Designation: A1101 – 16

Standard Specification for Sintered and Fully Dense Neodymium Iron Boron (NdFeB) Permanent Magnets[1]

This standard is issued under the fixed designation A1101; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This specification covers technically important, commercially available, magnetically hard sintered and fully dense neodymium iron boron ($Nd_2Fe_{14}B$, NdFeB, or "Neo") permanent magnets. These materials are available in a wide range of compositions with a commensurately large range of magnetic properties. The numbers in the $Nd_2Fe_{14}B$ name indicate the approximate atomic ratio of the key elements.

1.2 Neodymium iron boron magnets have approximate magnetic properties of residual magnetic induction, B_r, from 1.08 T (10 800 G) up to 1.5 T (15 000 G) and intrinsic coercive field strength, H_{cJ}, of 875 kA/m (11 000 Oe) to above 2785 kA/m (35 000 Oe). Special grades and isotropic (un-aligned) magnets can have properties outside these ranges (see Appendix X4). Specific magnetic hysteresis behavior (demagnetization curve) can be characterized using Test Method A977/A977M.

1.3 The values stated in SI units are to be regarded as standard. The values given in parentheses are mathematical conversions to customary (cgs-emu and inch-pound) units which are provided for information only and are not considered standard.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

A340 Terminology of Symbols and Definitions Relating to Magnetic Testing

A977/A977M Test Method for Magnetic Properties of High-Coercivity Permanent Magnet Materials Using Hysteresigraphs

2.2 *Other Standards:*

MMPA Standard No. 0100-00 Standard Specifications for Permanent Magnet Materials[3]

IEC 60404-8-1 Magnetic Materials Part 8: Specifications for Individual Materials Section 1 – Standard Specifications for Magnetically Hard Materials[4]

3. Terminology

3.1 The terms and symbols used in this specification, unless otherwise noted, are defined in Terminology A340.

3.2 Terms that are not defined in Terminology A340 but are in common usage and used herein are as follows.

3.2.1 Recoil permeability, $\mu_{(rec)}$, is the permeability corresponding to the slope of the recoil line. For reference see incremental, relative, and reversible permeabilities as defined in Terminology A340. In practical use, this is the slope of the normal hysteresis loop in the second quadrant and in proximity to the B-axis. The value of recoil permeability is dimensionless. Note that in producers' product literature recoil permeability is sometimes represented by the symbol μ_r, which is defined by Terminology A340 as relative permeability.

3.2.2 Magnetic characteristics change with temperature. Two key metrics of permanent magnet performance are residual induction, B_r, and intrinsic coercive field strength, H_{cJ}. The change in these characteristics over a defined and limited temperature range can be reversible, that is, nondestructive. This change is represented by values called reversible temperature coefficients. The symbol for reversible temperature coefficient of induction is $\alpha(B_r)$ and of (intrinsic) coercivity is $\alpha(H_{cJ})$. They are expressed in percent change per degree Celsius, %/°C, or the numerically equivalent percent per Kelvin, %/K, and represent the average rate of change of the

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Available from the Permanent Magnet Division of the SMMA (www.smma.org). It was previously available from The International Magnetics Association (IMA). The IMA had been the successor to the MMPA and both organizations (MMPA and IMA) no longer exist.

[4] Available from International Electrotechnical Commission (IEC), 3, rue de Varembé, 1st Floor, P.O. Box 131, CH-1211, Geneva 20, Switzerland, http://www.iec.ch.

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characteristic within the specified temperature range. The change in magnetic characteristics is nonlinear, so it is necessary to specify the temperature range over which the coefficient applies.

3.2.3 The maximum recommended working temperature of a permanent magnet, T_w, is a semi-arbitrary value sometimes assigned by magnet manufacturers to their products. T_w is not normative. See Appendix X6 for a more complete discussion.

4. Classification

4.1 The classification of neodymium iron boron permanent magnets is given in Table 1. Cross-reference to MMPA standard No. 0100-00 and IEC 60404-8-1 is provided in Appendix X1.

5. Ordering Information

5.1 Orders for parts conforming to this specification shall include the following information:

5.1.1 Reference to this specification and year of issue/revision.

5.1.2 Reference to an applicable part drawing.

5.1.3 Magnetic property requirements, if they are more stringent than the minimum values listed in the tables.

5.1.4 Quantity required.

5.1.5 The required magnetization state of the provided material (unmagnetized, fully magnetized, magnetized and thermally stabilized, magnetized and then partially demagnetized). This information should appear on the part drawing whenever possible.

5.1.6 Certification of magnetic property evaluation.

5.1.7 Marking and packaging requirements.

5.1.8 Exceptions to this specification or special requirements such as plating, coating, or functional testing as mutually agreed upon by the producer and user.

