EARTH MAGNETS

	Dimensions		Tolerances	
	inches	mm	inches	mm
Size: Unfinished surfaces: Dimensions perpendicular to pressing (die formed)	0 to 0.125 0.126 to 0.625 0.626 to 0.875 0.876 and up	0 to 3 3 to 16 16 to 22 22 and up	± 0.006 ± 0.012 ± 0.018 ± 2.5%	± 0.15 ± 0.30 ± 0.45 ± 2.5%
Dimensions parallel to pressing (punch formed)	any	any	± 2.5% or ± 0.02 whichever is greater	± 2.5% or ± 0.05 whichever is greater
Finished surfaces: Plane ground	any	any	± 0.005	± 0.125
Center or centerless ground	0 to 1.5 over 1.5	0 to 38 over 38	± 0.004 ± 0.008	± 0.10 ± 0.20
Parallelism: Between finished surfaces			1/2 total tolerance between surfaces	1/2 total tolerance between surfaces
Angles including squareness: Between two unfinished surfaces Between one finished, one unfinished Between two finished surfaces			± 1° ± 1° ± 0.005 from true angles as measured on the shorter of two surfaces in question or ± 1/2° whichever is greater	± 1° ± 1° ± 0.125 from true angles as measured on the shorter of two surfaces in question or ± 1/2° whichever is greater
Concentricity: Between inside and outside Surfaces: Unfinished surfaces	0 to 0.5 0.5 to 1.0 1.0 to 1.5	0 to 12.5 12.5 to 25 25 to 38	± 0.010 TIR ± 0.020 TIR ± 0.030 TIR	± 0.25 TIR ± 0.50 TIR ± 0.75 TIR
Finished surfaces	any	any	± 0.007 TIR	± 0.18 TIR
Surface Roughness: Finished surfaces	any	any	63 microinches over at least 95% of the ground surface	1.6μm over at least 95% of the ground surface

TABLE IV – 3
TYPICAL PHYSICAL PROPERTIES
SINTERED RARE EARTH MAGNETS

Material	Density		Modulus of elasticity		Ultimate Tensile strength		Coefficient of thermal expansion		Electrical resistivity Ohm-cm x 10^{-6} (at 20ºC)
							Perpendicular To orientation	Parallel To orientation	
	g/cm^3	lbs/in^3	psi	Pa x 10^9	psi	Pa x 10^6	10^{-6} / ºC	10^{-6} / ºC	
1-5 Alloys	8.4	0.303	23 x 10^6	159	6,000	41	13.0	6.0	53
2-17 Alloys	8.4	0.303	17 x 10^6	117	5,000	35	11.0	8.0	86
Nd-Fe-B	7.4	0.267	22 x 10^6	152	12,000	83	4.8	3.4	160

TABLE IV – 4
TYPICAL THERMAL PROPERTIES
SINTERED RARE EARTH MAGNETS

Material	Reversible Temperature Coefficient Of Residual Induction (- 100ºC to + 100ºC) % Change per ºC	Curie Temperature		Max. Service Temperature*	
		ºC	ºF	ºC	ºF
1-5 Alloys	-0.040	750	1380	300	570
2-17 Alloys	-0.035	825	1520	350	660
Nd-Fe-B	-0.090	310	590	150**	300

SECTION V

IRON-CHROMIUM-COBALT MAGNETS

1.0 CHEMICAL COMPOSITION

These alloys are primarily of the Iron-Chromium-Cobalt composition. Some grades may also contain additions of vanadium, silicon, titanium, zirconium, manganese, molybdenum or aluminum.

2.0 MANUFACTURING METHODS

The Iron-Chromium-Cobalt alloys are formed either by casting to size or by casting in the form of an ingot which is then rolled and/or drawn either to final shape or to form which can then be cut. Heat treatment is essential to develop the magnetic properties. The magnetic properties can be increased in a preferred direction by applying a magnetic field during heat treatment. Although this alloy is hard and brittle in its fully heat treated condition, it is sufficiently ductile to be rolled, drawn, machined, turned or threaded prior to its final heat treatment.

3.0 MAGNETIC PROPERTIES

The magnetic properties of the commercial grades of Iron-Chromium-Cobalt alloys are listed in Table V-l.

4.0 DIMENSIONS AND TOLERANCES

Standard tolerances for cast, rolled and drawn Iron-Chromium-Cobalt magnets are listed in Table V-2.

5.0 MECHANICAL CHARACTERISTICS

The following general specifications are for mechanical characteristics and visual conditions.

