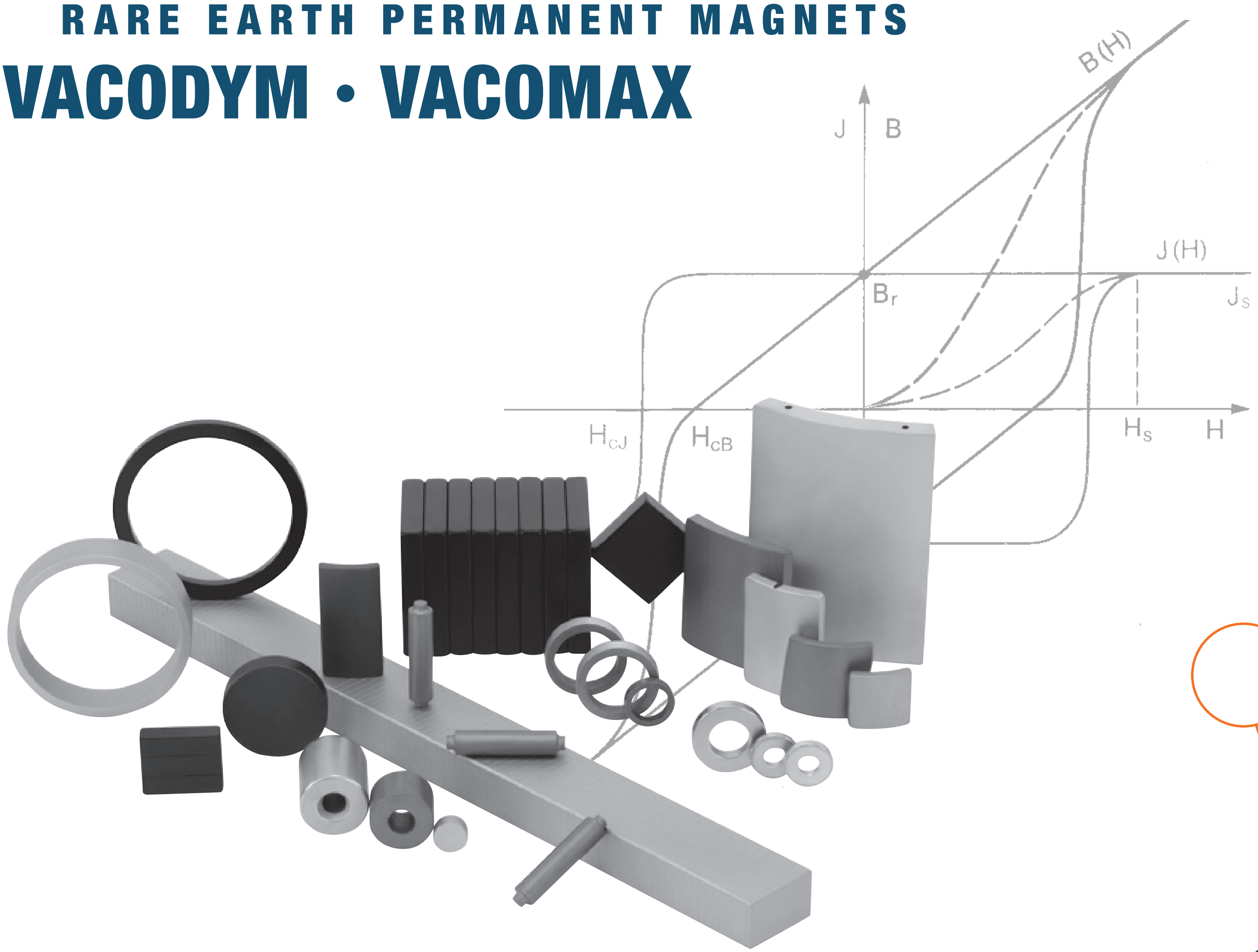
RARE EARTH PERMANENT MAGNETS

VACODYM • VACOMAX



ADVANCED MATERIALS – THE KEY TO PROGRESS

VAC®
VACUUMSCHMELZE

THE COMPANY
VACUUMSCHMELZE

VACUUMSCHMELZE GmbH & Co. KG (VAC) is one of the world's leading producers of special metallic materials with particular physical properties and products produced from them. With approximately 4,100 employees worldwide, the company is represented in 50 countries and currently achieves a turnover of approximately EUR 400 million. The headquarters and registered office of the company is Hanau, Germany, with additional production plants in Slovakia, Finland, Malaysia and China.

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1. RARE EARTH PERMANENT MAGNETS

VACODYM AND VACOMAX

Together with permanent magnets, VAC's product range also includes soft magnetic semi-finished products and parts, inductive components, magnetic shielding and other materials with special physical properties. Apart from rare earth permanent magnets, the range of magnets also includes ductile permanent magnets and magnetically semi-hard materials. The latter are mainly characterized by low-cost shaping options and adjustable permanent magnet properties.

We have been working on magnetic properties of special metallic materials and their applications for more than 70 years. In 1973, we started producing rare earth (RE) and cobalt-based permanent magnets using powder metallurgical processes. Under the trade name VACOMAX®, this new material group has found widespread applications as a result of optimized production processes and close customer partnerships.

In 1986, we started to produce VACODYM®*) magnets on an industrial scale. These magnets are produced on the basis of neodymium-iron-boron alloys and have the highest energy densities available today. From melting the alloy under vacuum to coating the finished parts, we can carry out all steps in-house and can thus ensure optimised material properties over the entire production process. As the European market leader, we are today one of the world's top-rated producers of rare earth permanent magnets.

The magnetic properties of sintered magnets are influenced by the alloy composition and the pressing method. Magnets can be produced using three different processes. These three processes are reflected in the alloy name with the letters HR, TP or AP.

HR (High Remanence) refers to isostatically pressed magnets. In die-pressed designs, we differentiate between TP (Transverse-Pressed) and AP (Axial-Pressed). Details on the available product options are given in Section 8.

We continuously pursue intensive development to align our range of VACODYM alloys to market demands, for example, for electric drive systems for hybrid or pure electric vehicles in the field of electric mobility. Both coated, as well as uncoated magnets are used in permanent magnet synchronous machines, as "embedded" magnets or surface mounted magnets. In appropriate applications, the special orientation profile of our axial-pressed (AP) magnets can enhance performance.

In addition to our VACODYM 6XX and 8XX series, which are already well established in the market and can be used particularly in motor applications under normal ambient conditions without additional surface coating, we have introduced a number of new alloys to the market with our 2XX and 9XX series. VACODYM 238 and 247 do not represent a new performance class, but are dysprosium-free and thus reduce the dependency on price volatile heavy rare earth metals. The fields of application of this new VACODYM alloy series are particularly synchronous motors with operating temperatures of up to 130 °C, for example actuators or power steering motors.

For high temperature applications from 160 - 240 °C, we have developed the 9XX series comprising VACODYM 956, 965, 974, 983 and 992, which are characterized by increased coercivity when compared to the 8XX series, particularly in case of the high operating temperatures.

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*) = licensor Hitachi Metals Ltd. (Japan)

In the case of temperatures below approximately 140 Kelvin, the maximum energy density is reduced by up to 25 % for conventional VACODYM magnets. Conventional Nd-Fe-B magnets can therefore be normally used to the full extent only down to 140 Kelvin. For lower temperatures, we have developed two new alloys, VACODYM 131 TP and 131 DTP, which are characterized in that they exhibit the full potential of Nd-Fe-B magnets even at temperatures far below that of liquid nitrogen (77 Kelvin). Upon request, we would be pleased to send you further information on these new grades.

To increase the coercivities, the newly developed grain boundary diffusion procedure can also be used for all VACODYM alloys. More details can be found in Section 3 on page 8.

For systems with an operating temperature of up to 150 °C, we continue to produce magnets of the "7XX series", which are characterized by high remanent induction.

Cost-effective production units, modern testing techniques and a quality management system certified according to ISO 9001, ISO/TS 16949 and ISO 14001 are as much a matter of course as ongoing further training of our employees and active environmental protection. With these well-proven principles of our business policy, we continue to be your reliable and competent partner.

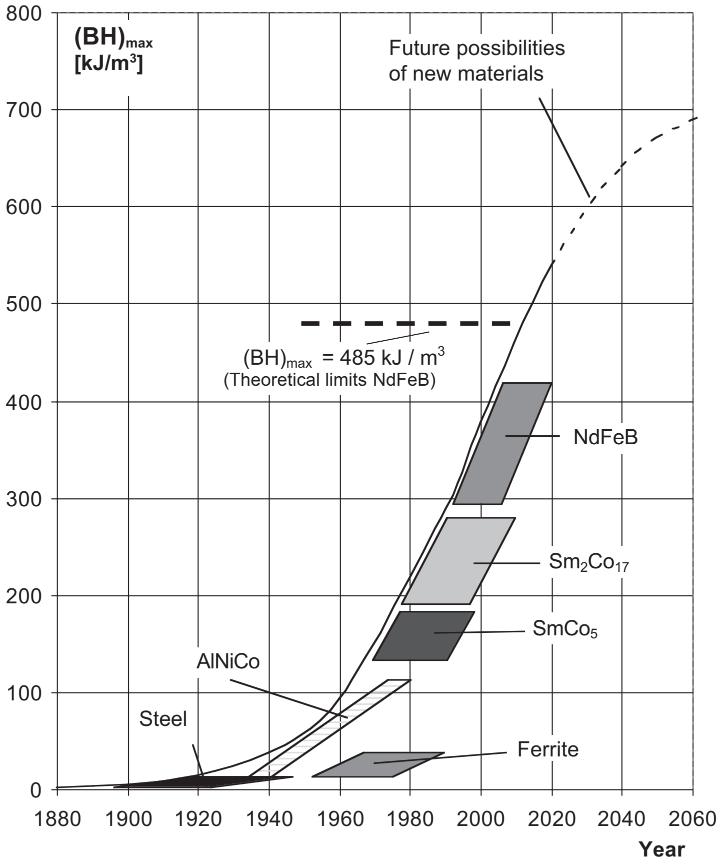

Fig. 1: Development of energy densities $(BH)_{max}$ of permanent magnets and their potential

2. PRODUCT RANGE

The product range of our rare earth magnets includes balanced sets of materials with different magnetic properties. As a result, it is relatively easy to select a material suitable for any specific application. VACODYM is the permanent magnet material offering the highest energy densities currently available. The excellent magnetic properties of this material group can be traced to the strongly magnetic matrix phase $Nd_2Fe_{14}B$ with very high saturation polarization and high magnetic anisotropy. A ductile neodymium-rich bonding phase at the grain boundaries gives these magnets good mechanical properties. Fig. 2 gives a comparative overview of the properties of our VACODYM magnets at 150 °C.

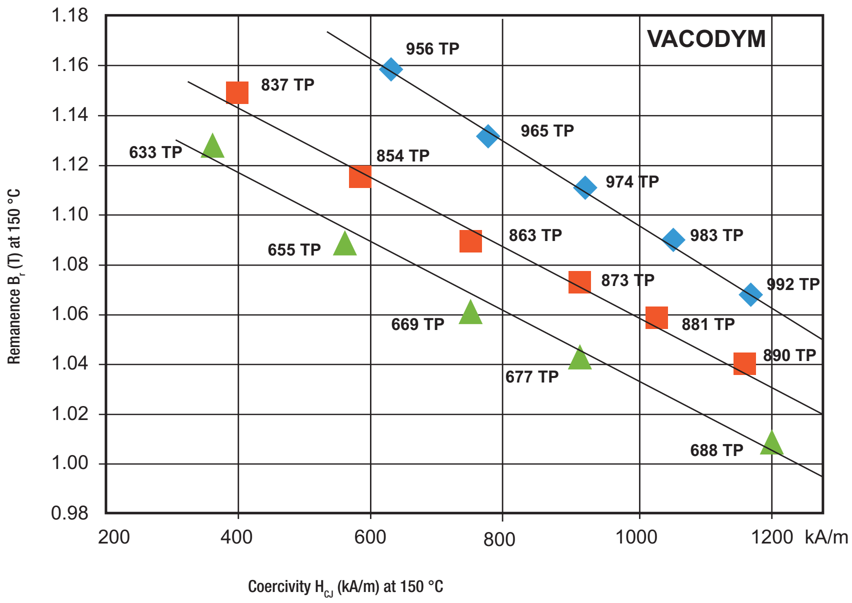

Fig. 2: Remanence B_r and coercivity H_{cJ} of transverse field pressed VACODYM magnets at 150 °C

VACOMAX is our permanent magnet material made from rare earths and cobalt. These magnets have particularly high coercivities with simultaneous high saturation polarization and excellent temperature and corrosion stability. In Fig. 3, the typical demagnetization curves of VACODYM and VACOMAX are compared with the classic permanent magnet materials AlNiCo and hard ferrite.

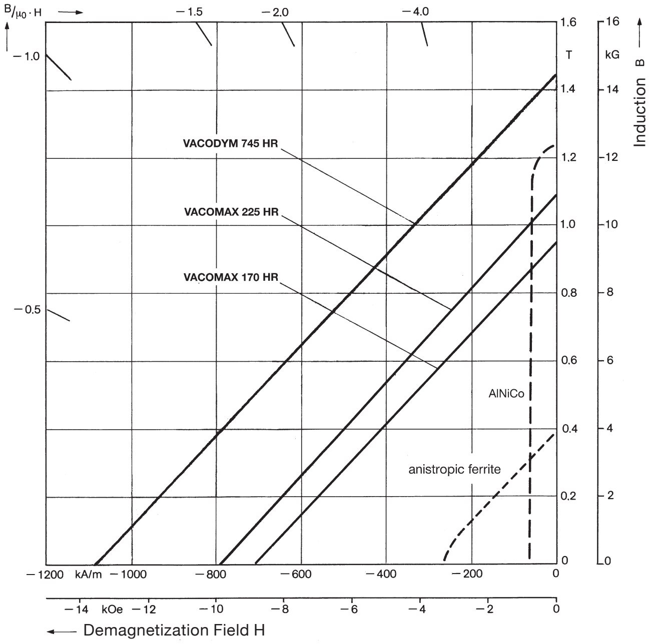

Fig. 3: Typical demagnetization curves of VACODYM and VACOMAX in comparison with AlNiCo and ferrite at room temperature.

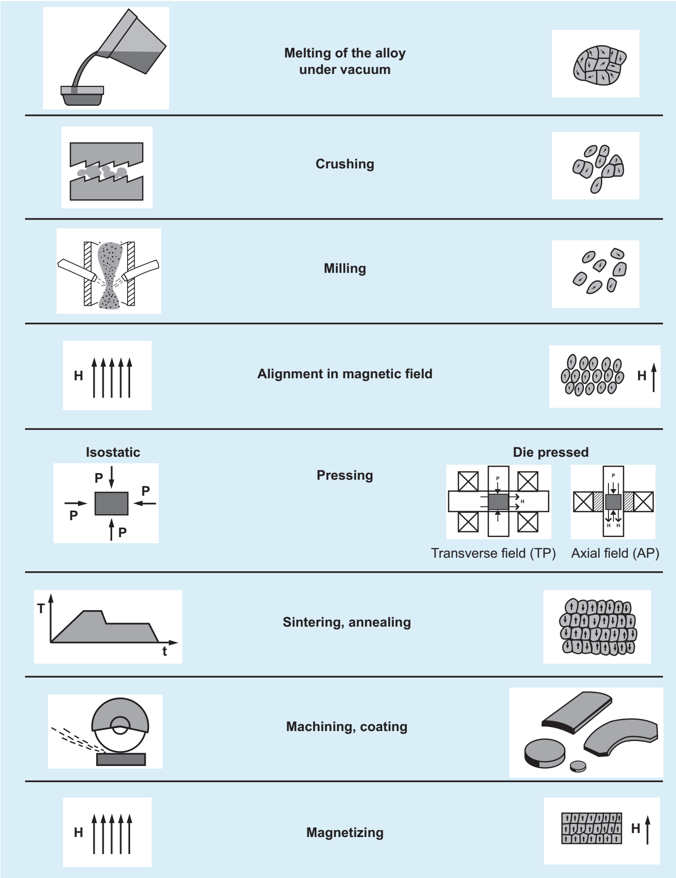

Fig. 4: Production

VAC has many years of experience in the production of permanent magnets and the design of magnetic circuits. As well as analytical methods, we utilize modern computer programs to analyze and design magnet systems. These include 2D and 3D field calculations using finite element methods. Their use decisively shortens the development times of systems. Therefore besides single magnets, we deliver increasing numbers of complete magnet systems according to customers' specifications.

Detailed information on these can be found in our ″Magnet Systems″ brochure.

The use of soft magnetic materials as flux carrying system components, e.g. VACOFLUX® and VACOFER®, enables us to meet customers' specifications. In many cases, proper assembly and magnetization of the systems is only possible when the magnets and other system components are assembled directly by the magnet producer.

Magnets made of VACODYM and VACOMAX are produced by sintering using powder metallurgical processes. The main work steps of the production process are illustrated in Fig. 4. Depending on the size, shape, tolerances, quantity and magnetic requirements, the magnetic parts are either cut from isostatically pressed blocks or are die pressed. During die-pressing, the powder particles can be aligned by strong magnetic fields parallel (axial field for AP grades) or perpendicular (transverse fields for TP grades) to the direction of pressing, depending on the geometry of the part. Isostatically or transverse-field pressed parts have approximately 5 - 8 % higher remanence values when compared to axial-field pressed magnets.

The typical demagnetization curves of our rare earth magnets for various temperatures are available at leading FEM companies.

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3. GRAIN BOUNDARY DIFFUSION

The coercivity of permanent magnets made of VACODYM can be increased considerably by using the grain boundary diffusion process. In this newly introduced production process, sintered permanent magnets are coated with heavy rare earths (HRE) and then undergo a special heat treatment. During the heat treatment, the applied material diffuses along the grain boundaries into the interior of the magnet and NdFeB grains are formed with HRE-rich shells, which, depending on the thickness of the part, result in an increase of coercivity ΔH_{cJ} at room temperature by 400 kA/m (5 kOe) up to a maximum of 550 kA/m (7 kOe) (for example illustrated for VACODYM 956 TP in Fig 5). With efficient use of HRE, the reduction of remanence can be limited to less than 0.01 T (0.1 kG).

When compared to conventionally produced magnet qualities with the same coercivity, additional magnet qualities can be produced using the diffusion process which have an approx. 2 % lower proportion of dysprosium and a 0.04 T (0.4 kG) higher remanence B_r.

This refining step can, in principle, be applied to all VACODYM sintered magnets that are ground on all sides and is indicated with the letter "D" in the alloy name (e.g. 956 DTP). Starting from the base material and up to a part thickness < 5 mm, an increase of $H_{cJ,min}$ by 400 kA/m (5 kOe) can be guaranteed without a considerable reduction of the remanence. However, the characteristic diffusion length of only a few millimeters (Fig. 6) results in restrictions if the part thickness exceeds 5 mm. In such cases, we recommend consulting our team of experts.