6. Chemical Composition

6.1 Neodymium iron boron magnets should be specified primarily by magnetic performance. Chemical composition can have an influence on both magnetic and physical characteristics but should only be specified when other options are insufficient to meet user requirements. Agreement on composition must be mutually arrived at by producer and user.

6.2 The general chemical composition of neodymium iron boron includes the elements neodymium, iron, and boron. Approximate chemical compositions are listed in Table X3.1 and are typical but not mandatory.

6.3 There are a number of additional elements included in the alloy to adjust magnetic, chemical, or mechanical properties. See Appendix X3 for additional information.

7. Physical and Mechanical Properties

7.1 Typical thermal and physical properties are listed in Table X2.1 in Appendix X2.

7.2 Physical density values are given for information purposes only and are not mandatory.

7.3 Neodymium iron boron magnets are used for their magnetic characteristics. The end-use application should not rely on them for structural purposes due to low tensile and flexural strength. These materials are brittle, and can chip or break easily. Magnetic properties may also be affected by physical stress.

7.4 Strength testing of brittle materials such as neodymium iron boron is difficult, expensive, time-consuming, and there may be considerable scatter in the measured values. Producers typically make a complete set of measurements at the onset of production and they are seldom repeated.

8. Magnetic Property Requirements

8.1 Magnetic properties are listed in Table 1.

8.2 The values of magnetic properties listed in the table are specified minimum values at 20 ± 2 °C (68 ± 4 °F), determined after magnetizing to saturation in closed magnetic circuit.

8.3 The specified values of magnetic properties are valid only for magnet test specimens with a uniform cross-section along the axis of magnetization. Properties for anisotropic (magnetically oriented) magnets are measured along the axis of preferred orientation.

8.4 Because of the nature of permanent magnet production, magnetic testing of each lot is recommended, especially for applications where the magnet performance is closely specified. Such magnetic property evaluations shall be conducted in the manner described below. Where the magnet shape is not suitable for magnetic testing, a specimen shall be cut from the magnet using appropriate slicing and grinding techniques, paying attention to any magnetic orientation within the magnet.

8.4.1 The magnetic properties shall be determined in accordance with Test Method A977/A977M, or by using a suitable, mutually agreed upon magnetometric method.

8.4.2 When magnets are being purchased in the fully magnetized condition, the testing shall determine the magnetic properties from the as-received magnetization state, followed by magnetization to saturation and testing of the magnetic properties from the fully magnetized condition.

8.4.3 When magnets are being purchased in the unmagnetized condition or in an unknown state of magnetization, the test laboratory shall magnetize the test specimen(s) to saturation in the same orientation as the received specimen's indicated direction of magnetization and measure the magnetic properties from this fully magnetized condition.

8.4.4 When magnets are being purchased in a calibrated, stabilized, or "knocked-down" condition, magnets should be handled with care to prevent exposure to externally applied fields. Refer to Appendix X6 for an explanation of these terms. During testing using Test Method A977/A977M, the measurement should proceed in the second quadrant only, without attempting to saturate the magnet specimen, to avoid changing the magnetization state of the material prior to test.

8.4.5 Other test methods may be utilized as agreed to between producer and user. Such tests may include the open circuit magnetization Helmholtz test, field strength measurements in a defined magnetic circuit or adjacent to the magnet surface.

TABLE 1 Neodymium Iron Boron Permanent Magnets: Classification and Minimum Magnetic Property[A] Requirements