5.1 Surface Conditions

There should be no cracks, chips, burrs or other conditions that would interfere with the proper functioning of the end use device.

5.2 Chips

5.2.1 Magnets shall be free of loose chips or imperfecttions which will result in loose chips under normal handling and shipping conditions.

5.2.2 A chipped edge or surface shall be acceptable if not more than 10% of the edge or 5% of the surface is removed.

5.3 Visual Standards The use of mutually agreed upon visual standards is recommended in cases where such properties are critical.

5.4 Inspection Methods Inspection methods such as the use of penetrants, magnetic particle analysis, ultrasonics or x-ray shall not be acceptable methods for judging the quality of cast, rolled or drawn Iron-Chromium-Cobalt magnets except in cases where the magnet is expected to withstand abnormal conditions. In those cases the service conditions must be specified and a mutually acceptable service test devised.

6.0 PHYSICAL PROPERTIES

Typical values for density, thermal expansion, thermal conductivity and electrical resistivity are listed in Table V-3.

7.0 THERMAL PROPERTIES

Typical values for the reversible temperature coefficients of residual induction and intrinsic coercive force, Curie temperature and maximum service temperature are listed in Table V-4.

8.0 INSPECTION AND TESTING

8.1 Unless otherwise agreed upon by the manufacturer and the user, all lots of bulk magnet material and individual magnets will be inspected by the use of a statistical sampling plan. Such plans may be derived from, Quality Planning And Analysis: From Product Development Through Use, J.M. Juran and F. M. Gryna, 3rd Edition, McGraw Hill (1993), Chapter 19. ISBN 0-07-033183-9

8.2 A method of magnetic tests shall be chosen which causes the magnet to operate at one or more points on its major and/or minor hysteresis loops as indicated by the operating points of the magnet in its final magnetic circuit. The acceptance limits chosen shall be mutually agreeable to both the manufacturer and user. A magnet shall be chosen to serve as a calibration reference. Acceptability of a magnet will then be judged solely by comparison to the reference magnet, tested under identical conditions.

TABLE V-1
TYPICAL MAGNETIC PROPERTIES AND CHEMICAL COMPOSITIONS OF IRON-CHROMIUM-COBALT MAGNET MATERIALS

MMPA Brief Designation	MMPA Class*	IEC Code Reference	Magnetic Properties (nominal)					
			Residual Induction B_r		Coercive Force Hc		Max. Energy Product Product $(BH)_{max}$	
			(gauss)	(mT)	(oersteds)	(kA/m)	(MGOe)	(kJ/m^3)
	ISOTROPIC							
1.6/0.46	Fe Cr Co 1	R2	8800	880	460	37	1.60	12.7
1.6/0.35	Fe Cr Co 2	R2	9900	990	350	28	1.60	12.7
1.0/0.20	Fe Cr Co	R2	10500	1050	200	16	1.00	8.0
1.6/0.49	Fe Cr Co 1	R2	9000	900	490	39	1.63	13.0
	ANISOTROPIC							
5.2/0.61	Fe Cr Co 5	R2	13500	1350	600	48	5.25	41.8
2.0/0.25	Fe Cr Co 250	R2	14000	1400	250	20	2.00	15.9
4.4/0.64	Fe Cr Co 640	R2	12000	1200	641	51	4.40	35.0

* Composition is 15 to 35 weight percent Chromium, 5 to 20 Cobalt, balance iron with minor amounts of other elements present.

TABLE V-2
TOLERANCES
IRON-CHROMIUM-COBALT MAGNETS

	Dimensions (inches)			Dimensions (mm)			Tolerances (inches)		Tolerances (mm)	
ROLLED BARS										
Rounds or Squares	0	to	0.312	0.00	to	7.92	+/-	0.010	+/-	0.25
	0.312	to	0.625	7.92	to	15.88	+/-	0.015	+/-	0.38
	0.625	and over		15.88	and over		+/-	0.020	+/-	0.51
ROLLED FLATS										
Thickness	0.002	to	0.014	0.05	to	0.36	+/-	5%	+/-	5%
	0.014	to	0.095	0.36	to	2.41	+/-	5%	+/-	5%
	0.095	to	0.125	2.41	to	3.18	+/-	0.010	+/-	0.25
	0.125	to	0.250	3.18	to	6.35	+/-	0.015	+/-	0.38
	0.250	to	0.500	6.35	to	12.70	+/-	0.020	+/-	0.51
Width	0.125	to	8.000	3.18	to	203.20	+/-	0.005	+/-	0.13
	1.000	to	8.000	25.40	to	203.20	+/-	0.010	+/-	0.25
	0.000	to	0.500	0.00	to	12.70	+/-	0.015	+/-	0.38
	0.000	to	0.750	0.00	to	19.05	+/-	0.020	+/-	0.51
	0.750	to	1.000	19.05	to	25.40	+/-	0.025	+/-	0.64
CENTERLESS GROUND BARS										
Diameter	0.000	to	1.000	0.00	to	25.40	+/-	0.002	+/-	0.05
DRAWN BARS										
Diameter	0.000	to	0.190	0.00	to	4.83	+/-	0.003	+/-	0.08