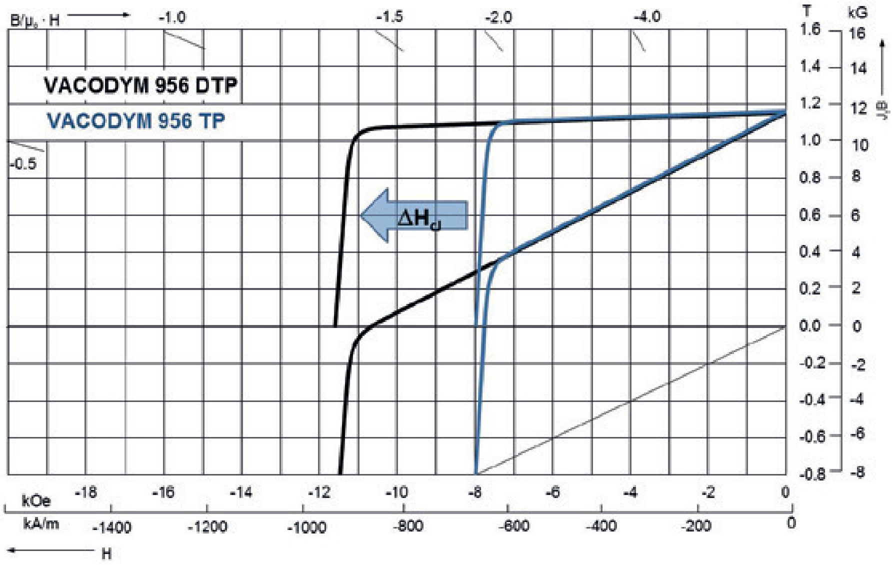


Fig. 5: Demagnetization curves of VACODYM 956 TP and VACODYM 956 DTP at 150 °C

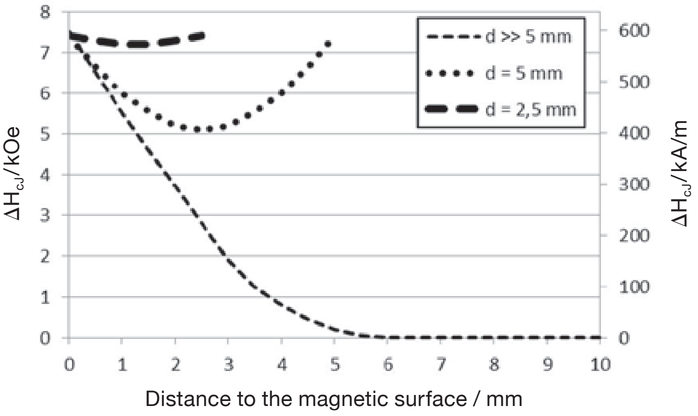
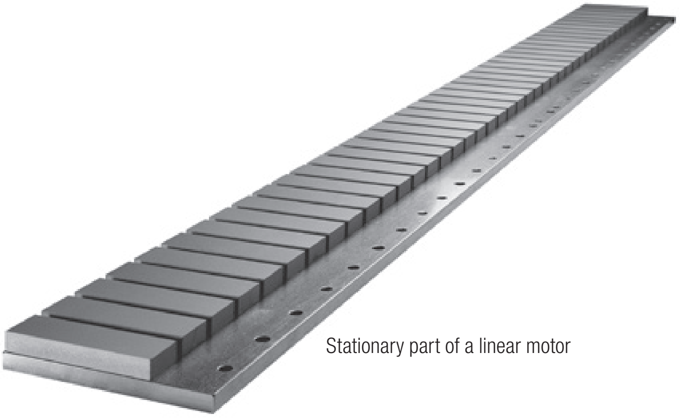


Fig. 6: Characteristic dependency of the increase in coercivity ΔH_{cJ} at room temperature with respect to the distance from the magnetic surface for magnets of different thicknesses d that are coated on both sides

4. APPLICATIONS


Stationary part of a linear motor

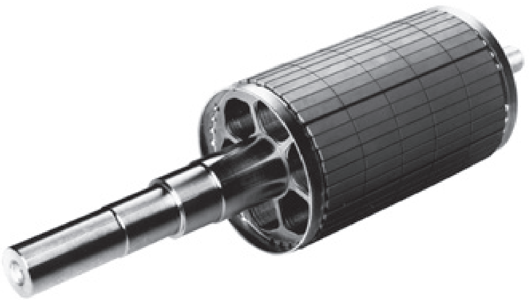
Magnets made of VACODYM and VACOMAX have a number of excellent magnetic properties when compared to conventional magnet materials, such as ALNICO or hard ferrite.

THEIR USE RESULTS IN SIGNIFICANT BENEFITS FOR THE USERS:

- Up to ten times higher energy densities when compared to those of AlNiCo and ferrite magnets allow for a reduction in the magnet volume (see Fig. 7), as well as miniaturization of systems and whole assemblies. This can result in saving cost for return paths, coils etc.

- Existing magnet systems can be improved in many cases. In general, we recommend redesigning the systems when using VACODYM and VACOMAX.

- New design principles are realized and new fields of application are therefore opened.


Rotor of a servo motor

MOTORS AND GENERATORS

Servo drives, DC machines, linear drives and heavy-duty machines (e.g. engines for rail and ship propulsion, wind turbine and hydroelectric generator systems) predominantly utilize VACODYM magnets. In addition, our Finnish subsidiary NEOREM Magnets specializes in the production of large-size magnets and advanced systems incorporating them (see www.neorem.fi). VACOMAX magnets continue to be used in the case of special requirements, particularly high temperatures. Another important area of application is that of small and fractional HP motors, e.g. dental motors.

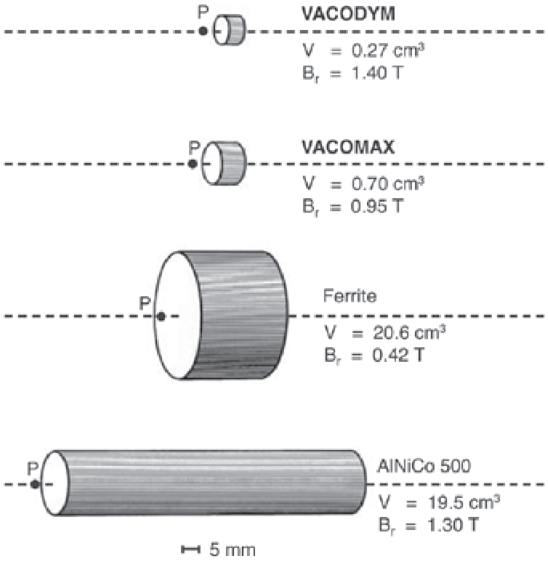


Fig. 7: Example illustrating the volume reduction achieved with VACODYM and VACOMAX: Each magnet is designed to produce a field of 100 mT at a distance of 5 mm from the surface of the pole.

AUTOMOTIVE ENGINEERING AND SENSORS

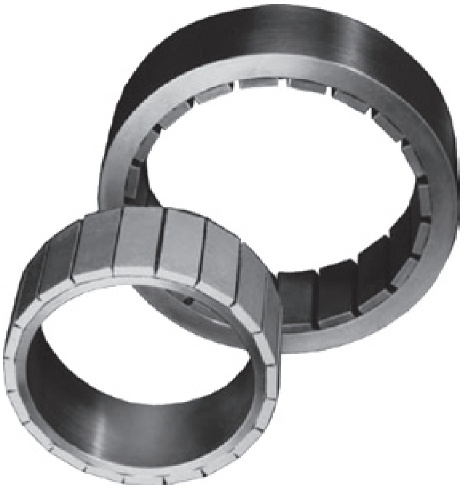
Sensors to measure varied operating data such as engine, gear and wheel rotary speed (e.g. ABS systems), acceleration (e.g. ESP, airbag) or positions (e.g. throttle valve position, injection systems, camshaft, crankshaft, fuel gauges) are equipped with VACOMAX or VACODYM magnets depending on the requirements for temperature and corrosion stability.

Synchronous motors as the main drives in electric and hybrid vehicles are also equipped with VACODYM magnets.

VACODYM magnets are also particularly suitable for actuators in engine management, auxiliary motors (power steering) and generators.

MRI (MAGNET RESONANCE IMAGING)

For imaging systems in medical engineering, permanent magnet systems with high remanent VACODYM grades are used as well as superconducting and electrically excited systems. The main advantages are the very low energy consumption, savings in weight, a maintenance-free structure and the possibility of building open, patient-friendly systems.



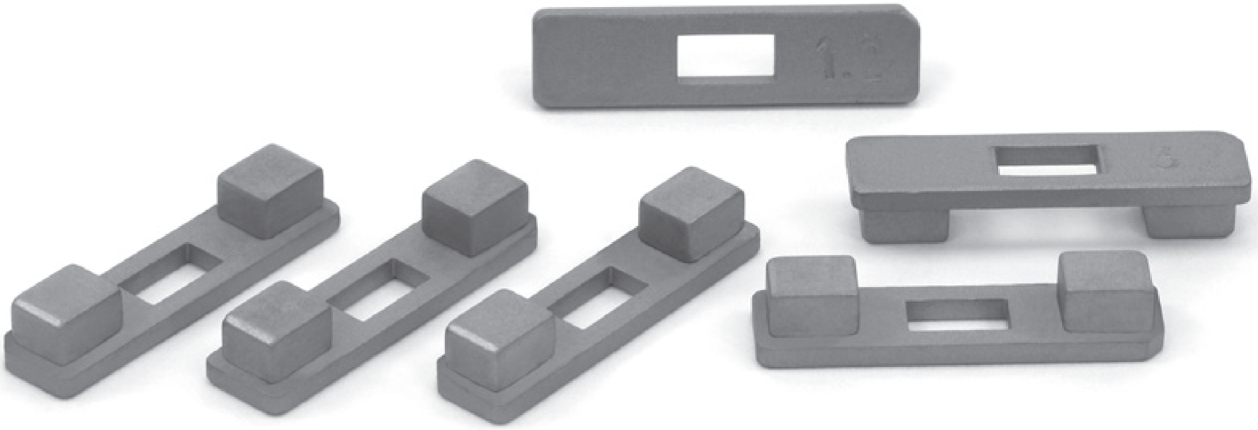
Concentric rotary coupling with VACODYM magnets

PERMANENT MAGNET BEARINGS

Different magnetic bearing principles have been developed for turbo-molecular vacuum pumps, centrifuges and similar applications. These usually employ axially magnetized ring magnets. The magnet material is selected according to the respective customer specifications.

MAGNETIC COUPLINGS

Magnetic couplings are preferred in automation and chemical processing technology as they ensure permanent hermetic separation of different media. Owing to increased temperature requirements, VACOMAX magnets are also used for numerous applications. We recommend VACODYM magnets for lower operating temperatures.



Sensor modules with VACOMAX magnets for double clutch gear unit (by courtesy of Volkswagen AG)

BEAM GUIDING SYSTEMS, WIGGLERS AND UNDULATORS

Permanent magnet beam guides are practically maintenance-free and require no energy supply. Systems with VACODYM or VACOMAX magnets have therefore established themselves in all cases where high field strengths must be achieved within a limited space, e.g. in wigglers, undulators, multipoles and particle detectors. For these applications, accurately matched and compatible magnet sets can be produced with narrow tolerances with regard to the magnetic properties, such as homogeneity and angular position between the preferred magnetic direction and part geometry. For large-volume parts, economic production processes result particularly from the possibilities of producing large magnet cross-sections with pole surfaces of up to approx. 100 cm^2.

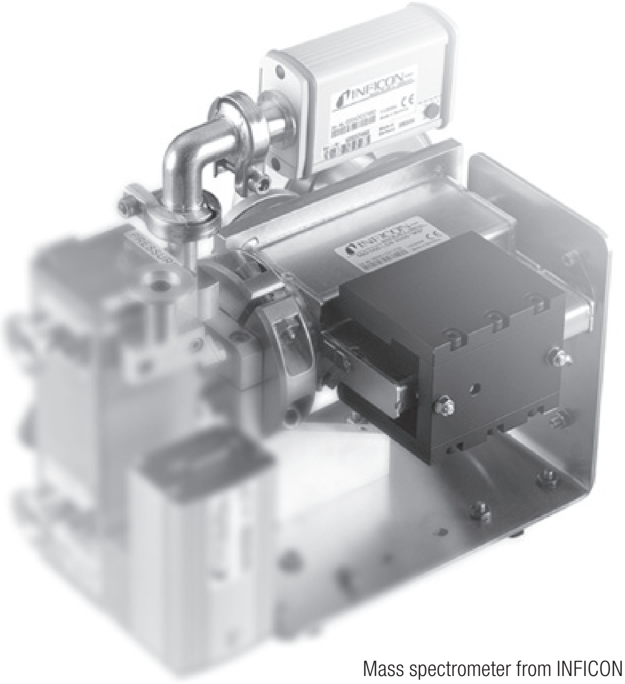
Undulator structure with VACODYM magnets

SWITCHES AND RELAYS

For the widely varying designs of Hall effect switches, polarized relays, revolution counters, etc., magnets or magnet systems with VACODYM or VACOMAX are used depending on the specifications.

MEASURING INSTRUMENTS

In this field, the applications range from electronic scales to pulse counting meters and mass spectrometers to NMR (Nuclear Magnetic Resonance) measuring systems. Depending on the construction principle selected, systems, armatures or rotors with VACODYM or VACOMAX magnets are used.



Mass spectrometer from INFICON GmbH with a VACOMAX magnet system

5. MATERIALS AND MAGNETIC PROPERTIES

5.1 CHARACTERISTIC PROPERTIES

TABLE 1: CHARACTERISTIC PROPERTIES OF VACODYM AT ROOM TEMPERATURE (20 °C)

Pressing direction	Material	Code[1]	See page	Remanence				Coercivity	
				B_r typ. Tesla	kG	B_r min. Tesla	kG	H_{cB} typ. kA/m	kOe
HR*	VACODYM 510 HR	360/95.5	21	1.41	14.1	1.38	13.8	980	12.3
	VACODYM 633 HR	315/127.5	22	1.35	13.5	1.29	12.9	1040	13.1
	VACODYM 655 HR	280/167	23	1.28	12.8	1.22	12.2	990	12.4
	VACODYM 677 HR	240/223	24	1.18	11.8	1.12	11.2	915	11.5
	VACODYM 722 HR	380/87.5	25	1.47	14.7	1.42	14.2	915	11.5
	VACODYM 745 HR	370/111.5	26	1.44	14.4	1.40	14.0	1115	14.0
TP*	VACODYM 238 TP	335/127	27	1.37	13.7	1.33	13.3	1058	13.3
	VACODYM 247 TP	330/143	28	1.36	13.6	1.32	13.2	1051	13.2
	VACODYM 633 TP	305/127.5	22	1.32	13.2	1.28	12.8	1020	12.8
	VACODYM 655 TP	280/167	23	1.26	12.6	1.22	12.2	970	12.2
	VACODYM 669 TP	255/200	29	1.22	12.2	1.17	11.7	940	11.8
	VACODYM 677 TP	240/223	24	1.18	11.8	1.13	11.3	915	11.5
	VACODYM 688 TP	225/262.5	30	1.14	11.4	1.09	10.9	885	11.1
	VACODYM 745 TP	355/111.5	26	1.41	14.1	1.37	13.7	1090	13.7
	VACODYM 764 TP	335/127.5	31	1.37	13.7	1.33	13.3	1060	13.3
	VACODYM 776 TP	305/167	32	1.32	13.2	1.28	12.8	1020	12.8
	VACODYM 837 TP	335/127.5	33	1.37	13.7	1.33	13.3	1060	13.3
	VACODYM 854 TP	310/167	34	1.32	13.2	1.28	12.8	1020	12.8
	VACODYM 863 TP	295/200	35	1.29	12.9	1.25	12.5	995	12.5
	VACODYM 872 TP	280/223	36	1.25	12.5	1.21	12.1	965	12.1
	VACODYM 881 TP	265/238.5	37	1.22	12.2	1.18	11.8	945	11.9
	VACODYM 890 TP	250/263	38	1.19	11.9	1.15	11.5	915	11.5
	VACODYM 956 TP	330/167	39	1.35	13.5	1.32	13.2	1030	13.0
	VACODYM 965 TP	310/187	40	1.31	13.1	1.28	12.8	1000	12.6
	VACODYM 974 TP	295/207	41	1.28	12.8	1.25	12.5	980	12.3
	VACODYM 983 TP	280/223	42	1.25	12.5	1.22	12.2	960	12.1
	VACODYM 992 TP	270/238.5	43	1.22	12.2	1.19	11.9	940	11.8

* For pressing direction illustrations, see page 16 and 17

[1] Coding based on IEC 60404-8-1, the magnetic values usually exceed the values of IEC

				Energy density				Temperature coefficients				Den-sity	Maximum operating temperature	
								20-100 °C		20-150 °C				
H_{cB} min.		H_{cJ} min.		$(BH)_{max}$ typ.		$(BH)_{max}$ min.		TC (B_r) typ.	TC (H_{cJ}) typ.	TC (B_r) typ.	TC (H_{cJ}) typ.	ϱ typ.	T_{max}[2]	
kA/m	kOe	kA/m	kOe	kJ/m^3	MGOe	kJ/m^3	MGOe	%/°C	%/°C	%/°C	%/°C	g/cm^3	°C	°F
915	11.5	955	12	385	48	360	45	-0.115	-0.790			7.5	60	140
980	12.3	1275	16	350	44	315	40	-0.095	-0.650	-0.105	-0.550	7.7	110	230
925	11.6	1670	21	315	40	280	35	-0.09	-0.610	-0.100	-0.550	7.7	150	300
850	10.7	2230	28	270	34	240	30	-0.085	-0.550	-0.095	-0.500	7.7	190	370
835	10.5	875	11	415	53	380	48	-0.115	-0.770			7.6	50	120
1065	13.4	1115	14	400	50	370	47	-0.115	-0.730			7.6	70	160
1008	12.7	1273	16	363	46	335	42	-0.111	-0.679	-0.120	-0.573	7.6	120	250
1000	12.6	1432	18	357	45	330	42	-0.111	-0.654	-0.120	-0.563	7.6	130	270
970	12.2	1275	16	335	42	305	39	-0.095	-0.650	-0.105	-0.570	7.7	110	230
925	11.6	1670	21	305	39	280	35	-0.090	-0.610	-0.100	-0.550	7.7	150	300
875	11.0	2000	25	290	36	255	32	-0.085	-0.570	-0.095	-0.510	7.7	170	340
860	10.8	2230	28	270	34	240	30	-0.085	-0.550	-0.095	-0.500	7.7	190	370
830	10.4	2625	33	250	32	225	28	-0.080	-0.510	-0.090	-0.460	7.8	220	430
1035	13.0	1115	14	385	48	355	45	-0.115	-0.730			7.6	70	160
1005	12.6	1275	16	360	46	335	42	-0.115	-0.700	-0.125	-0.590	7.6	100	210
970	12.2	1670	21	335	42	310	39	-0.110	-0.610	-0.120	-0.550	7.6	140	280
1010	12.7	1275	16	360	46	335	42	-0.110	-0.620	-0.120	-0.540	7.6	110	230
970	12.2	1670	21	335	42	310	39	-0.105	-0.600	-0.115	-0.530	7.7	150	300
950	11.9	2000	25	315	40	295	37	-0.100	-0.560	-0.110	-0.510	7.7	170	340
915	11.5	2230	28	300	38	280	35	-0.095	-0.530	-0.105	-0.490	7.7	190	370
900	11.3	2385	30	290	36	265	34	-0.093	-0.510	-0.103	-0.470	7.7	200	390
865	10.9	2625	33	270	34	250	31	-0.090	-0.500	-0.100	-0.460	7.7	220	430
995	12.5	1670	21	350	44	330	41	-0.100	-0.570	-0.108	-0.531	7.6	160	320
965	12.1	1870	23.5	330	41	310	39	-0.096	-0.530	-0.104	-0.498	7.6	180	360
945	11.9	2070	26	315	39	295	37	-0.094	-0.500	-0.102	-0.467	7.7	200	390
925	11.6	2230	28	300	38	280	35	-0.091	-0.470	-0.099	-0.445	7.7	210	410
900	11.3	2385	30	285	36	270	34	-0.088	-0.450	-0.097	-0.431	7.7	230	440

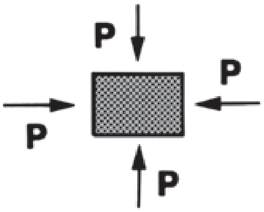
[2] The maximum operating temperature is governed by the layout of the system. The approx. values given refer to magnets operating at working points of $B/\mu_{oH} = -1$ (max. energy product). Users are recommended to consult VAC on any application of VACODYM involving temperatures above 150 °C

TABLE 1: CHARACTERISTIC PROPERTIES OF VACODYM AT ROOM TEMPERATURE (20 °C)