ASTM Designation[B]	Maximum Energy Product $(BH)_{max}$ kJ/m^3 (MGOe)	Residual Induction B_r mT (G)	Coercive Field Strength H_{cB} kA/m (Oe)	Intrinsic Coercive Field Strength H_{cJ} kA/m (Oe)
		ANISOTROPIC $Nd_2Fe_{14}B$		
ND-SA-333/875	333 (41.8)	1325 (13250)	832 (10450)	875 (11000)
ND-SA-355/875	355 (44.6)	1369 (13690)	832 (10450)	875 (11000)
ND-SA-370/875	370 (46.5)	1397 (13970)	832 (10450)	875 (11000)
ND-SA-385/875	385 (48.4)	1426 (14260)	832 (10450)	875 (11000)
ND-SA-407/875	407 (51.1)	1465 (14650)	832 (10450)	875 (11000)
ND-SA-222/955	222 (27.9)	1082 (10820)	820 (10300)	955 (12000)
ND-SA-244/955	244 (30.7)	1136 (11360)	861 (10820)	955 (12000)
ND-SA-259/955	259 (32.5)	1168 (11680)	907 (11400)	955 (12000)
ND-SA-281/955	281 (35.3)	1218 (12180)	907 (11400)	955 (12000)
ND-SA-296/955	296 (37.2)	1250 (12500)	907 (11400)	955 (12000)
ND-SA-311/955	311 (39.1)	1281 (12810)	907 (11400)	955 (12000)
ND-SA-333/955	333 (41.8)	1325 (13250)	907 (11400)	955 (12000)
ND-SA-355/955	355 (44.6)	1369 (13690)	907 (11400)	955 (12000)
ND-SA-370/955	370 (46.5)	1397 (13970)	907 (11400)	955 (12000)
ND-SA-385/955	385 (48.4)	1426 (14260)	907 (11400)	955 (12000)
ND-SA-222/1114	222 (27.9)	1082 (10820)	820 (10300)	1114 (14000)
ND-SA-244/1114	244 (30.7)	1136 (11360)	861 (10820)	1114 (14000)
ND-SA-259/1114	259 (32.5)	1168 (11680)	885 (11120)	1114 (14000)
ND-SA-281/1114	281 (35.3)	1218 (12180)	923 (11600)	1114 (14000)
ND-SA-296/1114	296 (37.2)	1250 (12500)	947 (11900)	1114 (14000)
ND-SA-311/1114	311 (39.1)	1281 (12810)	971 (12200)	1114 (14000)
ND-SA-333/1114	333 (41.8)	1325 (13250)	1004 (12620)	1114 (14000)
ND-SA-355/1114	355 (44.6)	1369 (13690)	1058 (13300)	1114 (14000)
ND-SA-370/1114	370 (46.5)	1397 (13970)	1058 (13300)	1114 (14000)
ND-SA-385/1114	385 (48.4)	1426 (14260)	1058 (13300)	1114 (14000)
ND-SA-207/1353	207 (26.0)	1045 (10450)	792 (9950)	1353 (17000)
ND-SA-222/1353	222 (27.9)	1082 (10820)	820 (10300)	1353 (17000)
ND-SA-244/1353	244 (30.7)	1136 (11360)	861 (10820)	1353 (17000)
ND-SA-259/1353	259 (32.5)	1168 (11680)	885 (11120)	1353 (17000)
ND-SA-281/1353	281 (35.3)	1218 (12180)	923 (11600)	1353 (17000)
ND-SA-296/1353	296 (37.2)	1250 (12500)	947 (11900)	1353 (17000)
ND-SA-311/1353	311 (39.1)	1281 (12810)	971 (12200)	1353 (17000)
ND-SA-333/1353	333 (41.8)	1325 (13250)	1004 (12620)	1353 (17000)
ND-SA-355/1353	355 (44.6)	1369 (13690)	1038 (13040)	1353 (17000)
ND-SA-370/1353	370 (46.5)	1397 (13970)	1058 (13300)	1353 (17000)
ND-SA-207/1592	207 (26.0)	1045 (10450)	792 (9950)	1592 (20000)
ND-SA-222/1592	222 (27.9)	1082 (10820)	820 (10300)	1592 (20000)
ND-SA-244/1592	244 (30.7)	1136 (11360)	861 (10820)	1592 (20000)
ND-SA-259/1592	259 (32.5)	1168 (11680)	885 (11120)	1592 (20000)
ND-SA-281/1592	281 (35.3)	1218 (12180)	923 (11600)	1592 (20000)
ND-SA-296/1592	296 (37.2)	1250 (12500)	947 (11900)	1592 (20000)
ND-SA-311/1592	311 (39.1)	1281 (12810)	971 (12200)	1592 (20000)
ND-SA-333/1592	333 (41.8)	1325 (13250)	1004 (12620)	1592 (20000)
ND-SA-355/1592	355 (44.6)	1369 (13690)	1038 (13040)	1592 (20000)
ND-SA-207/1989	207 (26.0)	1045 (10450)	792 (9950)	1989 (25000)
ND-SA-222/1989	222 (27.9)	1082 (10820)	820 (10300)	1989 (25000)
ND-SA-244/1989	244 (30.7)	1136 (11360)	861 (10820)	1989 (25000)
ND-SA-259/1989	259 (32.5)	1168 (11680)	885 (11120)	1989 (25000)
ND-SA-281/1989	281 (35.3)	1218 (12180)	923 (11600)	1989 (25000)
ND-SA-296/1989	296 (37.2)	1250 (12500)	947 (11900)	1989 (25000)
ND-SA-311/1989	311 (39.1)	1281 (12810)	971 (12200)	1989 (25000)
ND-SA-333/1989	333 (41.8)	1325 (13250)	1004 (12620)	1989 (25000)
ND-SA-207/2387	207 (26.0)	1045 (10450)	792 (9950)	2387 (30000)
ND-SA-222/2387	222 (27.9)	1082 (10820)	820 (10300)	2387 (30000)
ND-SA-244/2387	244 (30.7)	1136 (11360)	861 (10820)	2387 (30000)
ND-SA-259/2387	259 (32.5)	1168 (11680)	885 (11120)	2387 (30000)
ND-SA-281/2387	281 (35.3)	1218 (12180)	923 (11600)	2387 (30000)
ND-SA-207/2785	207 (26.0)	1045 (10450)	792 (9950)	2785 (35000)
ND-SA-222/2785	222 (27.9)	1082 (10820)	820 (10300)	2785 (35000)
ND-SA-244/2785	244 (30.7)	1136 (11360)	861 (10820)	2785 (35000)