TABLE V- 3
PHYSICAL PROPERTIES OF IRON-CHROMIUM-COBALT MAGNETS

Brief Designation	MMPA Class	IEC Code Reference	Density		Electrical Resistivity Ohm-cm x10^{-6} (at 20ºC)	Thermal Conductivity W/(m • K)	Coefficient Of Thermal Expansion 10^{-6}/ºC
			Lb/in^3	g/cm^3			
1.6/0.35	FeCrCo 2	R2	0.278	7.7	70	21	10
5.2/0.61	FeCrCo 5	R2	0.278	7.7	70	21	10
2.0/0.25	FeCrCo 250	R2	0.278	7.7	70	21	10

TABLE V- 4
THERMAL PROPERTIES OF IRON-CHROMIUM-COBALT MAGNETS

Brief Designation	MMPA Class	IEC Code Reference	Reversible Temperature Coefficient B_r % Change per ºC (–50 to +200ºC)	Curie Temperature ºC	Max Service Temperature ºC
1.6/0.35	FeCrCo 2	R2	0.036	640	500
5.2/0.61	FeCrCo 5	R2	0.020	640	500
2.0/0.25	FeCrCo 250	R2	0.030	640	500

APPENDIX A
PERMANENT MAGNET MATERIALS
NOT COVERED IN PRODUCT SECTIONS
(See Section I Scope)

Magnetic Materials	**$(BH)_{max}$**		**Magnetic Properties**			
			B_r		**H_c/H_{ci}**	
	(MGOe)	**(kJ/m^3)**	**(gauss**	**(mT)**	**(oersteds)**	**(kA/m)**
31/2% Cr Steel	0.13	1.03	10300	1030	60	5
3% Co Steel	0.38	3.02	9700	970	80	6
17% Co Steel	0.69	5.49	10700	1070	160	13
38% Co Steel	0.98	7.79	10400	1040	230	18
Ceramic 2	1.80	14.30	2900	290	2400/3000	191/239
Ceramic 6	2.45	19.50	3200	320	2820/3300	224/263
Alnico4	1.35	10.70	5600	560	720	57
PtCo	9.00	71.60	6450	645	4000	318
Vicalloy 1	0.80	6.36	7500	750	250	20
Remalloy	1.00	7.95	9700	970	250	20
Cunife1	1.40	11.10	5500	550	530	42
MnAIC	5.00	39.80	5450	545	2550/3150	202/251
RE Cobalt 5/16	5.00	39.80	4700	470	4500/16000	358/1273
RE Cobalt 14/14	14.00	111.30	7500	750	700/14000	56/1114

APPENDIX B
GLOSSARY OF TERM

A_g Area of the air gap, or the cross sectional area of the air gap perpendicular to the flux path, is the average cross sectional area of that portion of the air gap within which the application interaction occurs. Area is measured in sq. cm. in a plane normal to the central flux line of the air gap.

A_m Area of the magnet, is the cross sectional area of the magnet perpendicular to the central flux line, measured in sq. cm. at any point along its length. In design, A_m is usually considered the area at the neutral section of the magnet.

B Magnetic induction, is the magnetic field induced by a field strength, H, at a given point. It is the vector sum, at each point within the substance, of the magnetic field strength and resultant intrinsic induction. Magnetic induction is the flux per unit area normal to the direction of the magnetic path.

B_d Remanent induction, is any magnetic induction that remains in a magnetic material after removal of an applied saturating magnetic field, Hs. (B_d is the magnetic induction at any point on the demagnetization curve; measured in gauss.)

B_d/H_d Slope of the operating line, is the ratio of the remanent induction, B_d, to a demagnetizing force, H_d. It is also referred to as the permeance coefficient, shear line, load line and unit permeance.

B_dH_d Energy product, indicates the energy that a magnetic material can supply to an external magnetic circuit when operating at any point on its demagnetization curve; measured in megagauss-oersteds.