Pressing direction	Material	Code[1]	See page	Remanence				Coercivity	
				B_r typ.		B_r min.		H_{cB} typ.	
				Tesla	kG	Tesla	kG	kA/m	kOe
AP*	VACODYM 238 AP	303/135.5	27	1.30	13.0	1.26	12.6	995	12.5
	VACODYM 247 AP	298/151	28	1.29	12.9	1.25	12.5	987	12.4
	VACODYM 633 AP	280/135.5	22	1.26	12.6	1.22	12.2	965	12.1
	VACODYM 655 AP	255/167	23	1.20	12.0	1.16	11.6	915	11.5
	VACODYM 669 AP	225/200	29	1.16	11.6	1.12	11.2	885	11.1
	VACODYM 677 AP	215/223	24	1.13	11.3	1.08	10.8	860	10.8
	VACODYM 688 AP	200/262.5	30	1.08	10.8	1.03	10.3	830	10.4
	VACODYM 745 AP	325/111.5	26	1.34	13.4	1.31	13.1	1025	12.9
	VACODYM 764 AP	305/135.5	31	1.30	13.0	1.27	12.7	995	12.5
	VACODYM 776 AP	280/167	32	1.26	12.6	1.22	12.2	965	12.1
	VACODYM 837 AP	300/135.5	33	1.30	13.0	1.26	12.6	995	12.5
	VACODYM 854 AP	275/167	34	1.26	12.6	1.21	12.1	965	12.1
	VACODYM 863 AP	250/200	35	1.21	12.1	1.17	11.7	925	11.6
	VACODYM 872 AP	235/223	36	1.17	11.7	1.13	11.3	890	11.2
	VACODYM 881 AP	230/238.5	37	1.14	11.4	1.10	11.0	875	11.0
	VACODYM 890 AP	210/263	38	1.11	11.1	1.07	10.7	845	10.6
	VACODYM 956 AP	295/167	39	1.29	12.9	1.26	12.6	975	12.3
	VACODYM 965 AP	280/187	40	1.25	12.5	1.22	12.2	945	11.9
	VACODYM 974 AP	265/207	41	1.22	12.2	1.19	11.9	925	11.6
	VACODYM 983 AP	250/223	42	1.19	11.9	1.16	11.6	905	11.4
	VACODYM 992 AP	240/238.5	43	1.16	11.6	1.13	11.3	885	11.1

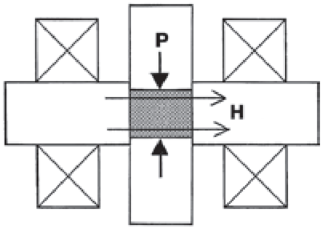
*Pressing direction

HR



*Pressing direction

TP



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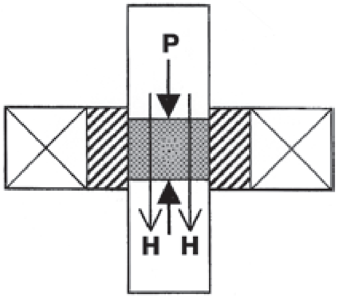
[1] Coding based on IEC 60404-8-1, the magnetic values usually exceed the values of IEC

				Energy density				Temperature coefficients				Den-sity	Maximum operating temperature	
								20-100 °C		20-150 °C				
H_{cB} min.		H_{cJ} min.		$(BH)_{max}$ typ.		$(BH)_{max}$ min.		TC (B_r) typ.	TC (H_{cJ}) typ.	TC (B_r) typ.	TC (H_{cJ}) typ.	ϱ typ.	T_{max}[2)]	
kA/m	kOe	kA/m	kOe	kJ/m³	MGOe	kJ/m³	MGOe	%/°C	%/°C	%/°C	%/°C	g/cm³	°C	°F
946	11.9	1353	17	323	41	298	37	-0.111	-0.667	-0.120	-0.568	7.6	120	250
938	11.8	1512	19	318	40	293	37	-0.111	-0.642	-0.120	-0.557	7.6	130	270
915	11.5	1355	17	305	38	280	35	-0.095	-0.640	-0.105	-0.570	7.7	120	250
865	10.9	1670	21	275	35	255	32	-0.090	-0.610	-0.100	-0.550	7.7	160	320
820	10.3	2000	25	255	32	225	28	-0.085	-0.570	-0.095	-0.510	7.7	180	360
805	10.1	2230	28	240	30	215	27	-0.085	-0.550	-0.095	-0.500	7.7	200	390
770	9.7	2625	33	225	28	200	25	-0.080	-0.510	-0.090	-0.460	7.8	230	440
970	12.2	1115	14	340	43	325	41	-0.115	-0.730			7.6	80	180
955	12.0	1355	17	325	41	305	38	-0.115	-0.690	-0.125	-0.580	7.6	110	230
915	11.5	1670	21	305	38	280	35	-0.110	-0.610	-0.120	-0.550	7.6	150	300
950	11.9	1355	17	325	41	300	37	-0.110	-0.620	-0.120	-0.540	7.6	120	250
905	11.4	1670	21	305	38	275	35	-0.105	-0.600	-0.115	-0.530	7.7	160	320
875	11.0	2000	25	280	35	250	32	-0.100	-0.560	-0.110	-0.510	7.7	180	360
845	10.6	2230	28	260	33	235	30	-0.095	-0.530	-0.105	-0.490	7.7	200	390
830	10.4	2385	30	250	32	230	29	-0.093	-0.510	-0.103	-0.470	7.7	210	410
795	10.0	2625	33	235	29	210	26	-0.090	-0.500	-0.100	-0.460	7.7	230	440
940	11.8	1670	21	315	40	295	37	-0.100	-0.573	-0.108	-0.531	7.6	160	320
910	11.5	1870	23.5	295	37	280	35	-0.096	-0.531	-0.104	-0.498	7.6	180	360
890	11.2	2070	26	280	35	265	33	-0.094	-0.496	-0.102	-0.467	7.7	210	410
870	10.9	2230	28	270	34	250	32	-0.091	-0.473	-0.099	-0.445	7.7	220	430
850	10.7	2385	30	255	32	240	30	-0.088	-0.453	-0.097	-0.430	7.7	240	460

* Pressing direction

AP



[2)] The maximum operating temperature is governed by the layout of the system. The approx. values given refer to magnets operating at working points of $B/\mu_{oH} = -1$ (max. energy product). Users are recommended to consult VAC on any application of VACODYM involving temperatures above 150 °C.

Table 2: CHARACTERISTIC MAGNETIC PROPERTIES OF VACOMAX AT ROOM TEMPERATURE (20 °C)

Material Code[1]	See page	Remanence				Coercivity					
		B_r typ.		B_r min.		H_{cB} typ.		H_{cB} min.		H_{cJ} min.	
		Tesla	kG	Tesla	kG	kA/m	kOe	kA/m	kOe	kA/m	kOe
VACOMAX 240 HR 200/64	44	1.12	11.2	1.05	10.5	730	9.2	600	7.5	640	8.0
VACOMAX 225 HR 190/159	45	1.10	11.0	1.03	10.3	820	10.3	720	9.0	1590	20.0
VACOMAX 225 TP 190/159	45	1.07	10.7	1.03	10.3	790	9.9	720	9.0	1590	20.0
VACOMAX 225 AP 170/159	45	1.04	10.4	0.97	9.7	760	9.6	680	8.5	1590	20.0
VACOMAX 170 HR 170/120	46	1.01	10.1	0.95	9.5	755	9.5	710	8.9	1195	15.0
VACOMAX 145 S 140/200	47	0.90	9.0	0.85	8.5	660	8.3	600	7.5	1990	25.0

[1] Coding based on IEC 60404-8-1, the magnetic values usually exceed the IEC values

Table 3: OTHER CHARACTERISTIC PHYSICAL PROPERTIES OF VACODYM AND VACOMAX AT ROOM TEMPERATURE (20 °C)

Material	Curie temperature	Specific electrical resistance	Specific heat	Thermal conductivity	Coefficient of thermal expansion 20-100 °C		Young`s Modulus	Bending strength
					II c[3]	⊥ c[3]		
	°C	Ωmm²/m	J/(kg·K)	W/(m·K)	10^{-6}/K	10^{-6}/K	kN/mm²	N/mm²
VACODYM	310-370	1.4-1.6 (II c)[3] 1.2-1.4 (⊥ c)[3]	350-550	5-15	4-9	-2-0	140-170	120-400
VACOMAX Sm_2Co_{17}	800-850	0.65-0.95	300-500	5-15	8-12	10-14	140-170	80-150
VACOMAX $SmCo_5$	700-750	0.4-0.7	300-500	5-15	4-10	10-16	100-130	90-180

[3]) II c: parallel to the preferred magnetic direction
⊥ c: perpendicular to the preferred magnetic direction

The ranges given in the above table should be regarded as typical ranges and not as tolerance limits.

Energy density				Temperature coefficients				Density	Maximum operating temperature	
				20-100 °C		20-150 °C				
$(BH)_{max}$ typ.		$(BH)_{max}$ min.		TK (B_r) typ.	TK (H_{cJ}) typ.	TK (B_r) typ.	TK (H_{cJ}) typ.	ϱ typ.	T_{max}[2)]	
kJ/m³	MGOe	kJ/m³	MGOe	%/°C	%/°C	%/°C	%/°C	g/cm³	°C	°F
240	30	200	25	-0.030	-0.15	-0.035	-0.16	8.4	300	570
225	28	190	24	-0.030	-0.18	-0.035	-0.19	8.4	350	660
215	27	190	24	-0.030	-0.18	-0.035	-0.19	8.4	350	660
200	25	170	21	-0.030	-0.18	-0.035	-0.19	8.4	350	660
200	25	170	21	-0.040	-0.21	-0.045	-0.22	8.4	250	480
160	20	140	18	-0.040	-0.14	-0.045	-0.15	8.4	250	480

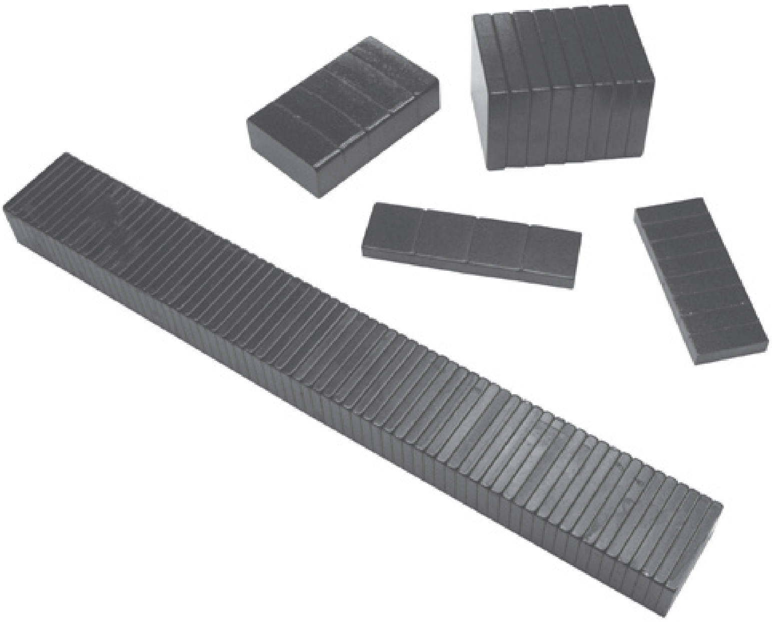
[2)] Users are recommended to consult VAC on any application of VACOMAX involving temperatures above 200 °C.

Compressive strength N/mm²	Vickers hardness HV	Stress crack resistance K_{IC} N/mm$^{3/2}$
600-1250	500-700	80-180
400-900	500-750	30-60
600-1100	500-700	40-80

Table 4: INNER MAGNETIZING FIELD STRENGTH FOR VACODYM AND VACOMAX

Material	$H_{mag\ min.}$	
	kA/m	kOe
VACODYM	2500	31
VACOMAX 225	3650	46
VACOMAX 240	2000	25
VACOMAX 145/170	2000	25

More information on magnetization can be found on page 49.



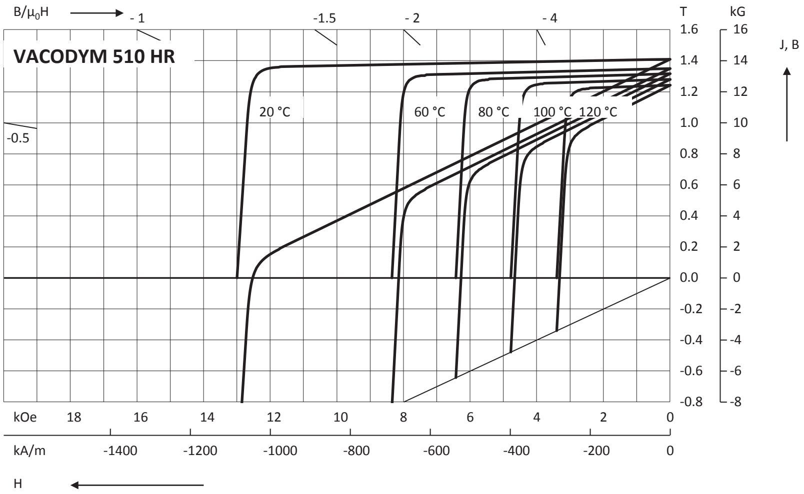
5.2 MATERIAL GRADES

VACODYM and VACOMAX are anisotropic materials with a reversible permeability at the working point $\mu_{rev} < 1.1$. The exact value depends on the material grade and the magnet geometry. VACODYM and VACOMAX do not have open porosity, i.e. the pores are not interconnected. Therefore both materials can be utilized for vacuum applications. The following pages illustrate demagnetization curves of different material grades at various temperatures. Additionally, the typical irreversible losses are given for different working points depending on the temperature. These charts are based on HR or TP grades. Axial field pressed magnets have slightly reduced losses under comparable conditions. The diagrams of typical irreversible losses take thermal after-effects into consideration (logically, these are not included in the demagnetization curves J(H) and B(H) shown). The resulting time and temperature-dependent opposing field must be considered in the magnet design, in addition to the demagnetizing field determined by the respective working point (also see Appendix 12, page 70). It may be assumed for practical purposes that these additional opposing fields are in the range of approx. 150 kA/m. Magnet dimensions incorporating considerations of long-term stability should therefore be based on the irreversible losses shown in the following diagrams. The magnetic data and measured curves refer to magnets whose minimum dimensions are 10 mm perpendicular to the preferred direction and 5 mm parallel to it. In the case of smaller dimensions, there may be deviations from the curves shown.

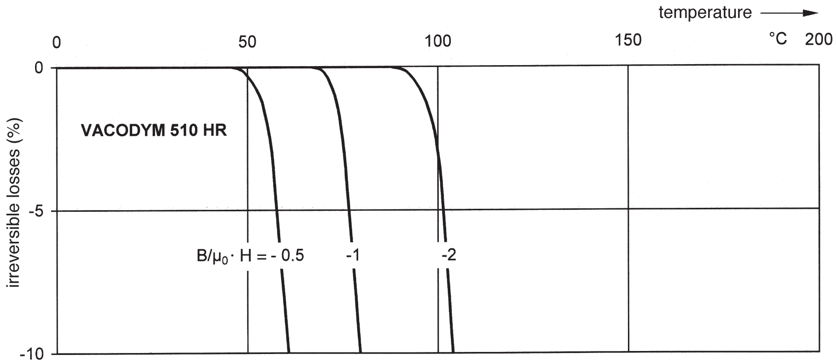
5.2.1 SINTERED MAGNETS BASED ON NdFeB

VACODYM 510

Typical demagnetization curves B(H) and J(H) at different temperatures



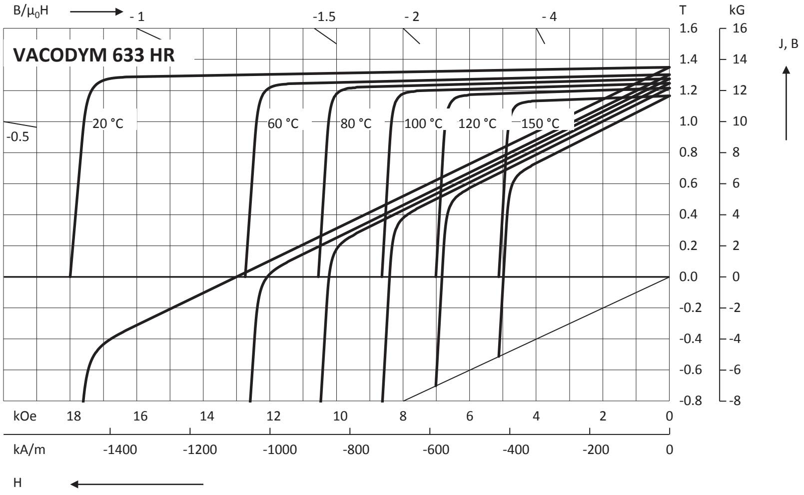
Typical irreversible losses at different working points as a function of temperature

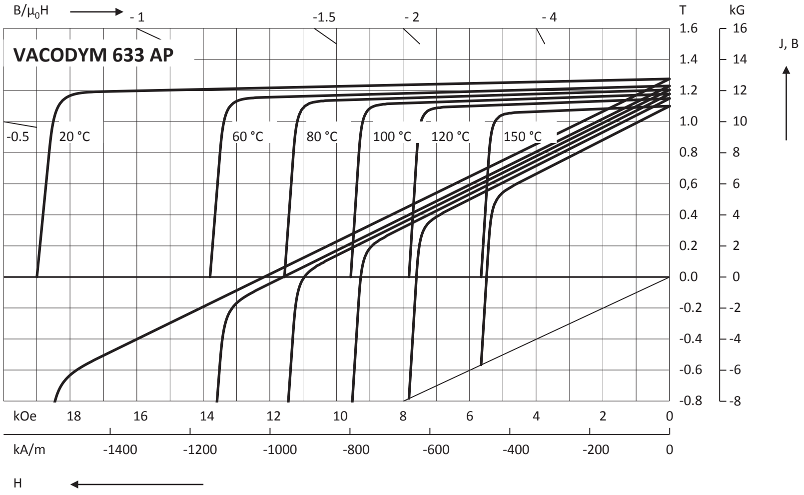


SINTERED MAGNETS BASED ON NdFeB

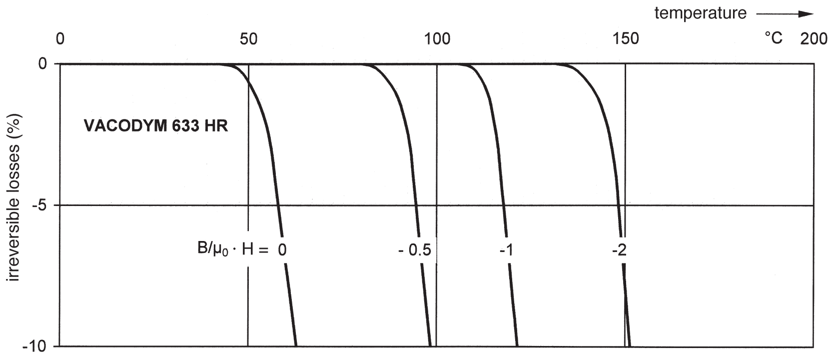
VACODYM 633

Typical demagnetization curves B(H) and J(H) at different temperatures





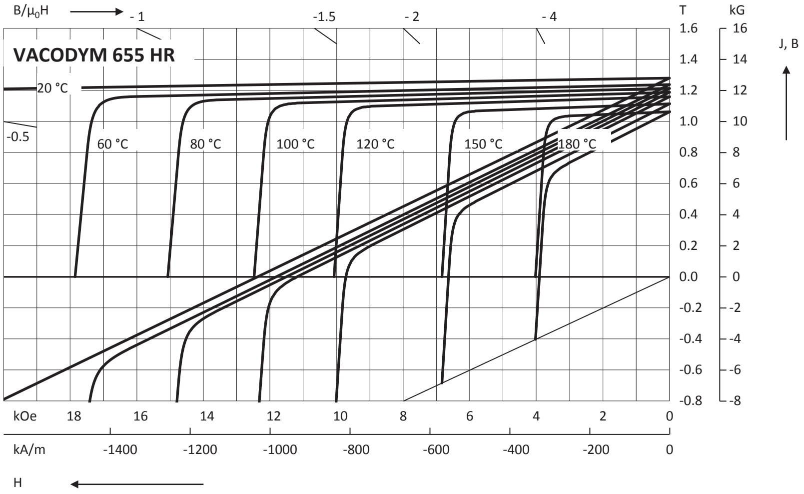
Typical irreversible losses at different working points as a function of temperature