[A]Magnetic properties at 20 °C (68 °F).
[B]The ASTM designation conforms to the requirements of this specification. ASTM Designations are of the form *MM-TT-XX/YY* where:

MM = material (ND = neodymium iron boron),
TT = type of processing and orientation (S = sintered; I = isotropic (non-oriented), A = anisotropic (oriented)),
XX = energy product in kJ/m^3 rounded to the nearest integer, and
YY = intrinsic coercivity in kA/m rounded to the nearest integer.

9. Workmanship, Finish, and Appearance

9.1 Dimensions and tolerances shall be as specified on the magnet drawing and must be agreed upon between the producer and the user.

9.2 Though porosity and voids are uncommon in Neodymium iron boron magnets, their appearance shall not in themselves constitute reason for rejection unless agreed upon between producer and user. Allowable amounts of porosity and voids shall be documented in writing and included as part of the ordering or contracting process.

9.3 Magnets shall be free of adhered magnetic particles and surface residue which may interfere with assembly or proper device function.

9.4 Chips shall be acceptable if no more than 10 % of any surface identified as a magnetic pole surface is removed.

9.5 Cracks visible to the naked eye shall not be permitted unless otherwise agreed to by producer and user.

10. Sampling

10.1 A lot shall consist of parts of the same form and dimensions, produced from a single mixed powder batch or sintering run, and from an unchanged process, without discontinuity in production, and submitted for inspection at one time.

10.2 The producer and user shall agree upon a representative number of specimens for testing. Typically, a suitable number of parts, as mutually agreed upon between producer and user, shall be randomly selected from each lot. It is advisable to test a minimum of two parts from each lot, and more if there is reason to suspect that the magnetic properties are not uniform throughout the lot.

11. Rejection and Rehearing

11.1 Parts that fail to conform to the requirements of this specification shall be rejected. Rejection should be reported to the producer promptly and in writing. In case of dissatisfaction with the results of the test, the producer may make a claim for a rehearing.

11.2 The disposition of rejected parts shall be subject to agreement between the producer and user.

12. Certification

12.1 When specified in the purchase order or contract, the user shall be furnished certification that samples representing each lot have been either tested or inspected as directed in this specification and that the requirements have been met.

12.2 When specified in the purchase order or contract, a report of the test results shall, at a minimum, include:

12.2.1 Grade of material.

12.2.2 Lot or batch number.

12.2.3 Magnetic test results.

12.2.4 Results of any other tests stipulated in the purchase order or contract.

13. Packaging and Package Marking

13.1 Packaging shall be subject to agreement between the producer and the user.

13.2 Parts furnished under this specification shall be in a container identified by the name or symbol of the parts producer.

13.3 Magnetized parts shall be properly labeled as such for safe handling and shipping purposes.

13.3.1 Magnetized parts to be shipped via aircraft must be packaged in an appropriate manner to meet applicable requirements for air shipment. These requirements may vary depending upon local, national, and international laws. It is the responsibility of the producer to ensure packaging meets all relevant regulations. This may require rearranging the parts within the shipping container, adding sheets of steel or other magnetically soft shielding material, or both, or other specialized packaging procedures as determined by regulation, carrier policy, or by agreement between producer and user, to reduce the magnetic field external to the shipping container below the required levels.

14. Keywords

14.1 coercive field strength; magnetic field strength; magnetic flux density; magnetic properties; maximum energy product; neodymium iron boron magnet; neo magnet; permanent magnet; residual induction; sintered rare earth magnet

APPENDIXES

(Nonmandatory Information)

X1. CLASSIFICATION

X1.1 See Table X1.1.

TABLE X1.1 Neodymium Iron Boron Permanent Magnets: Classification and Grade Cross Reference

NOTE 1—"..." indicates that there is no known published data.