$(BH)_{max}$ Maximum energy product, is the maximum product of (B_dH_d) which can be obtained on the demagnetization curve.

B_{is} (or J) Saturation intrinsic induction, is the maximum intrinsic induction possible in a material.

B_g Magnetic induction in the air gap, is the average value of magnetic induction over the area of the air gap, A_g; or it is the magnetic induction measured at a specific point within the air gap; measured in gauss.

Bi (or J) Intrinsic induction, is the contribution of the magnetic material to the total magnetic induction, B. It is the vector difference between the magnetic induction in the material and the magnetic induction that would exist in a vacuum under the same field strength, H. This relation is expressed by the equation:

$$B_i = B - H$$

where: B_i = intrinsic induction in gauss; B = magnetic induction in gauss; H = field strength in oersteds.

B_m Recoil induction, is the magnetic induction that remains in a magnetic material after magnetizing and conditioning for final use; measured in gauss.

B_o Magnetic induction, at the point of the maxi-mum energy product $(BH)_{max}$; measured in gauss.

B_r Residual induction (or flux density), is the magnetic induction corresponding to zero magnetizing force in a magnetic material after saturation in a closed circuit; measured in gauss.

f Reluctance factor, accounts for the apparent magnetic circuit reluctance. This factor is required due to the treatment of H_m and H_g as constants.

F Leakage factor, accounts for flux leakage from the magnetic circuit. It is the ratio between the magnetic flux at the magnet neutral section and the average flux present in the air gap. $F = (B_m A_m)/(B A_g)$.

F Magnetomotive force, (magnetic potential difference), is the line integral of the field strength, H, between any two points, p_1 and p_2.

$$F = \int_{p_1}^{p_2} H\,dl$$

F = magnetomotive force in gilberts
H = field strength in oersteds
dl = an element of length between the two points, in centimeters.

H Magnetic field strength, (magnetizing or demagnetizing force), is the measure of the vector magnetic quantity that determines the ability of an electric current, or a magnetic body, to induce a magnetic field at a given point; measured in oersteds.

H_c Coercive force of a material, is equal to the de magnetizing force required to reduce residual induction, Br, to zero in a magnetic field after magnetizing to saturation; measured in oersteds.

H_{ci} Intrinsic coercive force of a material indicates its resistance to demagnetization. It is equal to the demagnetizing force which reduces the intrinsic induction, Bi, in the material to zero after magnetizing to saturation; measured in oersteds.

H_d is that value of H corresponding to the remanent induction, B_d; measured in oersteds.

H_m is that value of H corresponding to the recoil induction, B_m; measured in oersteds.

H_O is the magnetic field strength at the point of the maximum energy product $(BH)_{max}$; measured in oersteds.

H_s Net effective magnetizing force, is the magnetizing force required in the material, to magnetize to saturation measured in oersteds.

J, see B; Intrinsic induction.

J_s, see Bis Saturation intrinsic induction.

ℓg Length of the air gap, is the length of the path of the central flux line of the air gap; measured in centimeters.

ℓm Length of the magnet, is the total length of magnet material traversed in one complete revolution of the center- line of the magnetic circuit; measured in centimeters.

ℓm/D Dimension ratio, is the ratio of the length of a magnet to its diameter, or the diameter of a circle of equivalent cross-sectional area. For simple geometries, such as bars and rods, the dimension ratio is related to the slope of the operating line of the magnet, B_d/H_a.

***P* Permeance,** is the reciprocal of the reluctance, R, measured in maxwells per gilbert.

R **Reluctance,** is somewhat analogous to electrical resistance. It is the quantity that determines the magnetic flux, ø, resulting from a given magnetomotive force, *F*.

where: $R = F/ø$

R = reluctance, in gilberts per maxwell
F = magnetomotive force, in gilberts
ø = flux, in maxwells

T_c **Curie temperature,** is the transition temperature above which a material loses its magnet properties.

T_{max} **Maximum service temperature,** is the maximum temperature to which the magnet may be exposed with no significant long range instability or structural changes.

V_g **Air gap volume,** is the useful volume of air or non-magnetic material between magnetic poles; measured in cubic centimeters.

μ **permeability,** is the general term used to express various relationships between magnetic induction, B, and the field strength, H.

μ_{re} **recoil permeability,** is the average slope of the recoil hysteresis loop. Also known as a minor loop.