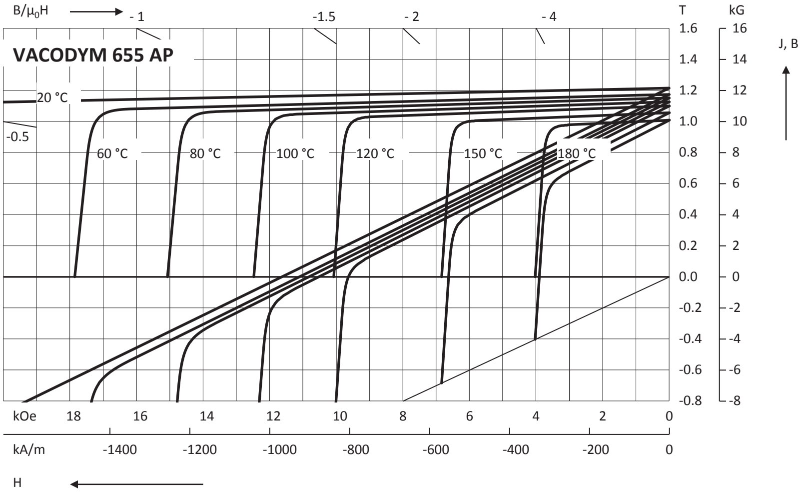


SINTERED MAGNETS BASED ON NdFeB

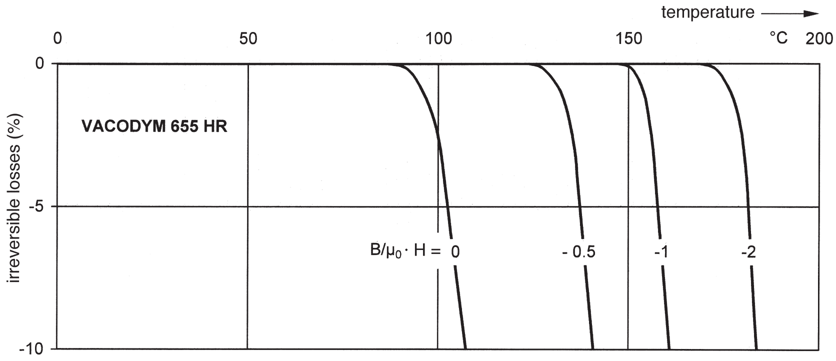
VACODYM 655

Typical demagnetization curves B(H) and J(H) at different temperatures





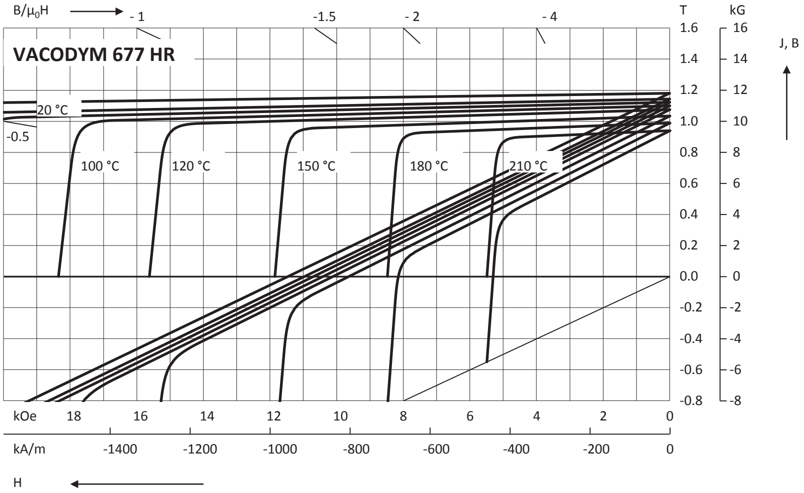
Typical irreversible losses at different working points as a function of temperature

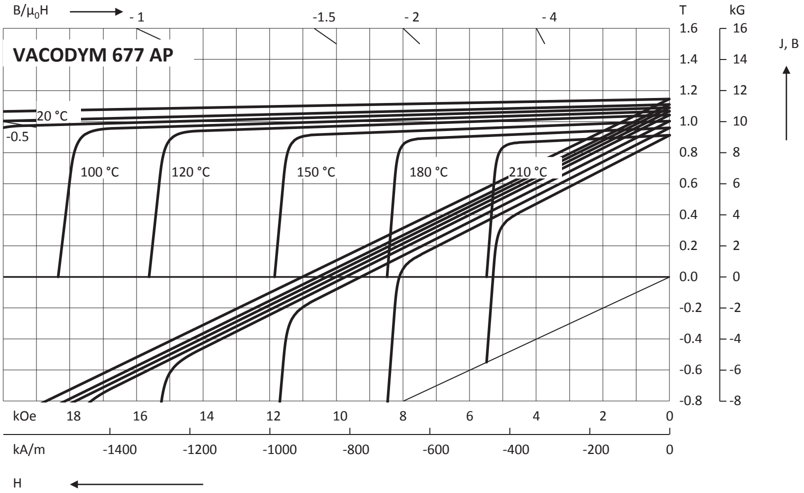


SINTERED MAGNETS BASED ON NdFeB

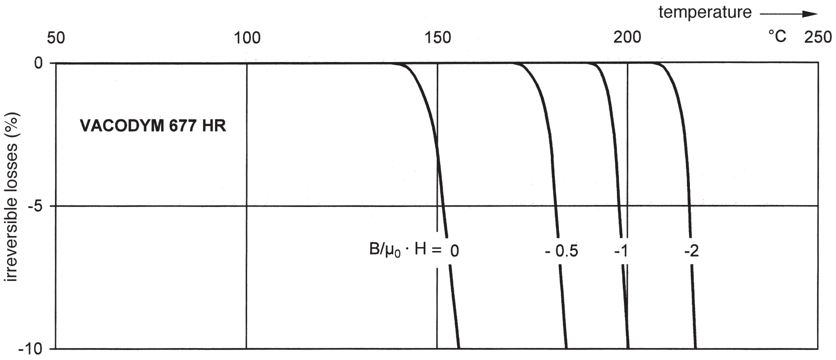
VACODYM 677

Typical demagnetization curves B(H) and J(H) at different temperatures





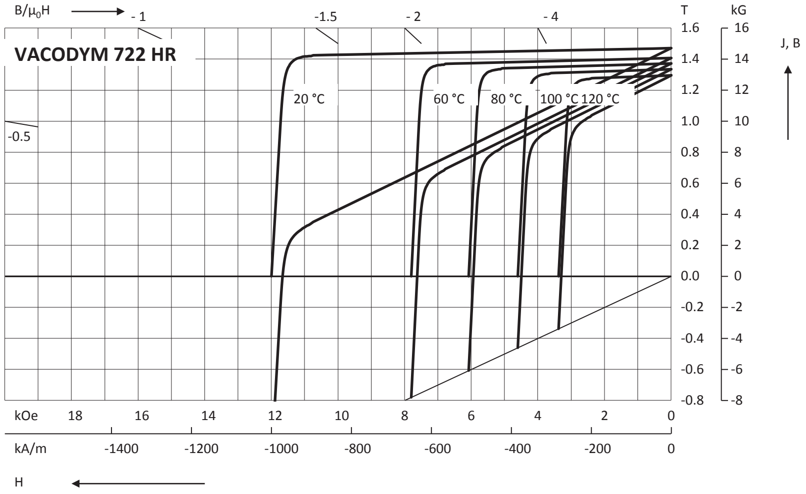
Typical irreversible losses at different working points as a function of temperature



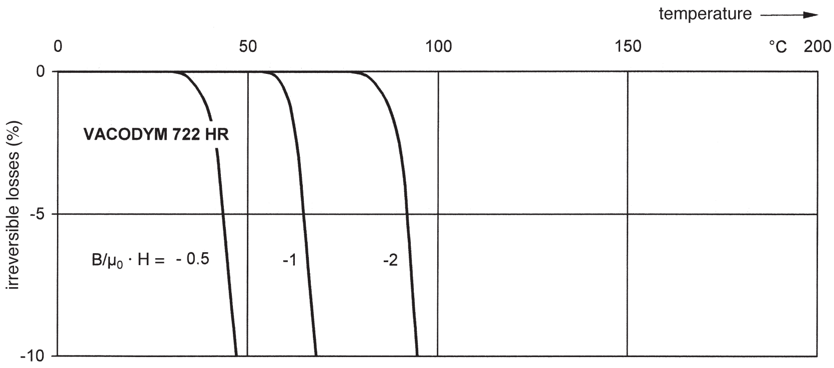
SINTERED MAGNETS BASED ON NdFeB

VACODYM 722

Typical demagnetization curves B(H) and J(H) at different temperatures



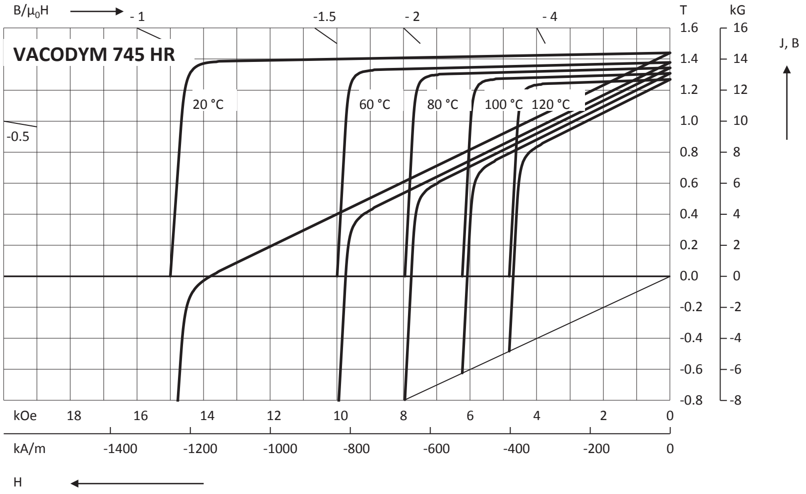
Typical irreversible losses at different working points as a function of temperature

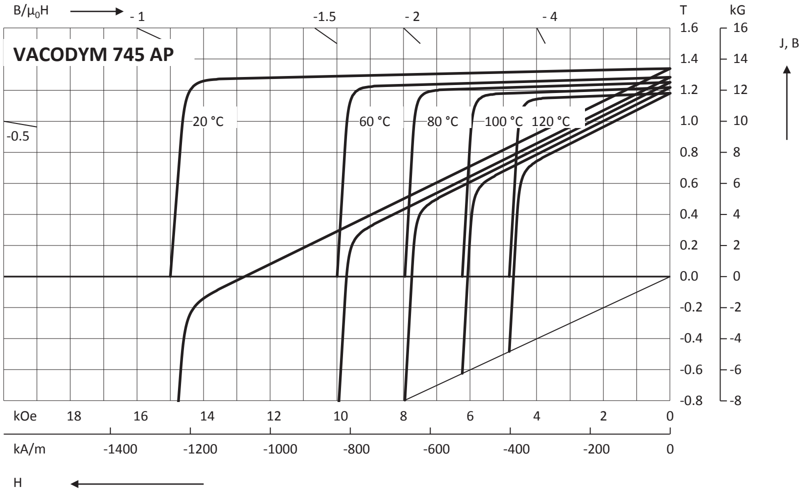


SINTERED MAGNETS BASED ON NdFeB

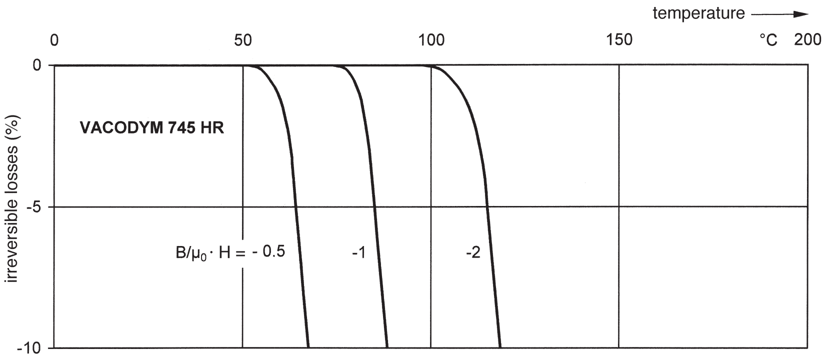
VACODYM 745

Typical demagnetization curves B(H) and J(H) at different temperatures





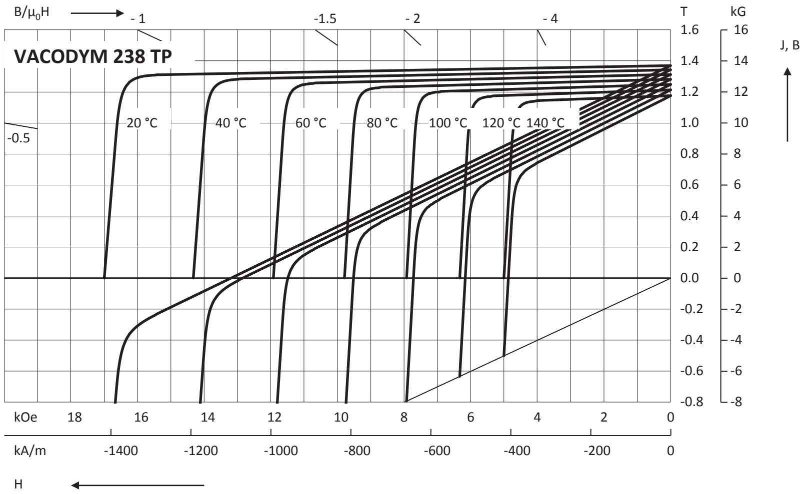
Typical irreversible losses at different working points as a function of temperature

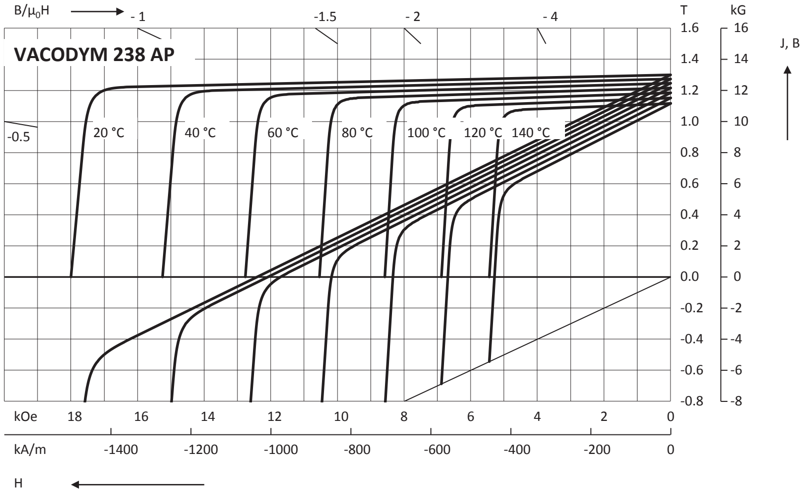


SINTERED MAGNETS BASED ON NdFeB

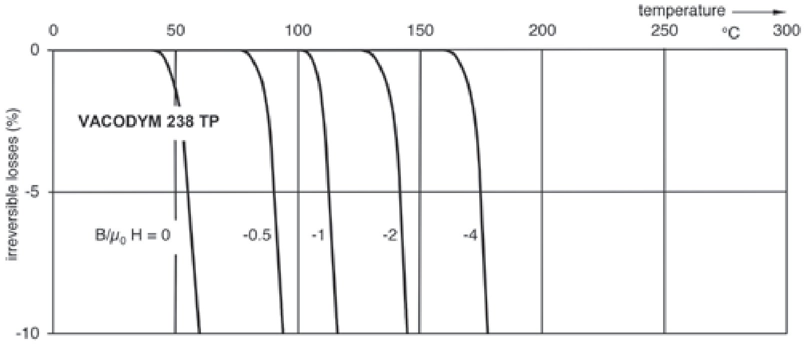
VACODYM 238

Typical demagnetization curves B(H) and J(H) at different temperatures





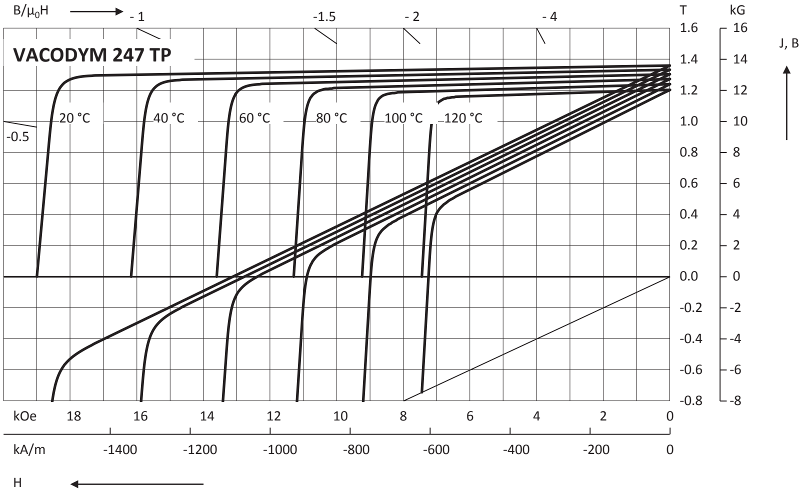
Typical irreversible losses at different working points as a function of temperature

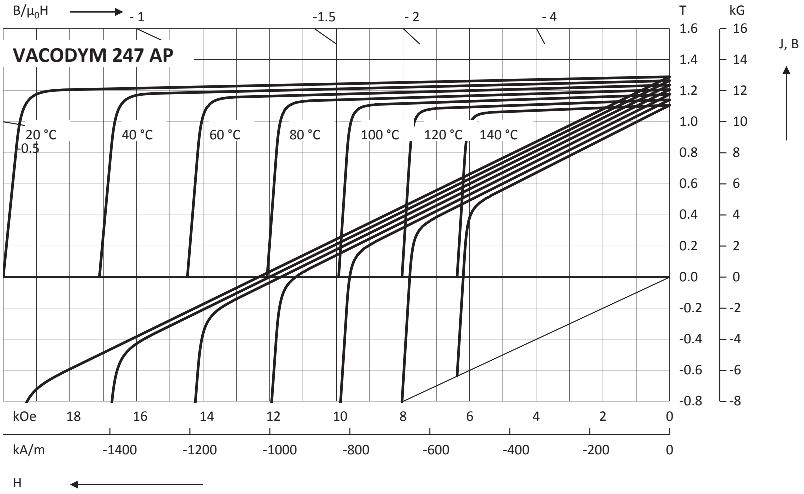


SINTERED MAGNETS BASED ON NdFeB

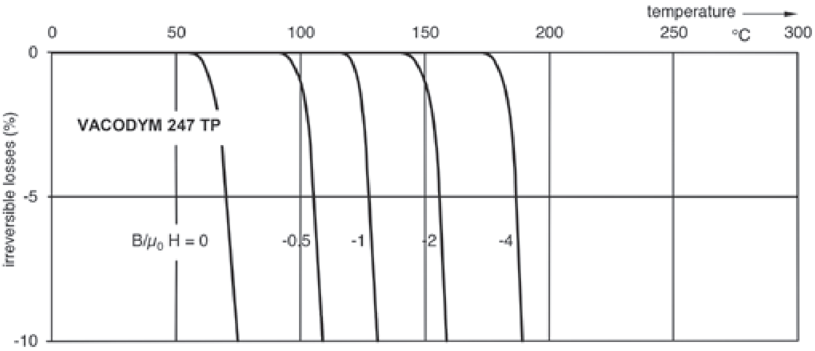
VACODYM 247

Typical demagnetization curves B(H) and J(H) at different temperatures





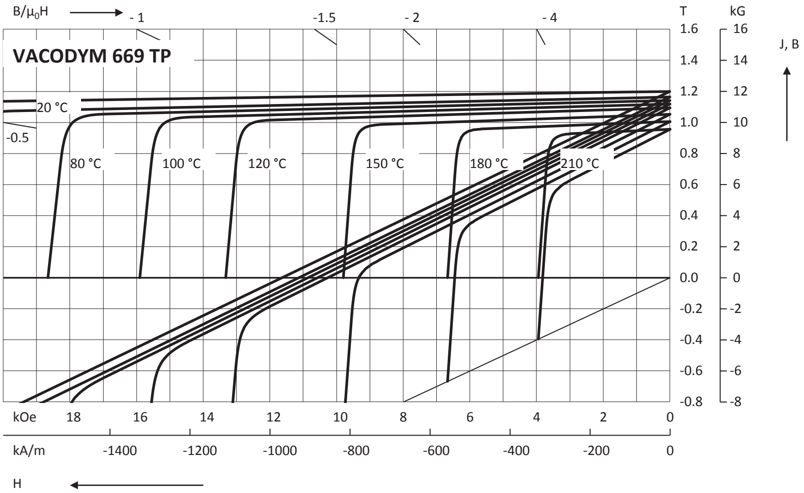
Typical irreversible losses at different working points as a function of temperature