ASTM	MMPA	IEC	
ASTM Designation[A]	MMPA Brief Designation	IEC Brief Designation	IEC Code Number
(none)	...	REFeB 170/190	R7-1-1
ND-SA-207/1592	...	REFeB 210/130	R7-1-2
ND-SA-244/1114	...	REFeB 250/120	R7-1-3
ND-SA-281/955	...	REFeB 290/80	R7-1-4
ND-SA-207/1592	...	REFeB 200/190	R7-1-5
ND-SA-244/1592	...	REFeB 240/180	R7-1-6
ND-SA-281/1114	...	REFeB 280/120	R7-1-7
ND-SA-311/955	...	REFeB 320/88	R7-1-8
ND-SA-207/2387	...	REFeB 210/240	R7-1-9
ND-SA-244/1592	...	REFeB 240/200	R7-1-10
ND-SA-311/1353	...	REFeB 310/130	R7-1-11
ND-SA-259/2387	...	REFeB 250/240	R7-1-12
ND-SA-259/1989	...	REFeB 260/200	R7-1-13
ND-SA-355/1592	...	REFeB 340/130	R7-1-14
ND-SA-370/875	...	REFeB 360/90	R7-1-15
ND-SA-370/1114	...	REFeB 380/100	R7-1-16
(none)	24/41	...	...
ND-SA-207/2387	26/32	...	...
ND-SA-207/1592	28/23	...	...
ND-SA-207/2387	28/32	...	...
ND-SA-222/1592	30/19	...	...
ND-SA-222/1989	30/27	...	...
ND-SA-244/1353	32/16	...	...
ND-SA-244/2387	32/31	...	...
ND-SA-259/1592	34/22	...	...
ND-SA-281/1592	36/19	...	...
ND-SA-281/1989	36/26	...	...
ND-SA-281/1353	38/15	...	...
ND-SA-281/1989	38/23	...	...
ND-SA-296/1353	40/15	...	...
ND-SA-296/1989	40/23	...	...
ND-SA-311/1353	42/15	...	...
ND-SA-333/1353	44/15	...	...
ND-SA-355/1592	48/11	...	...
ND-SA-370/955	50/11	...	...

[A] The ASTM designation conforms to the requirements of this specification. The ASTM cross-referenced grades are the closest approximation of the MMPA and IEC grades where they exist. MMPA and IEC designations are included for reference only. ASTM Designations are of the form *MM-TT-XX/YY* where:

MM = material (ND = neodymium iron boron),
TT = type of processing and orientation (S = sintered; I = isotropic (non-oriented), A = anisotropic (oriented)),
XX = energy product in kJ/m^3 rounded to the nearest integer, and
YY = intrinsic coercivity in kA/m rounded to the nearest integer.

X2. TYPICAL THERMAL, ELECTRICAL, AND MECHANICAL PROPERTIES

X2.1 See Table X2.1.

TABLE X2.1 Neodymium Iron Boron Permanent Magnets: Typical Thermal, Electrical, and Mechanical Properties[A]

Property	Symbol	Orient.[B]	Units	$Nd_2Fe_{14}B$
THERMAL, ELECTRICAL, AND MISCELLANEOUS PROPERTIES				
Recoil Permeability[C]	$\mu_{(rec)}$		(None)	1.035 to 1.060
Reversible Temperature Coefficient of Induction (B_r)[D]	α (B_r)		%/°C	–0.09 to –0.12
Reversible Temperature Coefficient of Coercivity (H_{cJ})[D]	α (H_{cJ})		%/°C	–0.43 to –0.63
Coefficient of Thermal Expansion[E]		//	10^{-6} /°C	4 to 9
		⊥	10^{-6} /°C	–2 to 0
Curie Temperature	T_c		°C	310 to 350
Maximum Recommended Working Temperature[F]	T_w		°C	80 to 230
Specific Heat	*C*		J/(kg•K)	350 to 550
Thermal Conductivity	*k*		W/(m•K)	5 to 15
Resistivity	ρ		$10^{-6}\Omega$•m	1.2 to 1.6
PHYSICAL AND MECHANICAL PROPERTIES				
Density			g/cm^3	7.5 to 7.8
Tensile Strength (Ultimate Tensile Strength)			MPa	30 to 41
Bending (Flexural) Strength			MPa	150 to 400
Compressive Strength			MPa	600 to 1200
Young's Modulus (Modulus of Elasticity)	*E*		GPa	140 to 170
Hardness (Vicker's Hardness)			Hv	500 to 700

[A]Thermal properties are moderately variable from one producer to another. These are typical values and should be confirmed with the producer. Mechanical property testing of brittle materials is difficult and is rarely performed. The values in this table should be considered typical.
[B]Orientation is either parallel (axial, //) or perpendicular (transverse, ⊥) to the easy axis of magnetization (the direction of magnetization within the magnet). Several properties are dependent upon this direction and are measured in both orientations. Other measurements may not be affected by direction of magnetization and are reported in one, usually unspecified axis.
[C]Recoil permeability is nonmandatory and approximate. Values presented here are based upon manufacturer information and IEC 60404-8-1. In the CGS system, recoil permeability is without units though often interpreted to be Gauss/Oersted. Recoil permeability, $\mu_{(rec)}$, is sometimes called relative permeability or relative recoil permeability. Refer to Terminology A340 for further explanation.
[D]Temperature coefficients represent the average rate of change in magnetic property as a function of change in temperature. The values shown here are approximate for the temperature range of 20 to 150 °C (68 to 302 °F). Neodymium iron boron magnets are often used at temperatures other than 150 °C (302 °F) and the reader is advised to refer to producer specifications for performance at these temperatures.
[E]Values of the coefficient of thermal expansion is from 20 to 120 °C (68 to 248 °F).
[F]T_w = Maximum recommended working temperature as determined and published by neodymium iron boron magnet manufacturers. See Appendix X6 for additional information.