ø **magnetic flux,** is a contrived but measurable concept that has evolved in an attempt to describe the "flow" of a magnetic field. Mathematically, it is the surface integral of the normal component of the magnetic induction, B, over an area, A.

$$ø = \int\int B \cdot dA$$

where:
ø = magnetic flux, in maxwells
B = magnetic induction, in gauss
dA = an element of area, in square centimeters

When the magnetic induction, B, is uniformly distributed and is normal to the area, A, the flux, ø = BA.

A closed circuit condition exists when the external flux path of a permanent magnet is confined with high permeability material.

The demagnetization curve is the second (or fourth) quadrant of a major hysteresis loop. Points on this curve are designated by the coordinates B_d and H_d.

A fluxmeter is an instrument that measures the change of flux linkage with a search coil.

The gauss is the unit of magnetic induction, B, in the cgs electromagnetic system. One gauss is equal to one maxwell per square centimeter.

A gaussmeter is an instrument that measures the instantaneous value of magnetic induction, B. Its principle of operation is usually based on one of the following: the Hall-effect, nuclear magnetic resonance (NMR), or the rotating coil principle.

The gilbert is the unit of magnetomotive force, *F,* in the cgs electromagnetic system.

A hysteresis loop is a closed curve obtained for a material by plotting (usually to rectangular coordinates) corresponding values of magnetic induction, B, for ordinates and magnetizing force, H, for abscissa when the material is passing through a complete cycle between definite limits of either magnetizing force, H, or magnetic induction, B.

Irreversible losses are defined as partial demagnetization of the magnet, caused by exposure to high or low temperatures external fields or other factors. These losses are recoverable by remagnetization. Magnets can be stabilized against irreversible losses by partial demagnetization induced by temperature cycles or by external magnetic fields

A keeper is a piece (or pieces) of soft iron that is placed on or between the pole faces of a permanent magnet to decrease the reluctance of the air gap and thereby reduce the flux leakage from the magnet. It also makes the magnet less susceptible to demagnetizing influences.

Leakage flux is flux, ø, whose path is outside the useful or intended magnetic circuit: measured in maxwells.

The major hysteresis loop of a material is the closed loop obtained when the material is cycled between positive and negative saturation.

The maxwell is the unit of magnetic flux in the cgs electromagnetic system. One maxwell is one line of magnetic flux.

The neutral section of a permanent magnet is defined by a plane passing through the magnet perpendicular to its central flux line at the point of maximum flux.

The oersted is the unit of magnetic field strength, H, in the cgs electromagnetic system. One oersted equals a magnetomotive force of one gilbert per centimeter of flux path.

An open circuit condition exists when a magnetized magnet is by itself with no external flux path of high permeability material.

The operating line for a given permanent magnet circuit is a straight line passing through the origin of the demagnetization curve with a slope of negative B_d/H_d. (Also known as permeance coefficient line.)

The operating point of a permanent magnet is that point on a demagnetization curve defined by the coordinates (B_dH_d) or that point within the demagnetization curve defined by the coordinates (B_mH_m).

An oriented (anisotropic) material is one that has better magnetic properties in a given direction.

A permeameter is an instrument that can measure, and often record, the magnetic characteristics of a specimen.

Reversible temperature coefficients are changes in flux which occur with temperature change. These are spontaneously regained when the temperature is returned to its original point.

Magnetic saturation of a material exists when an increase in magnetizing force produces no increase in intrinsic induction.

A search coil is a coiled conductor, usually of known area and number of turns, that is used with a fluxmeter to measure the change of flux linkage with the coil.

The temperature coefficient is a factor which describes the reversible change in a magnetic property with a change in temperature. The magnetic property spontaneously returns when the temperature is cycled to its original point. It usually is expressed as the percentage change per unit of temperature.

An unoriented (isotropic) material has equal magnetic properties in all directions.

APPENDIX C
MAGNETIC QUANTITIES
SYMBOLS, UNITS AND CONVERSION FACTORS

Quantity	Symbol	CGS Unit	Conversion* Factors	SI Unit
MAGNETIC FLUX	ø	Maxwell	10^{-8}	weber
MAGNETIC INDUCTION (magnetic flux density)	B	Gauss	10^{-4}	tesla
MAGNETO MOTIVE FORCE (magnetic potential difference)	F	Gilbert (oersted-cm)	$\frac{10}{4\pi}$	ampere-turn
MAGNETIC FIELD STRENGTH (magnetizing or demagnetizing force)	H	Oersted	$\frac{10^3}{4\pi}$	ampere/meter
ENERGY PRODUCT	B_dH_d	megagauss-oersted	$\frac{10^5}{4\pi}$	joule/meter^3

*Multiply quantity in CGS units by the conversion factor to obtain quantity in SI units

THH