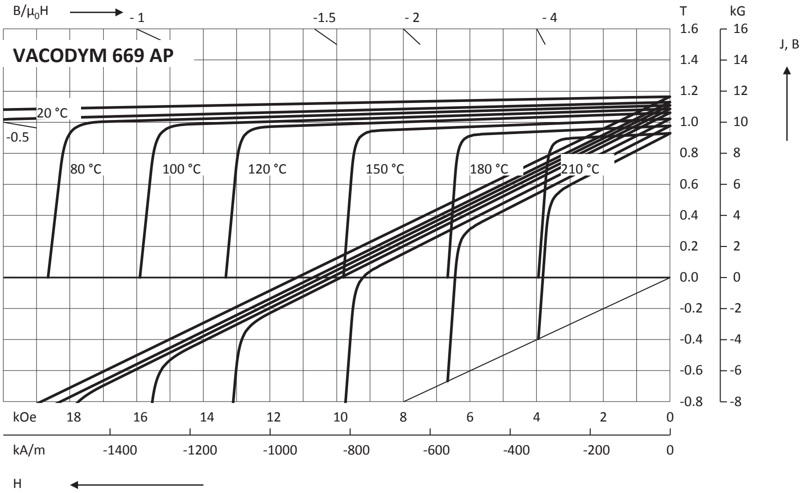


SINTERED MAGNETS BASED ON NdFeB

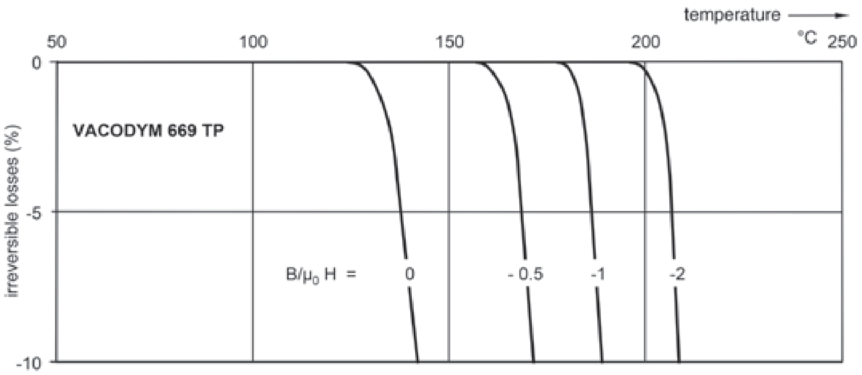
VACODYM 669

Typical demagnetization curves B(H) and J(H) at different temperatures





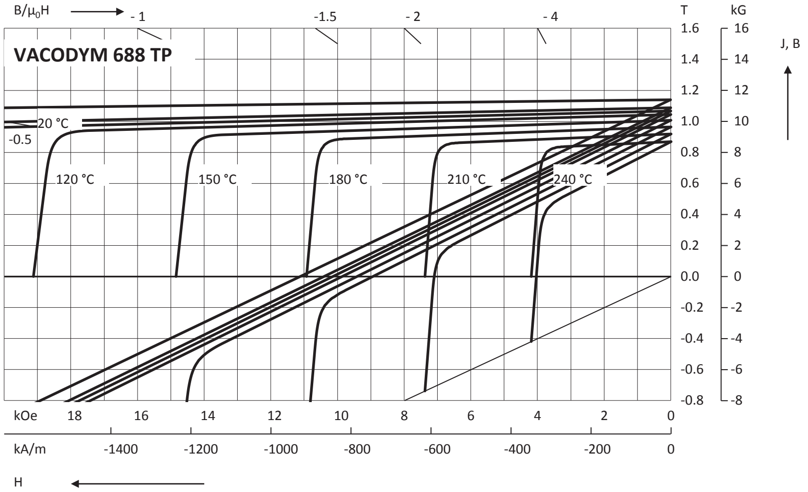
Typical irreversible losses at different working points as a function of temperature

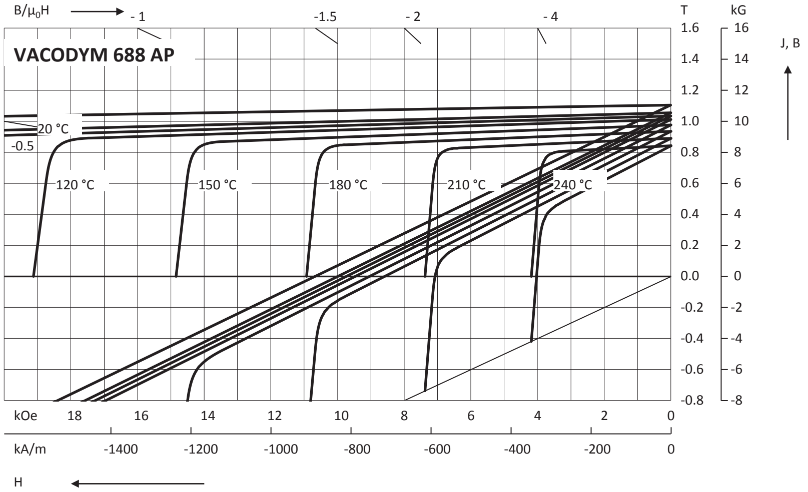


SINTERED MAGNETS BASED ON NdFeB

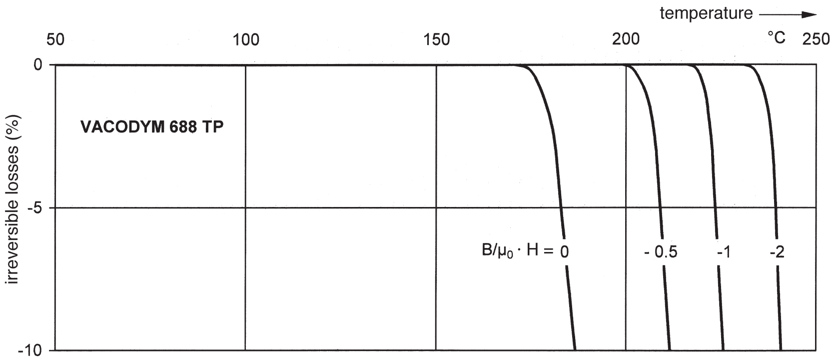
VACODYM 688

Typical demagnetization curves B(H) and J(H) at different temperatures





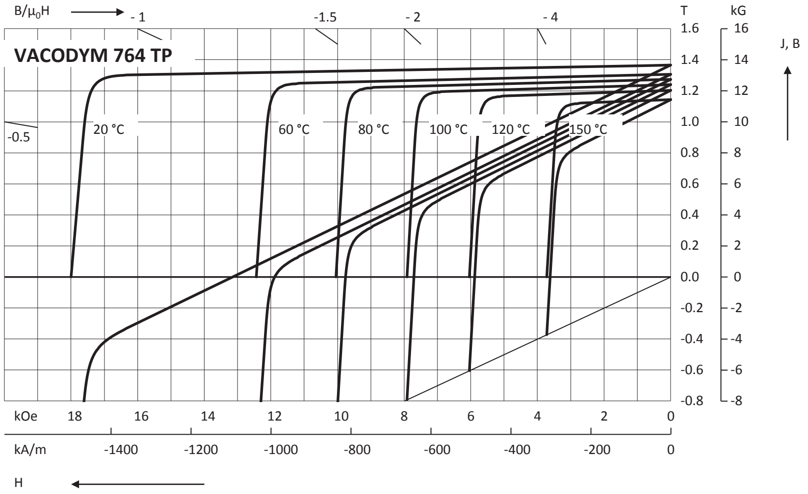
Typical irreversible losses at different working points as a function of temperature

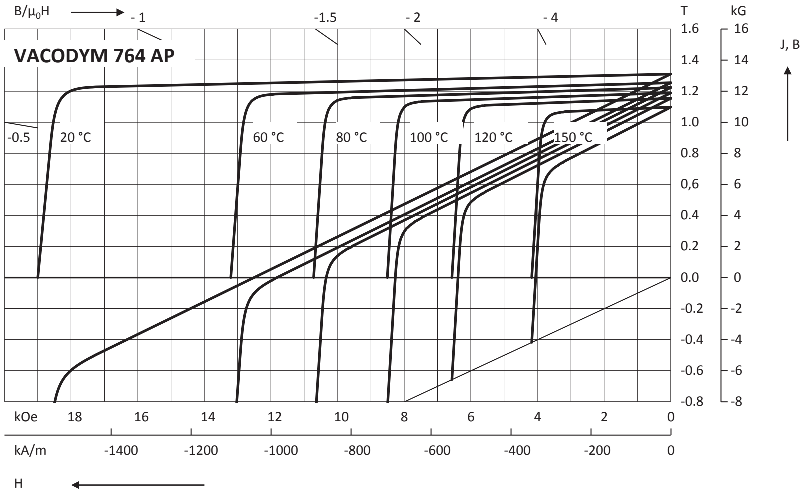


SINTERED MAGNETS BASED ON NdFeB

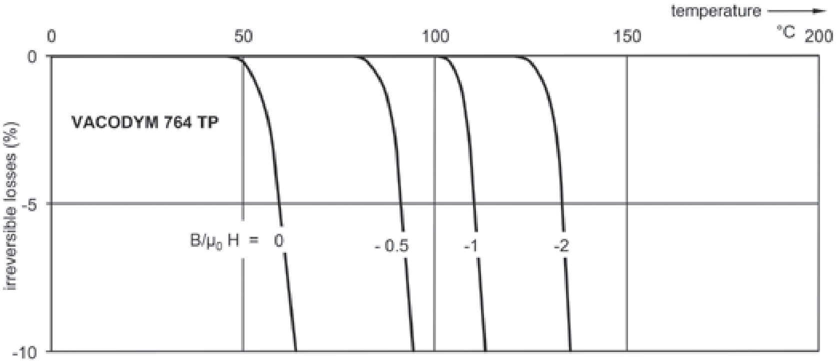
VACODYM 764

Typical demagnetization curves B(H) and J(H) at different temperatures





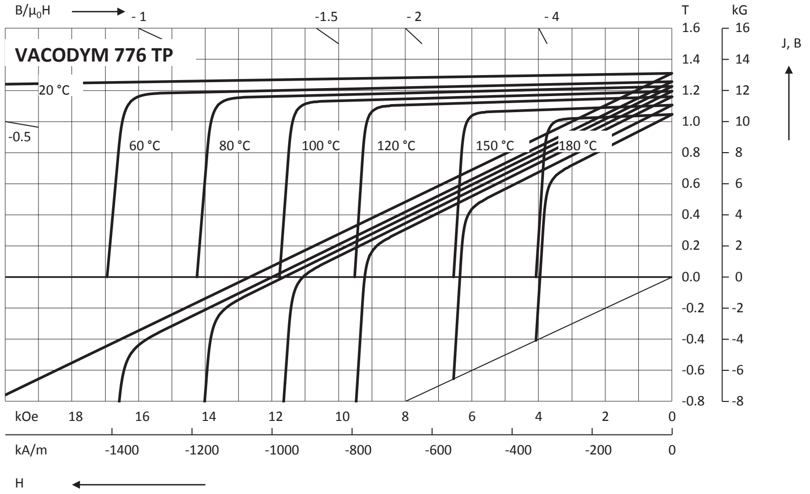
Typical irreversible losses at different working points as a function of temperature

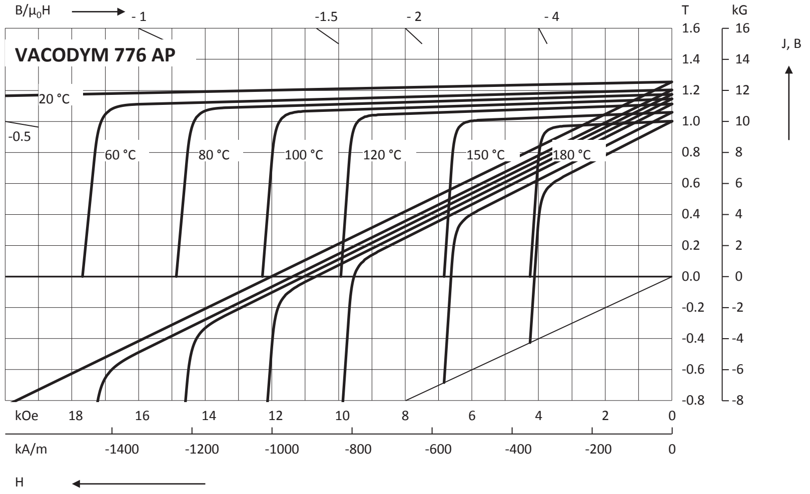


SINTERED MAGNETS BASED ON NdFeB

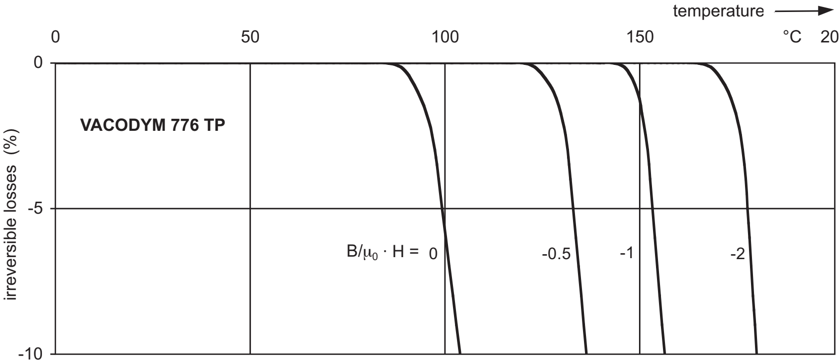
VACODYM 776

Typical demagnetization curves B(H) and J(H) at different temperatures





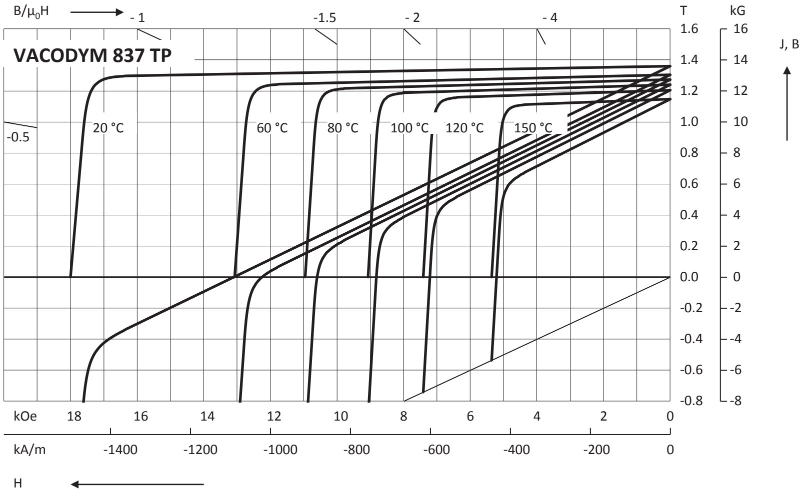
Typical irreversible losses at different working points as a function of temperature

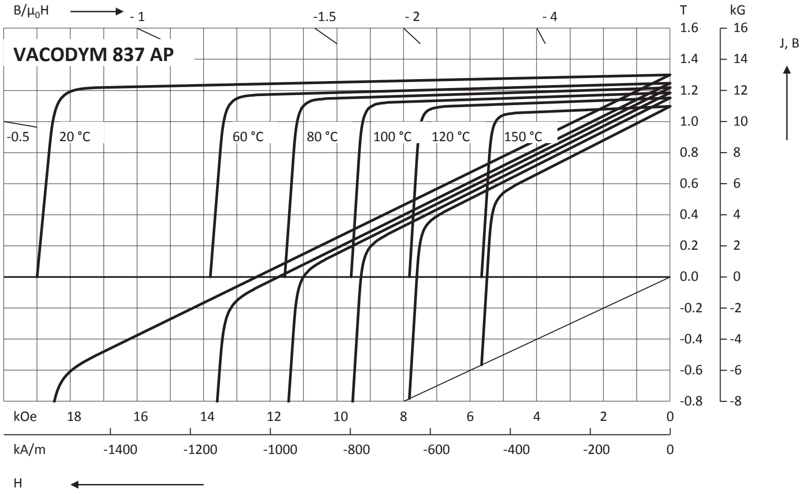


SINTERED MAGNETS BASED ON NdFeB

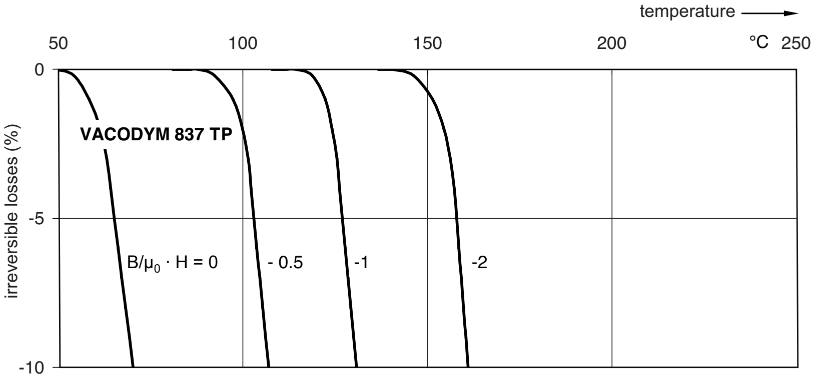
VACODYM 837

Typical demagnetization curves B(H) and J(H) at different temperatures





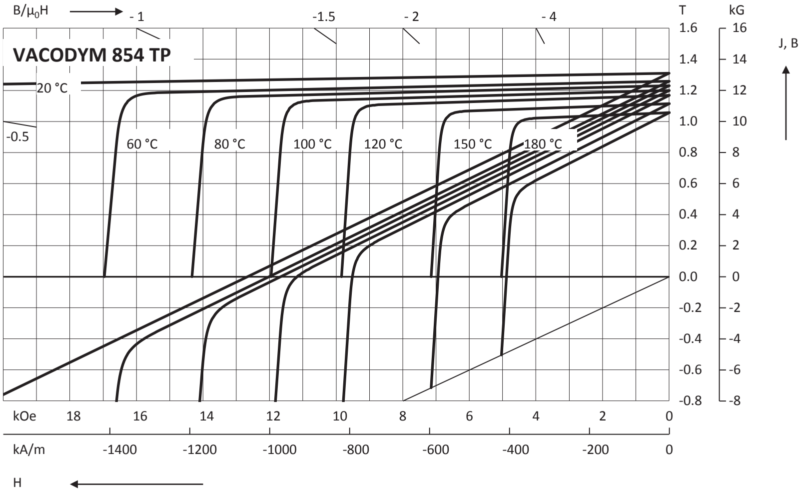
Typical irreversible losses at different working points as a function of temperature