X3. COMPOSITIONS OF NEODYMIUM-BORON-IRON

X3.1 The entire family of neodymium iron boron magnets is often referred to as NdFeB or "Neo" magnets. Neo magnets were first discovered by Norman Koon at the U.S. Naval Research Laboratories in 1980 and rapidly optimized and commercialized by Sumitomo (led by Musato Sagawa) and General Motors (led by John Croat). The first commercial sale was reported by Crucible Magnetics, Elizabethtown, Kentucky, in November 1984. Neo was so superior in magnetic strength and lower in cost than alternative high strength permanent magnet materials that it rapidly expanded into use in hard disk drives, industrial motors and numerous other applications. Neodymium iron boron formulations are named using formulas such as the following ones where the subscripted numbers represent the approximate atomic ratio:

NdFeB
$Nd_2Fe_{14}B$
$(Nd,Pr,Dy)_2$ $(Fe,Co)_{14}$ B

X3.2 Substitution by praseodymium for a portion of the neodymium increases the potential quantity of magnets which can be produced from available stocks of rare earth raw materials. Magnetic properties (residual induction and energy product) are diminished slightly so the very highest grades may use little or no praseodymium. For use at cryogenic temperatures, praseodymium is substituted for 80 % or more of the neodymium to avoid a spin reorientation that occurs at 135 K when only neodymium is used. High praseodymium grades are specialty products and not included in this specification except for informational purposes.

X3.3 Dysprosium (or terbium, or both) is substituted for some of the neodymium to increase the anisotropy field (increase intrinsic coercivity) permitting magnets to be used at higher temperatures. The presence of dysprosium also reduces the rate at which intrinsic coercivity is diminished as a function of rising temperature, that is, the Reversible Temperature Coefficient of Coercivity, $\alpha(H_{cJ})$, is reduced. Metallurgically speaking, praseodymium and dysprosium are substitutional to the neodymium in the alloy.

X3.4 Cobalt is also frequently added to Neo magnet formulations to raise the Curie temperature. This has the effect of reducing the Reversible Temperature Coefficient of Induction, $\alpha(B_r)$, producing less loss of magnetic field strength as a function of temperature rise. The fraction of cobalt added is kept low as it has a depressing effect on energy product in sintered Neo magnets and it is more expensive than iron. Cobalt is substitutional to iron.

X3.5 Other common additions include aluminum, gallium, copper, and niobium. These are used primarily to modify the grain boundary of the magnet structure or introduce domain wall pinning precipitates within the NdFeB crystal structure. Benefits of these materials are both magnetic and physical, with one important enhancement being improved corrosion resistance.

TABLE X3.1 Neodymium Iron Boron Permanent Magnet Typical Composition Range

Element	Weight %	Comments
Nd	11 to 33	Special grades with reduced Nd content have been produced by melt spinning. Standard sintered grades of Neo magnets require adequate rare earth content for liquid phase sintering, thus TRE (total rare earth) is in the range shown herein. Neodymium makes up the balance of what is not supplied by other rare earth content.
Pr	0 to 7	Pr can totally replace Nd, however, magnetic properties are reduced. A practical limit for addition is approximately 7 weight percent except in the higher energy product grades where the use of Pr is minimized.
Dy (or Tb)	0 to 11	Dysprosium (or terbium, or both) is substituted for neodymium to increase intrinsic coercivity, H_{cJ}. H_{cJ} is a measure of a magnet's resistance to demagnetization. Therefore higher Dy permits Neo magnets to be used at higher temperature and in the presence of demagnetizing fields.
TRE (Total Rare Earth)	30 to 33	Standard grades manufactured by a powder metallurgy process require between 30 and 33 weight percent rare earth to permit liquid phase sintering and to coat each grain creating maximum magnetic properties.
Fe	Balance	High iron content is what provides such high energy product. Fe content is usually expressed as the "balance" of the composition after all other content is added up and it is generally in the range of 61 to 67 weight percent.
Co	0 to 5	High temperature grades are achieved, in part, by raising the Curie temperature through cobalt additions. The presence of cobalt reduces the reversible temperature coefficient of induction.
B	0.85 to 1.20	Boron is the key to obtaining the tetragonal crystal structure of Neo magnets. Its content is varied within narrow limits based on the remainder of the formulation and is most often found to be ~1.05 % by weight.
Al	<0.3	Grain boundary modifier.
Cu	<0.5	Grain boundary modifier.
Ga	<0.5	Grain boundary modifier.
Nb	<1.0	Nb forms precipitates which lock domain walls and improve high temperature performance (resistance to demagnetization). Other elements that have been evaluated to achieve similar results include vanadium, titanium, and zirconium.