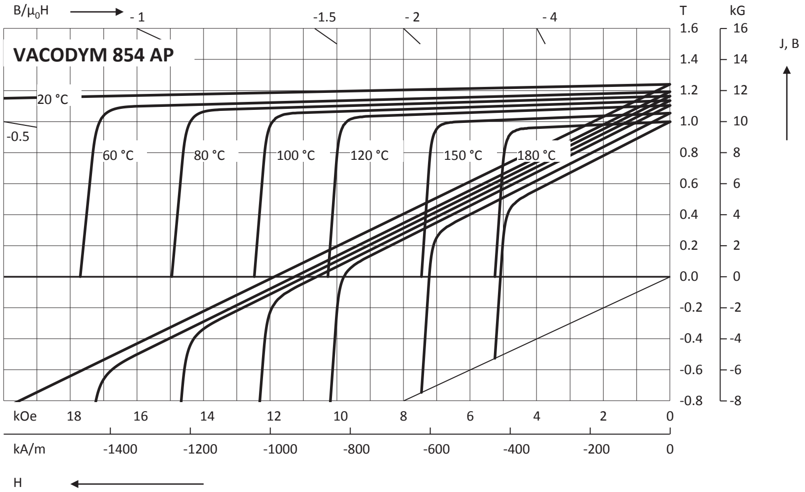


SINTERED MAGNETS BASED ON NdFeB

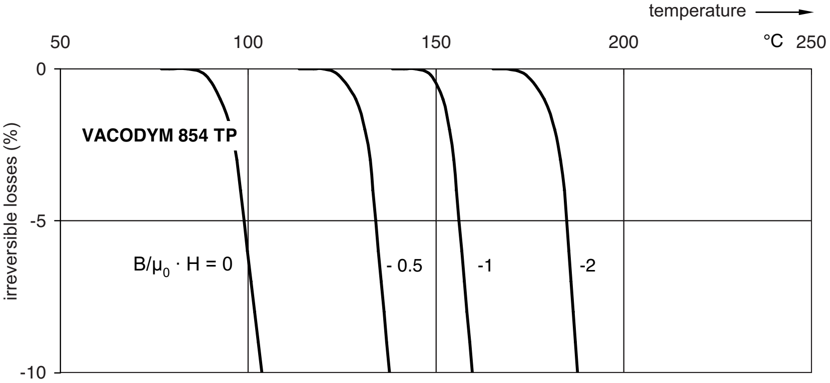
VACODYM 854

Typical demagnetization curves B(H) and J(H) at different temperatures





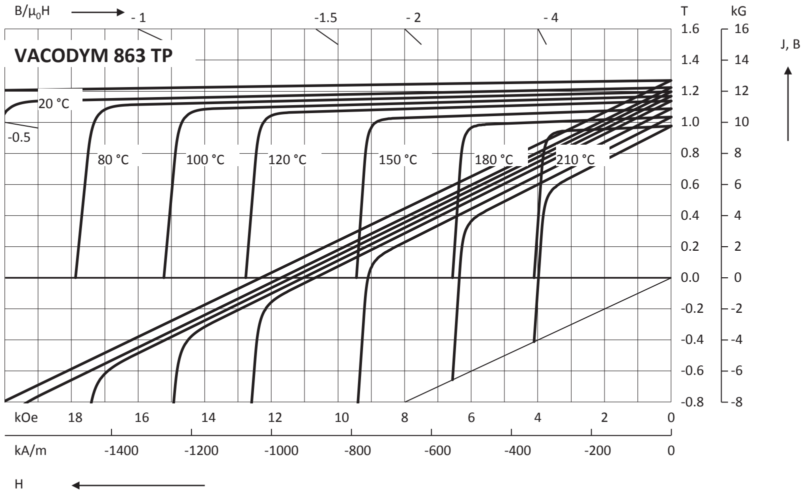
Typical irreversible losses at different working points as a function of temperature

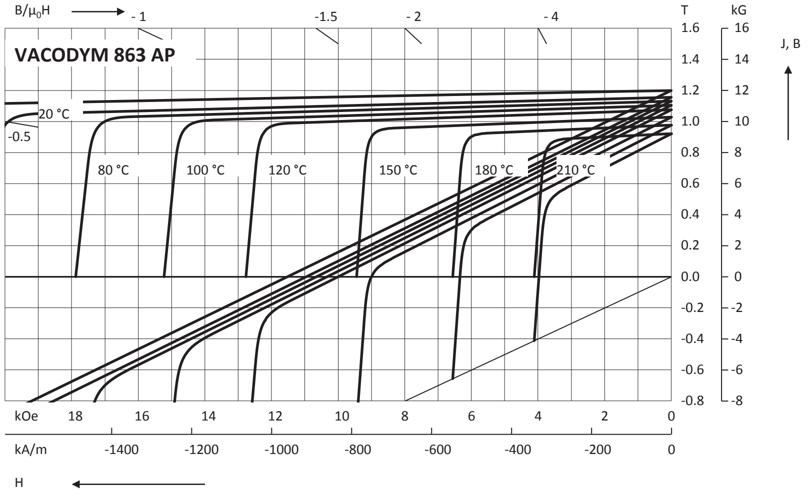


SINTERED MAGNETS BASED ON NdFeB

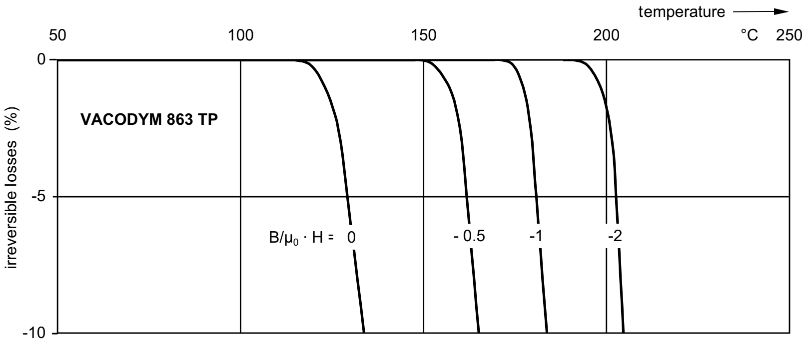
VACODYM 863

Typical demagnetization curves B(H) and J(H) at different temperatures





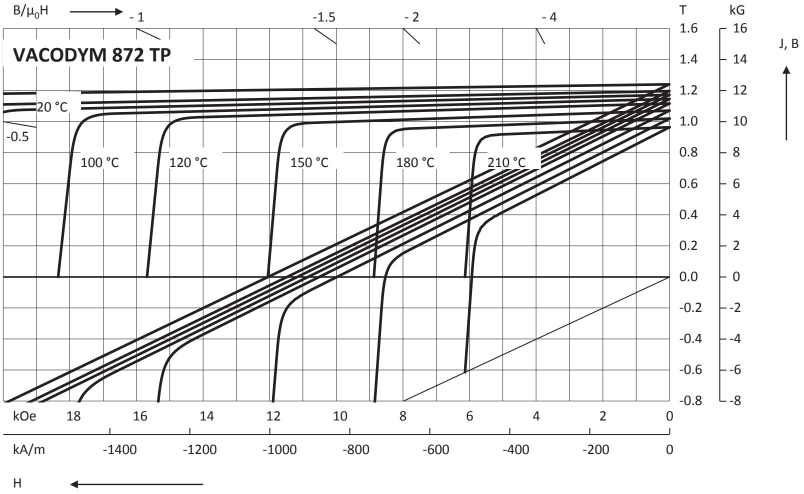
Typical irreversible losses at different working points as a function of temperature

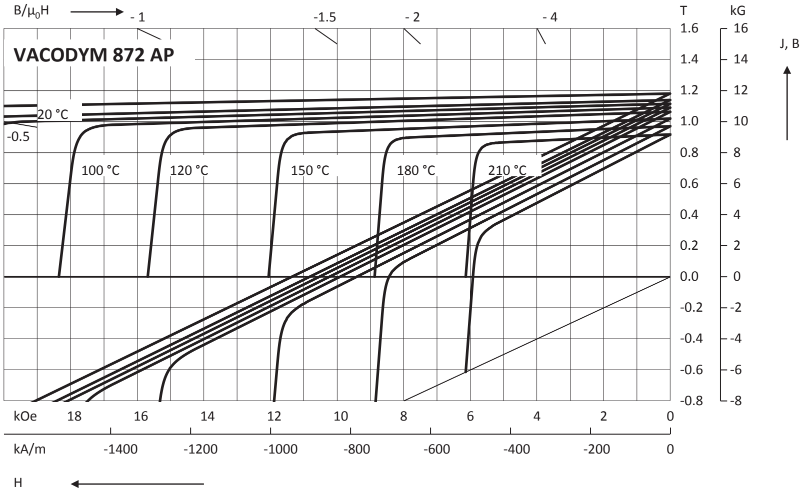


SINTERED MAGNETS BASED ON NdFeB

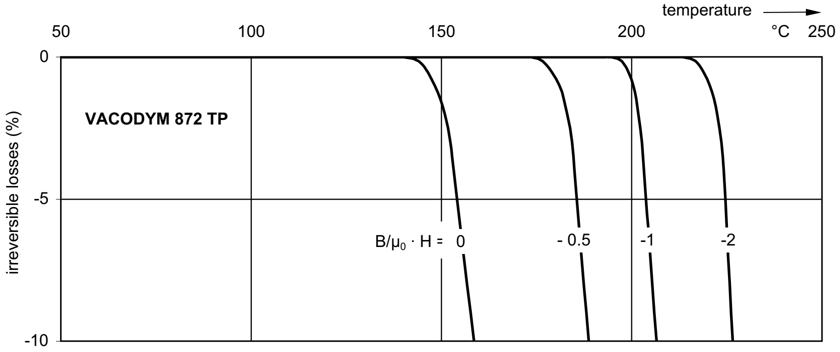
VACODYM 872

Typical demagnetization curves B(H) and J(H) at different temperatures





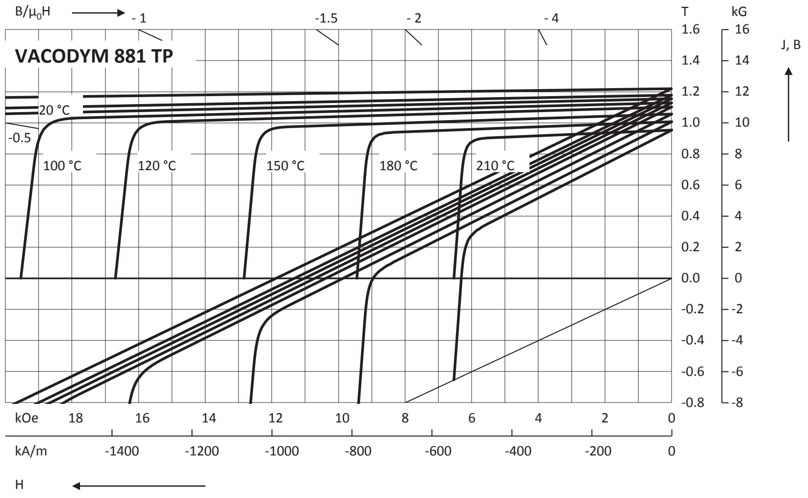
Typical irreversible losses at different working points as a function of temperature

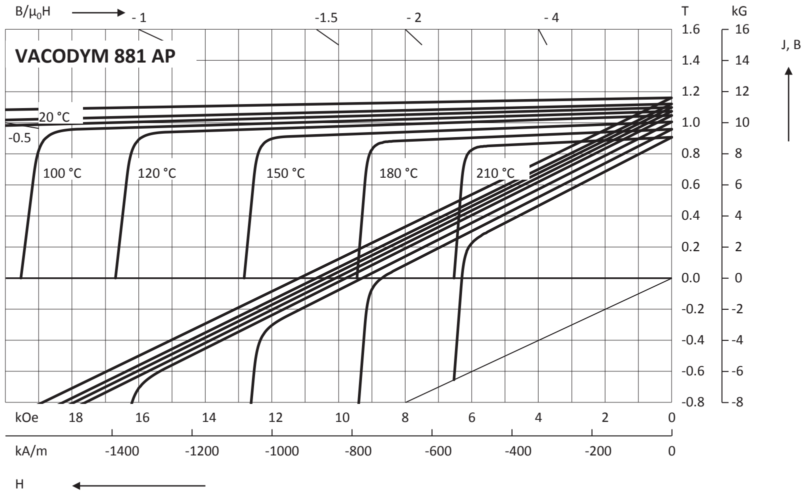


SINTERED MAGNETS BASED ON NdFeB

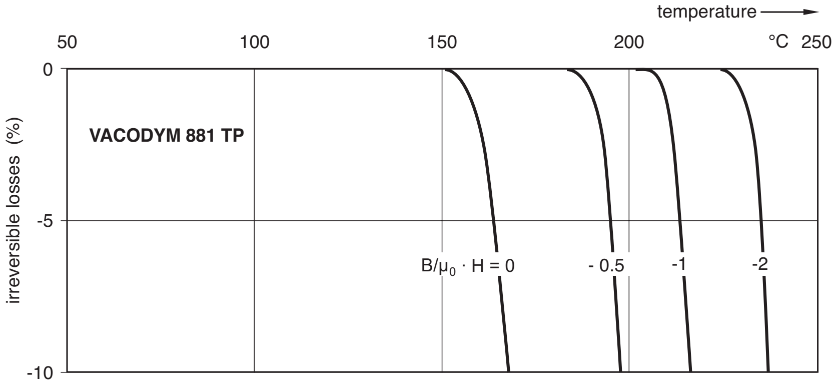
VACODYM 881

Typical demagnetization curves B(H) and J(H) at different temperatures





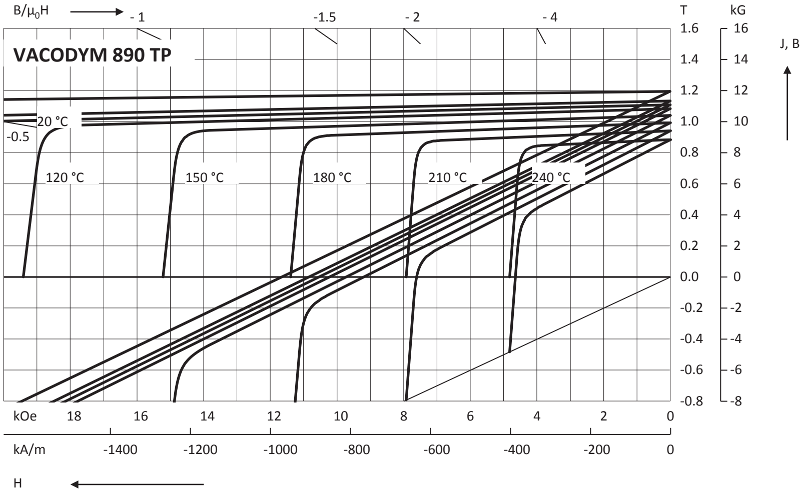
Typical irreversible losses at different working points as a function of temperature

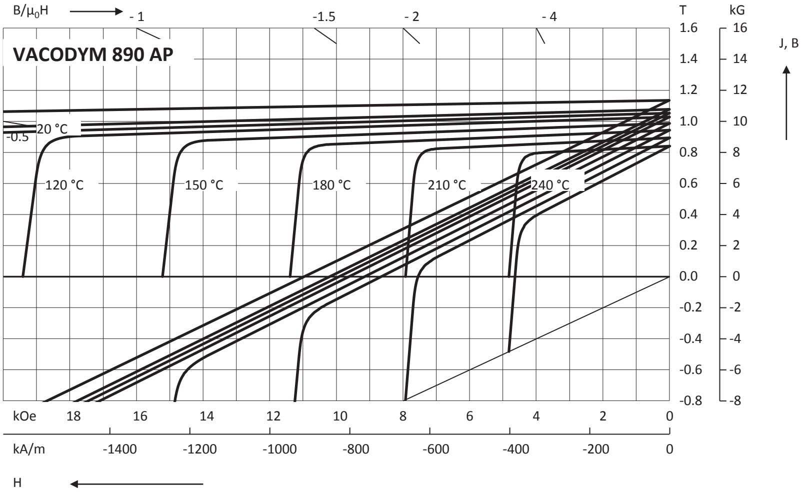


SINTERED MAGNETS BASED ON NdFeB

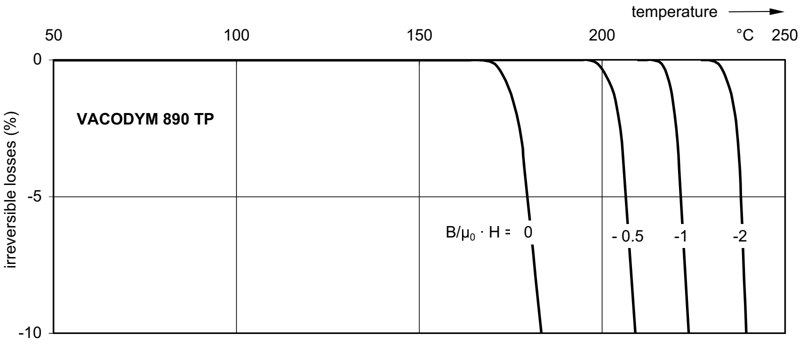
VACODYM 890

Typical demagnetization curves B(H) and J(H) at different temperatures





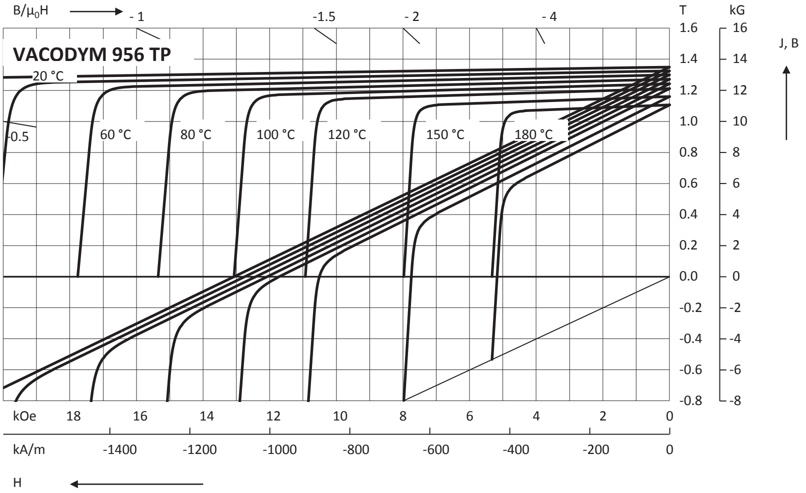
Typical irreversible losses at different working points as a function of temperature

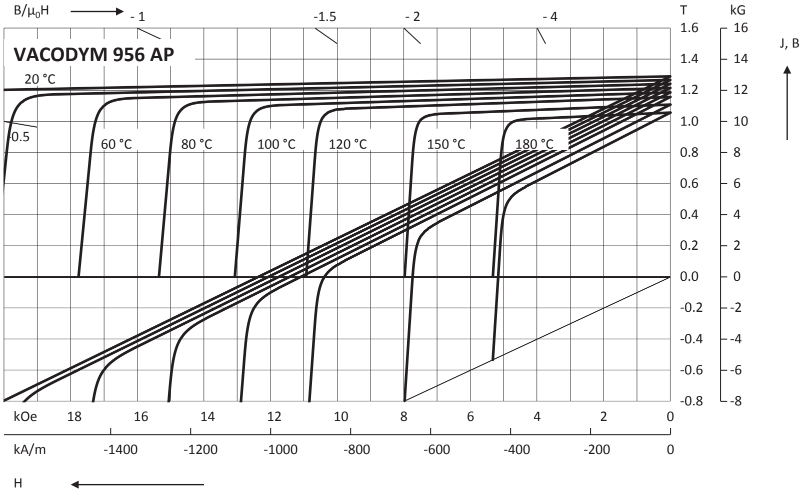


SINTERED MAGNETS BASED ON NdFeB

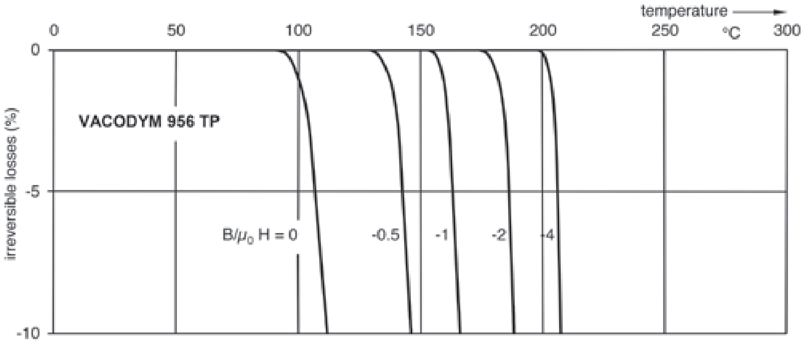
VACODYM 956

Typical demagnetization curves B(H) and J(H) at different temperatures





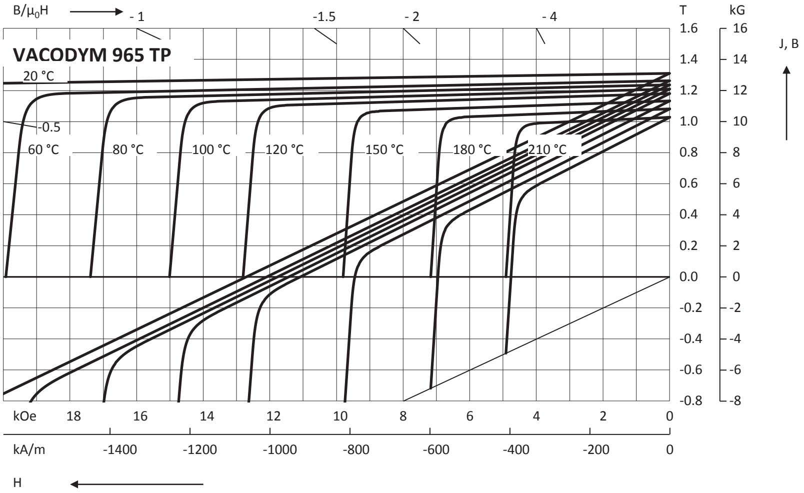
Typical irreversible losses at different working points as a function of temperature

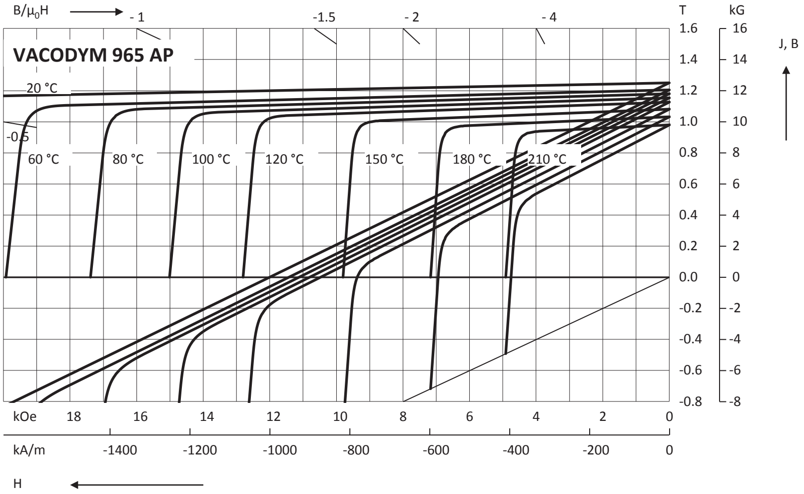


SINTERED MAGNETS BASED ON NdFeB

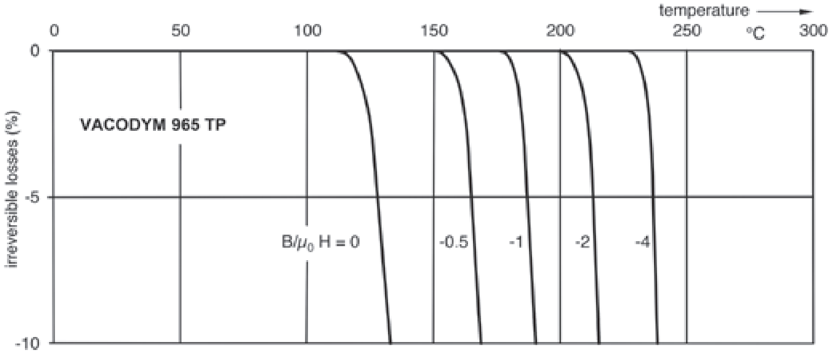
VACODYM 965

Typical demagnetization curves B(H) and J(H) at different temperatures





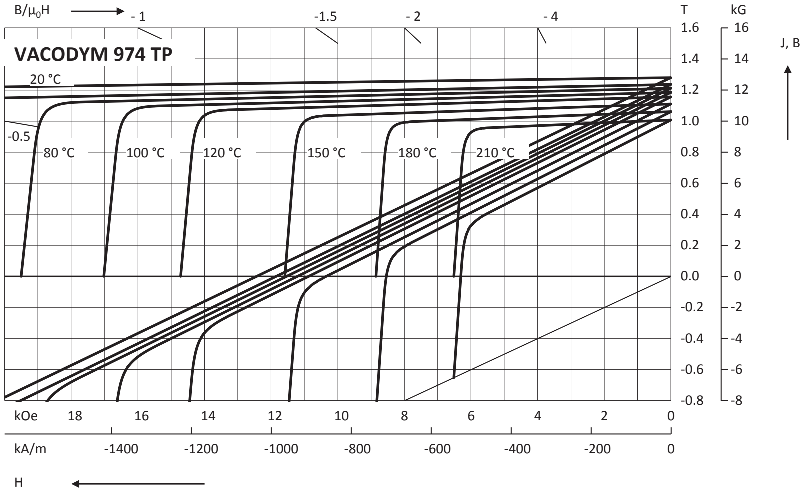
Typical irreversible losses at different working points as a function of temperature

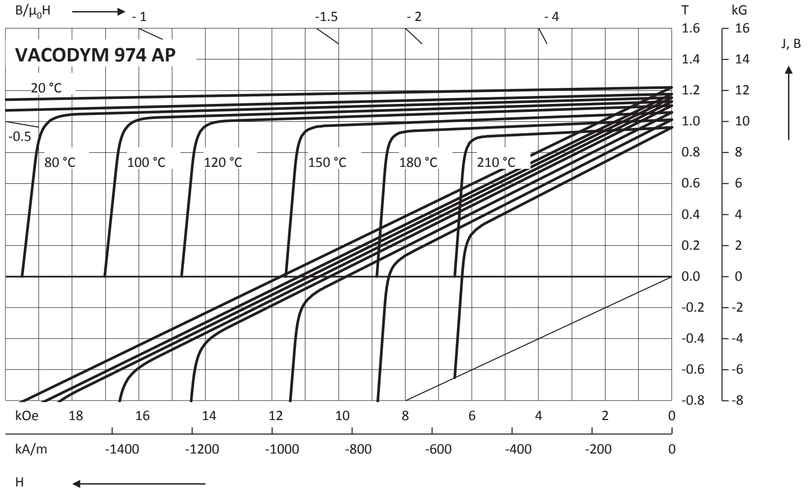


SINTERED MAGNETS BASED ON NdFeB

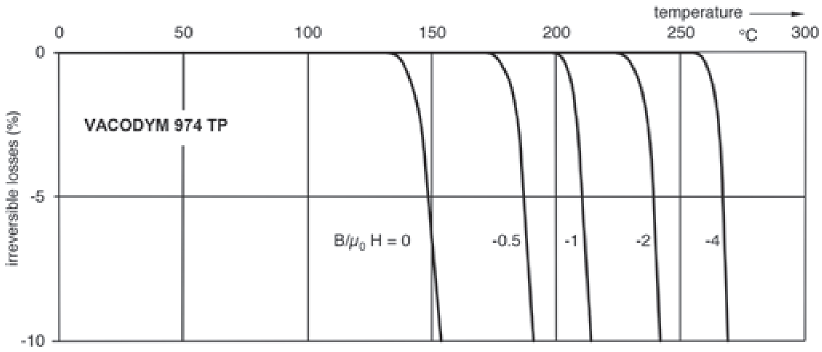
VACODYM 974

Typical demagnetization curves B(H) and J(H) at different temperatures





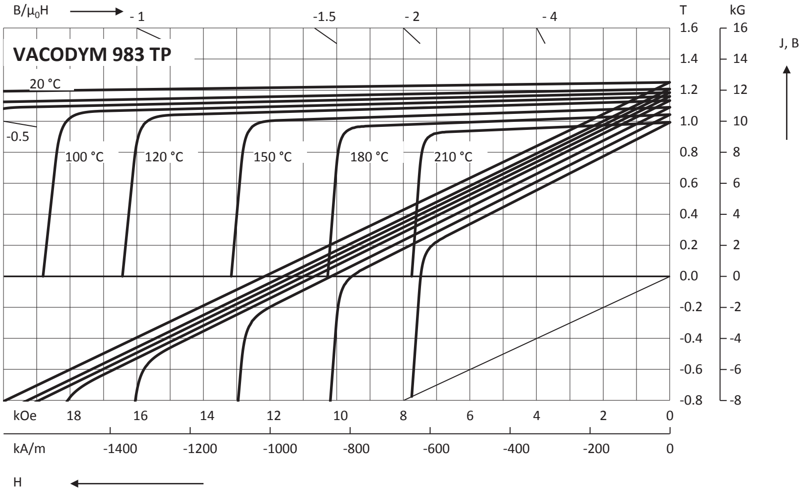
Typical irreversible losses at different working points as a function of temperature

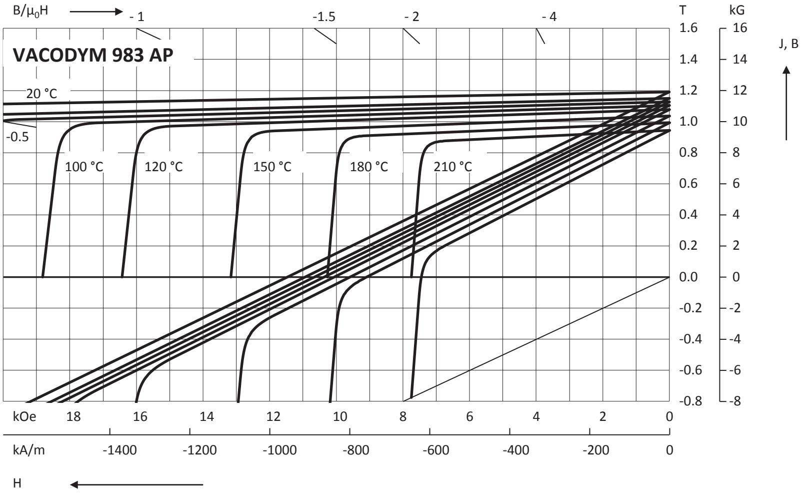


SINTERED MAGNETS BASED ON NdFeB

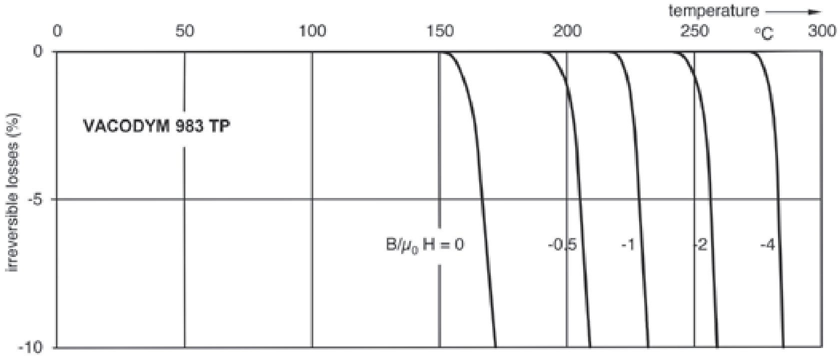
VACODYM 983

Typical demagnetization curves B(H) and J(H) at different temperatures





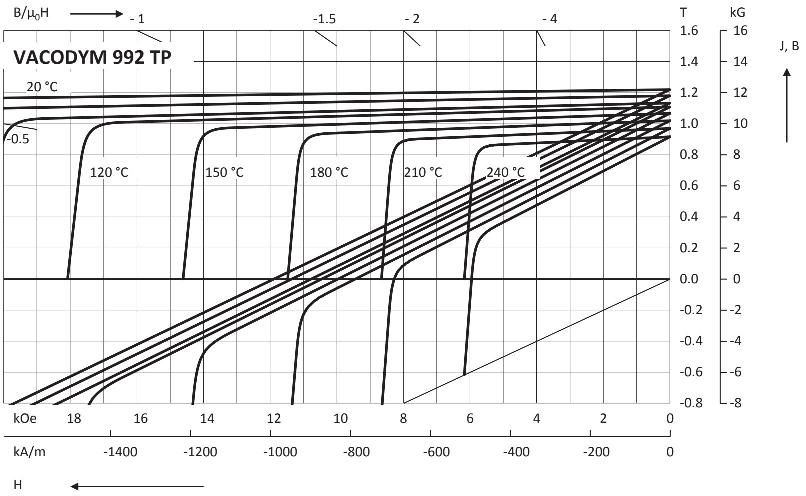
Typical irreversible losses at different working points as a function of temperature

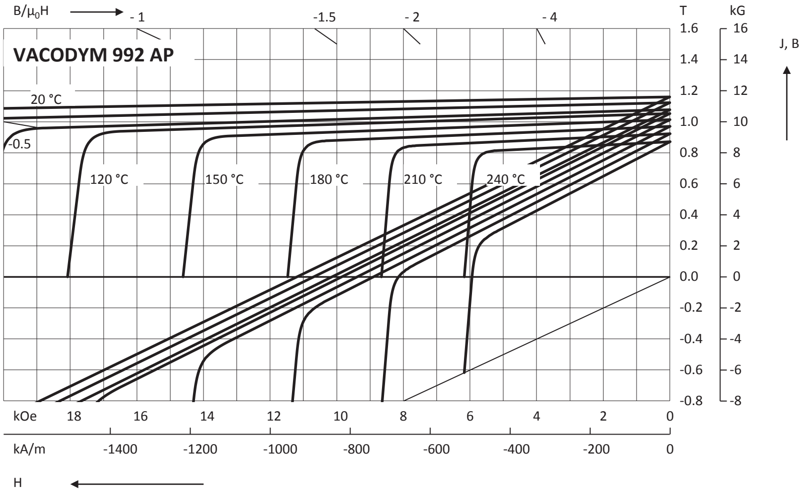


SINTERED MAGNETS BASED ON NdFeB

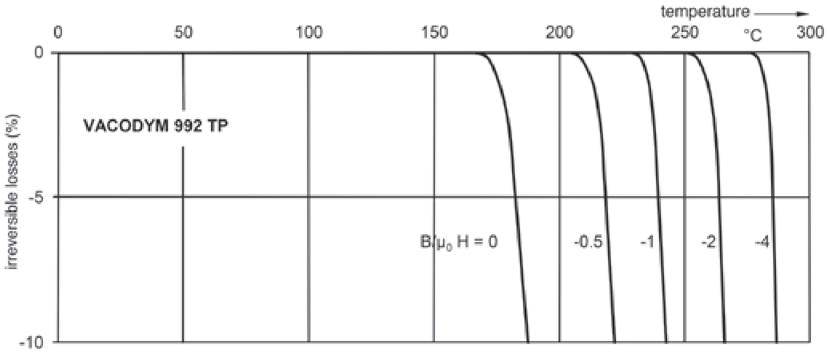
VACODYM 992

Typical demagnetization curves B(H) and J(H) at different temperatures





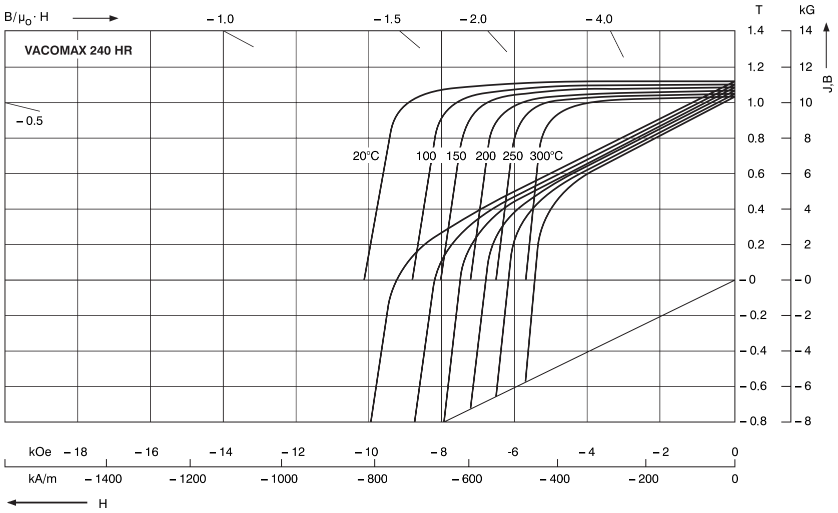
Typical irreversible losses at different working points as a function of temperature



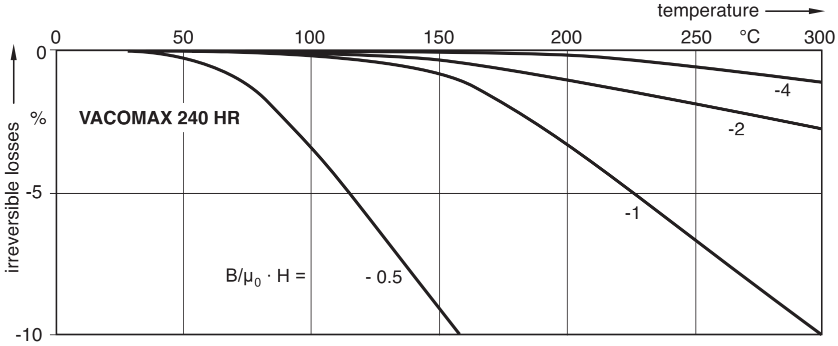
5.2.2 SINTERED MAGNETS BASED ON Sm_2Co_{17}

VACOMAX 240

Typical demagnetization curves B(H) and J(H) at different temperatures



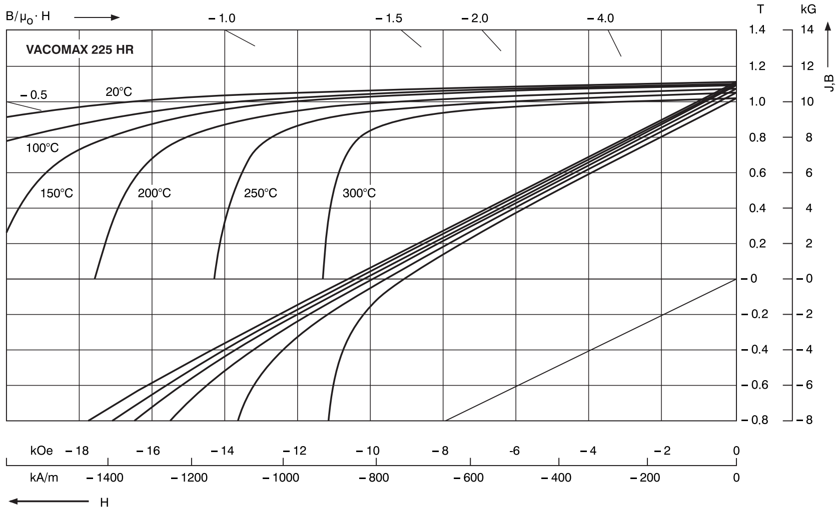
Typical irreversible losses at different working points as a function of temperature