X4. EXPLANATION OF GRADES OF NEODYMIUM IRON BORON

X4.1 Temperature Stable Grades

X4.1.1 These are nonstandard grades. Substitution of a portion of the neodymium by yttrium or gadolinium results in a more temperature-stable material. That is, the B_r (and magnetic field output) of the magnet does not change as rapidly with changes in temperature as for the standard grades. The trade-off is that room temperature B_r and energy product are reduced from the standard grades. Neo magnets are not often used where high temperature stability is required and since yttrium and gadolinium are generally more expensive than neodymium, these formulations are rarely specified or used. When temperature stability is required, samarium cobalt or Alnico magnets are usually specified.

X4.2 High Temperature and High Energy Product Grades

X4.2.1 Early in the discovery and use of neodymium iron boron magnets it was recognized there is a trade-off between high energy output and high temperature capability. High values of energy product are achieved by optimizing the ratio of neodymium, iron, and boron while minimizing contaminants, especially oxygen. While this produces high energy product, intrinsic coercivity of sintered magnets is limited to between 835 to 955 kA/m (10 500 and 12 000 Oe). These low values of coercivity make it impractical to use the magnets at temperatures over 80 °C (175 °F) or in the presence of large demagnetizing stress.

X4.2.2 To permit higher temperature operation requires increasing intrinsic coercivity, H_{cJ}, achieved through substitution of dysprosium for a portion of neodymium. (Terbium and other heavy rare earths, while also effective, are used to a lesser extent as they are in limited supply and more expensive). As dysprosium is substituted for neodymium, intrinsic coercivity increases. However, B_r and energy product decrease. Optimization of device design usually requires selection of the lowest dysprosium content that will survive at the maximum device operating temperature and in the presence of the maximum expected demagnetizing field. Minimizing dysprosium content is also important to minimize product cost and to minimize consumption of this limited-availability raw material.

X4.3 Low Temperature Performance Grades

X4.3.1 Neodymium iron boron can be utilized at temperatures as low as 140 K. However, manufacturer's published data seldom offers performance information for temperatures below 20 ºC. Users are advised to request such performance information from the producer.

X4.3.2 Between 135 and 140 K, neodymium iron boron undergoes a transformation and the uniaxial crystalline anisotropy devolves into a cone of anisotropy. This is referred to as "spin reorientation" and results in a rapid and large reduction in magnetic field strength as temperature is reduced below 140 K (–133 °C, –208 °F). This is a reversible phenomenon. When the magnet is warmed to greater than 140 K, uniaxial anisotropy is re-established.

X4.4 Isotropic Sintered Magnetic Grades

X4.4.1 The great majority of neodymium iron boron sintered magnets are manufactured with magnetic grains aligned parallel to each other to create what is called an anisotropic (oriented) magnet. This alignment provides the largest energy product but only in the specific direction of alignment. Upon occasion it is desirable to magnetize a finished magnet with an arrangement of poles that is not possible from a pre-oriented structure. In this case, during manufacture, the grains are left randomly oriented and the finished product is what is called isotropic (un-oriented). No isotropic published properties have been identified for sintered Neo magnets and the user is encouraged to enquire directly of the producer.

X4.4.2 Bonded magnets manufactured from rapidly quenched alloy are "isotropic" in that each particle of material has frozen into it a random mix of crystal orientations. Magnets made from this powder do not benefit from attempts to align the particles. Magnetic fields from the finished product are dependent upon how the magnet is magnetized. These rapidly quenched materials and bonded magnets made from them are not covered in this sintered magnet specification.

X4.4.3 Bonded magnets can also be manufactured from anisotropic powder, a material wherein each particle consists of grains in parallel alignment. The more common method of producing this type of powder is via a process called HDDR. HDDR stands for **h**ydrogenation, **d**isproportionation, **d**ecomposition, and **r**ecombination. Bonded magnets made from this powder are beyond the scope of this specification.

X5. THERMAL AND MECHANICAL PROPERTIES

X5.1 Thermal Properties

X5.1.1 Residual induction, B_r, and intrinsic coercivity, H_{cJ}, vary with change in temperature. Once a magnet has experienced all temperatures within the specified operating range, further exposure causes only a reversible change in the magnetic parameters and these are quantified by the reversible temperature coefficients of induction and of coercivity. The changes in magnetic properties are nonlinear. The reversible temperature coefficients represent the average change within the specified temperature range. For the values to accurately reflect the magnet's performance, the temperature range must be specified. Reversible temperature coefficients as presented here are typical and for the range 20 °C (68 °F) to the maximum recommended use temperature, T_w (unless otherwise specified). Producers' published coefficients are frequently rounded to two or even one significant digit. This rounding can create large errors in calculating the magnetic characteristics. Consult with the producer to confirm these values, obtain more precise values, and for coefficients for other temperature ranges.

X5.1.2 Coefficients of thermal expansion as presented in Table X2.1 are approximate for the temperature range 20 to 120 °C (68 to 248 °F). Because of the variability in temperature range reported for commercial product, grade of material, and specific formulation properties, a broad range of values is shown in the table.

X5.2 Mechanical Properties

X5.2.1 Neodymium iron boron is a brittle material. Brittle materials are difficult to test for mechanical properties and testing tends to yield a wide spread of property values. Furthermore, magnetic properties will change as a result of the magnet being subjected to stress. Magnets are not recommended to be part of a device's structural system and should be protected from stress to the greatest extent possible.

X6. OTHER TERMINOLOGY

X6.1 Maximum Recommended Working Temperature

X6.1.1 The maximum recommended working temperature of a permanent magnet, T_w, is a semi-arbitrary value sometimes assigned by magnet manufacturers to their products. T_w is not normative. It is generally a function of the linearity of the normal hysteresis loop in the second quadrant at the specified temperature. In one interpretation, it is the maximum temperature at which the normal hysteresis loop is linear in the second quadrant. In a less demanding interpretation, the normal loop must be linear only from the B_r point on the B-axis to the maximum energy operating point on the normal hysteresis loop.

X6.1.2 The maximum working temperature is also an indication of the temperature a material can sustain without experiencing structural or metallurgical change which might adversely affect magnetic or mechanical properties.

X6.2 Magnetic Condition – Calibrated, Stabilized, Knocked Down

X6.2.1 It is often the case that a magnet can become partially demagnetized in handling, assembly, or in use. There are also three common adjustments to the magnetic output made to meet application requirements as follows.

X6.2.2 Magnets that are exposed to extreme temperatures may experience partial demagnetization. This can be minimized by pre-treating the magnets thermally in an oven at a temperature providing equivalent knockdown to that experienced in use. To prevent partial demagnetization from exposure to magnetic fields, a demagnetizing field of predetermined field strength is applied to the magnet (an opposing or demagnetizing field). Magnets treated by either method are said to be stabilized as subsequent exposure to the defined (*a*) temperature or (*b*) magnetic field will cause minimal-to-no additional demagnetization.

X6.2.3 In the event an application requires magnets to provide a specific magnetic field strength and within a narrow tolerance range, it may be necessary to treat the magnets, usually magnetically, to a reverse magnetic (knockdown) field of a suitable magnitude. The intent of the reverse field is to knock down each magnet sufficiently to fall within a specific range of magnetic output. Stronger magnets may require a greater knockdown field; weaker magnets may require a smaller knockdown field. The result of treating the magnets is to reduce the variability of magnetic output within and among batches of magnets. In so doing, all magnets will undergo some level of demagnetization. Magnets thus treated are said to be calibrated.

X6.2.4 In either of the above cases, the treated magnets will have experienced some level of knockdown. Furthermore, there are times when magnets will require demagnetization in part or totally. Alnico and ferrite magnets can be demagnetized with relative ease by exposure to a ringing AC field or by extracting the magnet from an AC field. Accomplishing this for Neo and SmCo magnets is difficult due to their great resistance to demagnetization (high intrinsic coercive field strength). Neo magnets can be thermally treated above their Curie temperature, typically between 310 to 350 °C depending upon composition, to demagnetize them. SmCo magnets can also be demagnetized by treatment above their Curie temperature of ~825 °C, but exposure to such a high temperature may require a controlled thermal treatment to fully restore magnetic properties. In any event, when a magnet has been partially or totally demagnetized it is said to have been knocked down.

X7. SYMBOLS

X7.1 Several alternative abbreviations of magnetic properties are or have been in general use. *Residual induction* is without confusion shown as "Br." However, normal coercive field strength is variously shown as Hc, Hcb, bHc, or H_{cB}. *Intrinsic coercive field strength* is shown as Hci, iHc, jHc, or H_{cJ}. The older terms appear to have become settled on Br, Hc, and Hci, while the newer symbols are B_r, H_{cB}, and H_{cJ}. The modifying letters are often, for convenience, not subscripted and are lower case, for example, "Hcj."

X7.2 Origin of "*i*" in the abbreviation is *a priori* referring to the "intrinsic" (B-H versus H) characteristic while the absence of "*i*" refers to the normal (B versus H) characteristic. The intrinsic characteristic and curve is increasingly referred to as polarization with abbreviation "*J*."

X7.3 Abbreviations used within this specification conform to Terminology A340. ASTM standards are *living documents*, and it is recommended to refer to the most recent version.

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