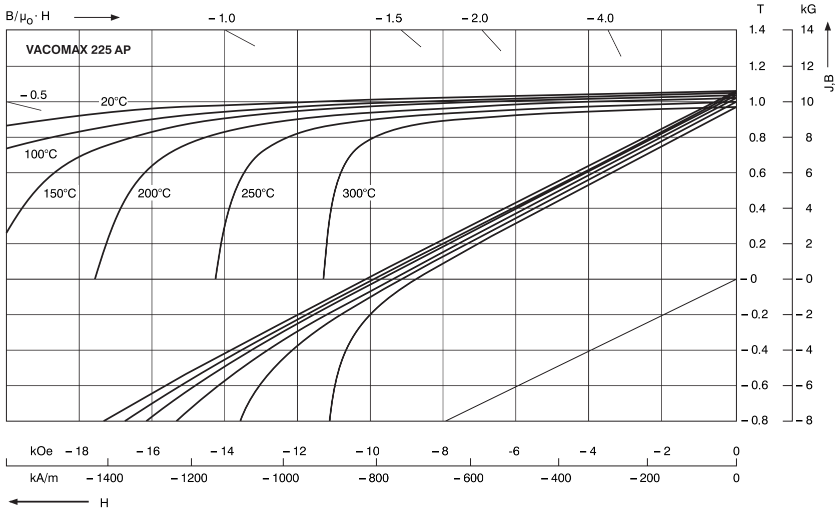


SINTERED MAGNETS BASED ON Sm_2Co_{17}

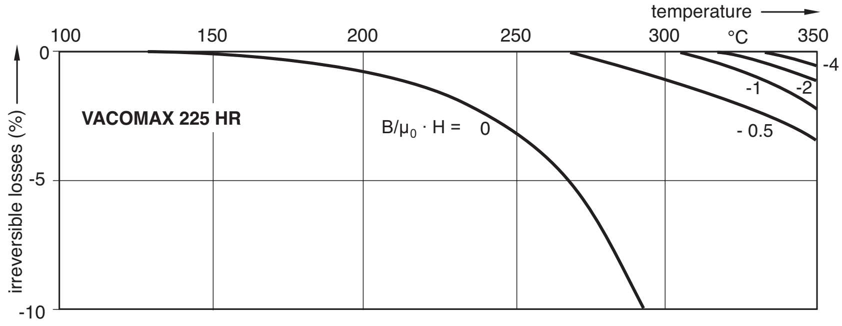
VACOMAX 225

Typical demagnetization curves B(H) and J(H) at different temperatures





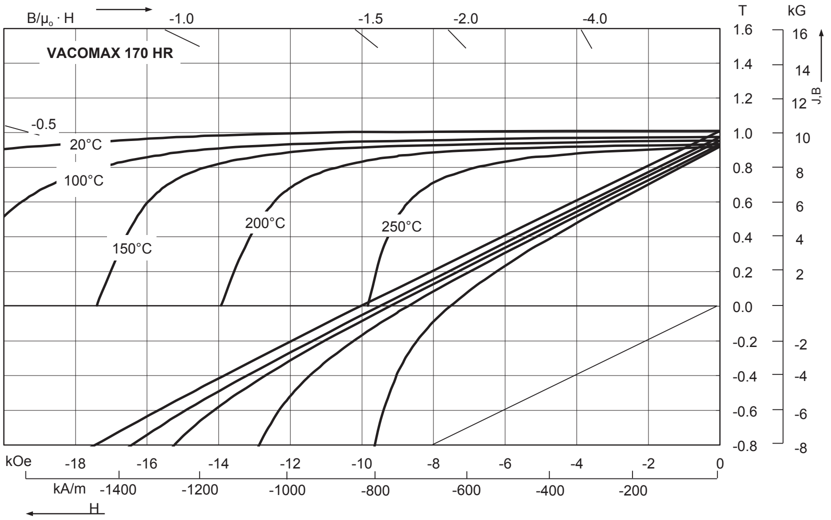
Typical irreversible losses at different working points as a function of temperature



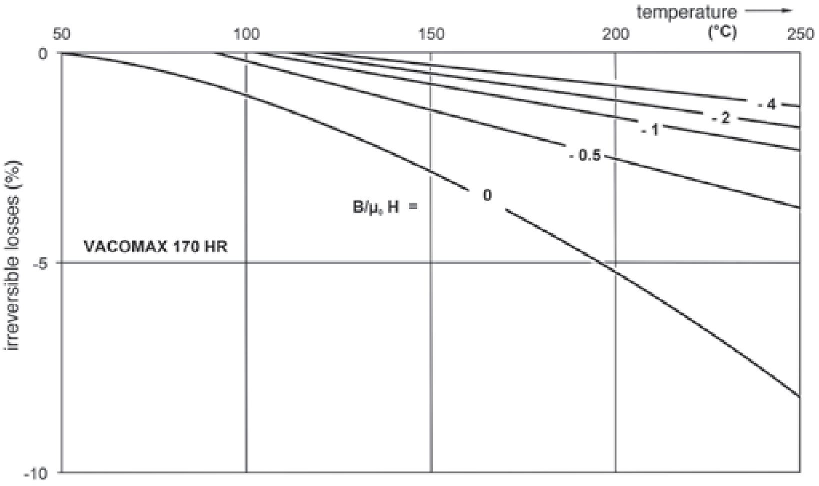
5.2.3 SINTERED MAGNETS BASED ON $SmCo_5$

VACOMAX 170 HR

Typical demagnetization curves B(H) and J(H) at different temperatures



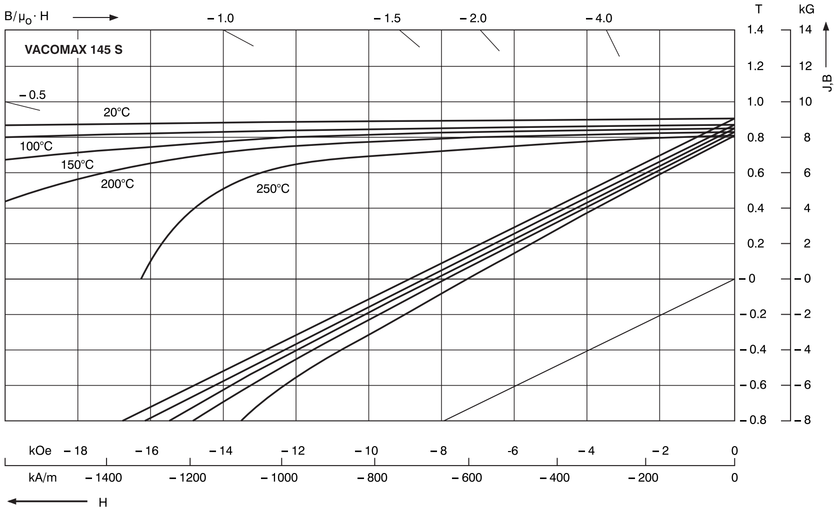
Typical irreversible losses at different working points as a function of temperature



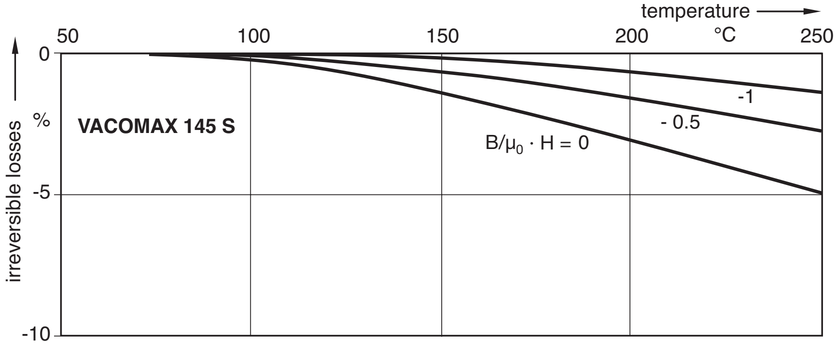
SINTERED MAGNETS BASED ON $SmCo_5$

VACOMAX 145

Typical demagnetization curves B(H) and J(H) at different temperatures



Typical irreversible losses at different working points as a function of temperature



5.3 TEMPERATURE DEPENDENCE AND MAGNETIC LOSSES

The magnetic properties of permanent magnets depend on the operating temperature. The typical demagnetization curves of VACODYM and VACOMAX at different temperatures are shown on the individual alloy pages (see pages 21-47). When selecting the material and the dimensions of the magnets, the characteristic magnetic values and their temperature dependence must be considered (see Appendix on page 69 ″Technical Principles and Terms″). The temperature dependence of the demagnetization curves causes changes in the flux density, commonly referred to as magnetic losses. These losses fall into two categories: reversible losses and irreversible losses based on changes in magnetization of small areas of the magnets in opposing fields and/or in the case of an increase in the temperature as well as structural changes.

Reversible changes in the flux density are attributed to the temperature dependence of the saturation polarization and are solely a function of the alloy composition. They are described by the temperature coefficient of the remanence; its mean values for the individual materials are given in tables 1 or 2 (see pages 14-19). If certain applications call for temperature compensation, we recommend the use of a magnetic shunt made of THERMOFLUX®. In systems with slightly reduced flux values in the range of 20 °C to 100 °C, this achieves temperature coefficients $|TC| < 0.01$ %/°C .

Irreversible losses from demagnetization processes depend on the working point of the magnet and the maximum operating temperature. The typical irreversible losses to be expected for various working points B/μ_{oH} for various material grades are given on the individual alloy pages.

Irreversible changes can be compensated for by means of a stabilization process (aging). The optimum stabilization conditions should be requested for the respective application. In most cases, it is sufficient to heat the magnets in the installed state as a complete system for approximately one hour to slightly above the maximum operating temperature. The ″thermal after-effect″ can also be covered with this operation (see page 20). This pre-treatment achieves good stabilization. However, the reduction of the flux density by the respective irreversible changes must be taken into account.

Losses caused by demagnetization of small areas of the magnet can be eliminated by remagnetization. The maximum operating temperatures are restricted predominantly by the reduction of the magnetic properties. In order to avoid undesired irreversible structural changes, which cannot be recovered even by remagnetization, VACODYM magnets must not be heated above 350 °C and VACOMAX magnets not above 400 °C.

Independent from this, chemical reactions with the ambient atmosphere and contact materials (e.g. adhesives) must be prevented. This applies particularly to reactions with potential hydrogen production (see Section 7 ″Corrosion Behaviour, Surface Protection and Coatings″). Radioactive radiation over a longer period can cause irreversible magnetic losses in RE magnets.

VACOMAX can be used at liquid helium temperatures. For applications using VACODYM below approx. 150 K, our new grades VACODYM 131 TP and 131 DTP are suitable. Please consult our experts to discuss your application.

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5.4 MAGNETIZATION OF RARE EARTH MATERIALS

Full magnetization is a precondition for achieving the typical key values that are listed in table 1 or 2 for the various permanent magnet materials. The required minimum field strengths of the inner magnetizing field H_{mag} are obtained from the magnetization behaviour of the respective materials. They are shown in table 4, page 19 and Fig. 8, page 50. To achieve the inner magnetizing field H_{mag}, the given external field H_{ext} must be increased by the value of the demagnetizing field H_a, determined by the working point (it must also be ensured that the magnetization field is maintained for long enough to avoid demagnetizing eddy currents):

$$|H_{ext}| = |H_{mag}| + |H_a|$$

Due to the high coercivities of VACODYM and VACOMAX, the magnets can also be magnetized outside the system. As a result, handling of the magnets and assembly of the systems is more difficult, but the actual magnetization is much easier. In the case of the low-coercive grades VACODYM 510, 722/745 and also with VACOMAX 240, it must be ensured that the working point of the freely sheared magnet lies sufficiently above the ″knee″ of the B(H) demagnetization curve (compare Section Technical Principles and Terms, page 69).

Users are recommended to contact our experts before magnetizing VACODYM and VACOMAX magnets in a system.

The polarity of magnets made of VACODYM and particularly VACOMAX can only be completely reversed in very high magnetic fields (> approx. 8,000 kA/m).

DEMAGNETIZATION CURVES OF VACODYM AND VACOMAX AS A FUNCTION OF MAGNETIZING FIELD STRENGTH H_{MAG}

The magnetization behaviour of VACODYM and VACOMAX of the $SmCo_5$ type (Fig. 8a and 8b) is based on the so-called 'nucleation mechanism'. This easy magnetization is possible only from the thermally demagnetized condition. The 'pinning mechanism' is characteristic of the VACOMAX type Sm_2Co_{17} (Fig. 8c and 8d). VACOMAX 240 is easier to magnetize than VACOMAX 225 due to a special heat treatment.

Fig. 8a

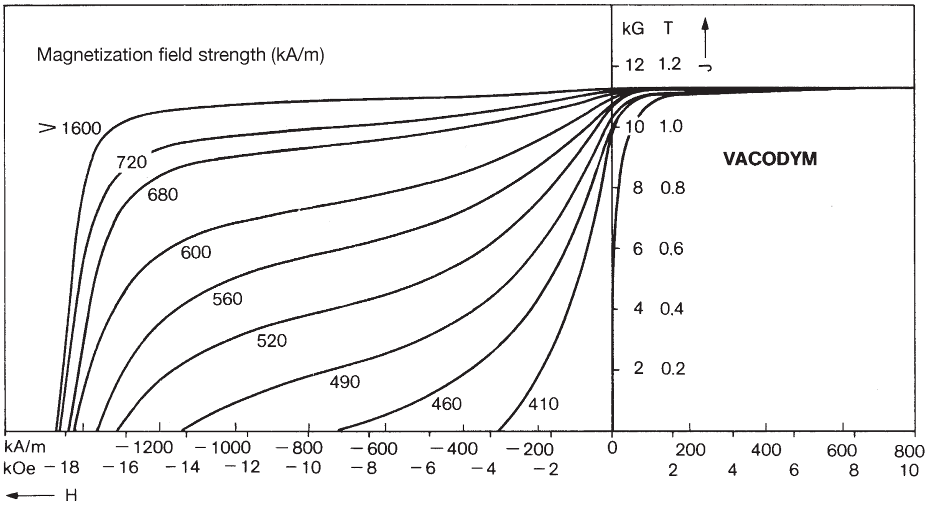


Fig. 8b

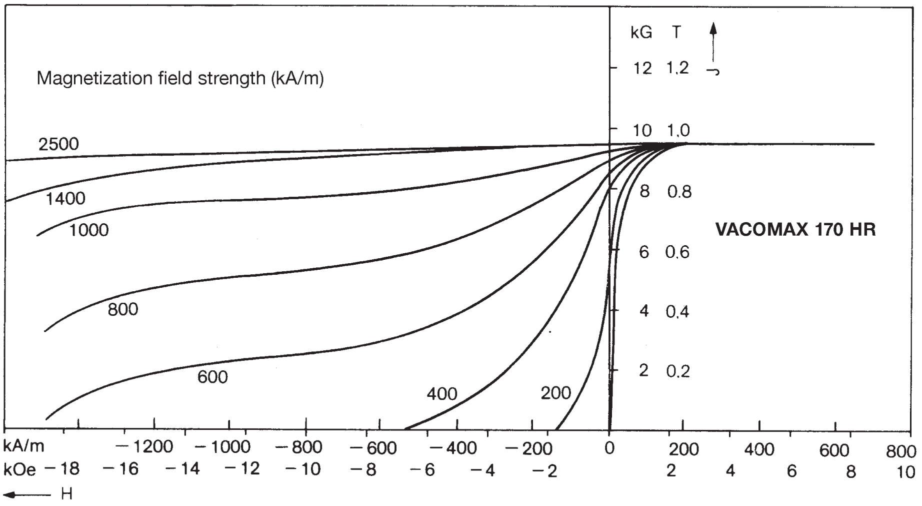


Fig. 8c

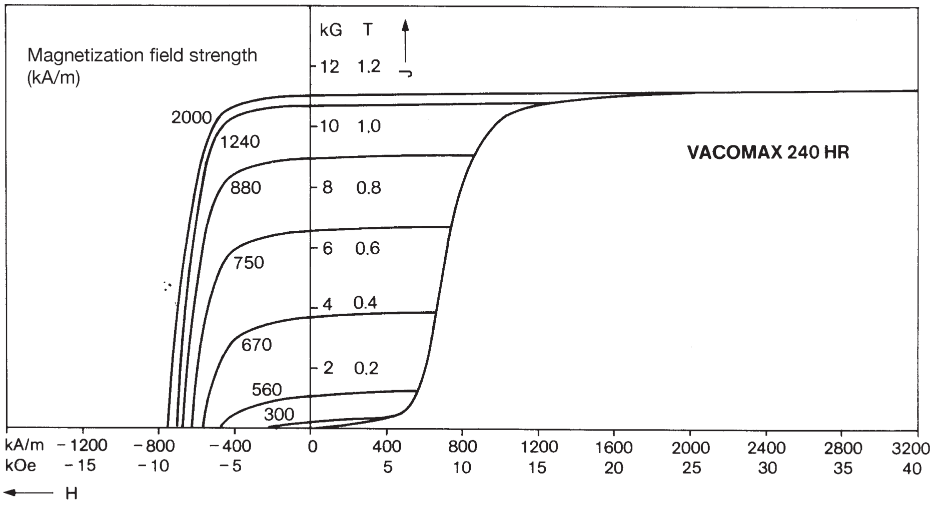
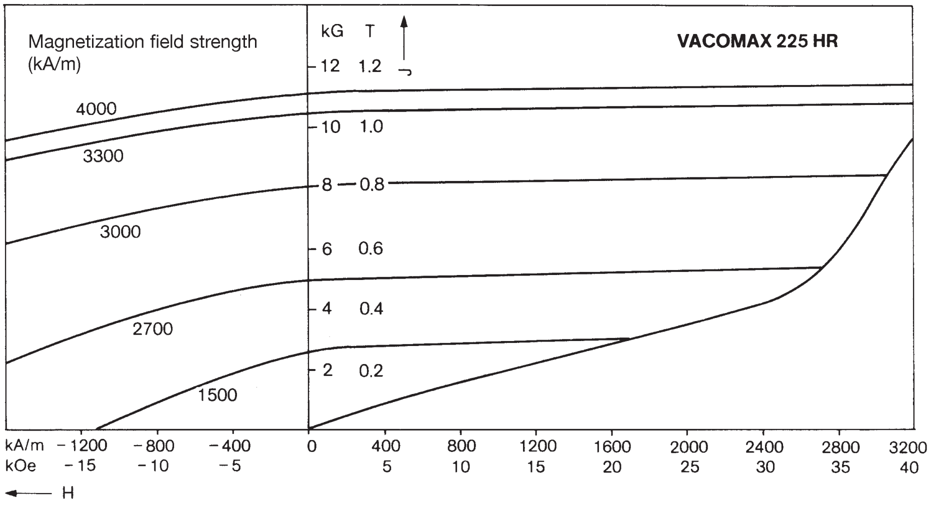

Magnetization field strength
(kA/m)
VACOMAX 240 HR
2000
1240
880
750
670
560
300
kG T
12 1.2
10 1.0
8 0.8
6 0.6
4 0.4
2 0.2
J
kA/m −1200 −800 −400 0 400 800 1200 1600 2000 2400 2800 3200
kOe −15 −10 −5 5 10 15 20 25 30 35 40
H

Fig. 8d


Magnetization field strength
(kA/m)
VACOMAX 225 HR
4000
3300
3000
2700
1500
kG T
12 1.2
10 1.0
8 0.8
6 0.6
4 0.4
2 0.2
J
kA/m −1200 −800 −400 0 400 800 1200 1600 2000 2400 2800 3200
kOe −15 −10 −5 5 10 15 20 25 30 35 40
H

6. LIMITATION OF IRREVERSIBLE LOSSES OF THE MAGNETIC MOMENT (H_{D5} VALUES)

A completely magnetized permanent magnet loses a part of its magnetic moment when it is exposed to an opposing magnetic field. Here, one must differentiate between reversible and irreversible losses. The reversible losses disappear when the magnet is no longer exposed to the opposing field. They are, in the first place, due to the reversible permeability of the magnet, which is in the range of $\mu_{rev} = 1.05$ for NdFeB-based magnets. In the case of the irreversible losses, parts of the magnet are reversed and losses remain after the removal of the opposing field.

In order to specify and also to measure the irreversible losses, two methods were used in the past:

- Aging of the magnet at increased temperatures and determination of the irreversible losses. This method is highly time and labour intensive and is therefore only used very rarely.

- Measurement of the J(H) curve and determination of the field strength, at the point at which J has reduced by 10 %. This field strength is also referred to as knee field strength $H_{K,90}$. The disadvantage of this method is that due to the reversible permeability of NdFeB-magnets with high coercivities H_{cJ}, not the irreversible losses, but only the reversible losses are taken into account.

The standardization bodies have therefore decided to measure the irreversible losses for NdFeB-magnets in an alternative way and to include these in the standard IEC 60404-8-1 Ed. 3. VACUUMSCHMELZE follows this new definition for its VACODYM magnets.

The measurement is based on the determination of the J(H) curve with a hysteresis graph (see Fig. 9). In order to eliminate the effects of the surface processing, the reversible permeability μ_{rev} is determined in the H field range of 20-70 %, where H_{cJ} has a linear fit on the J(H) curve. The point of intersection with the J/B axis is then $B_{r,lin}$. This value can then be below the remanence B_r of the magnet due to the surface effects. This straight line is shifted by 5 % to lower J values (point of intersection B_p with the J/B axis at 95 % of $B_{r,lin}$). The intersection of these straight lines is then determined with the J(H) curve and the corresponding H field is read. This field is named H_{D5} and represents the field strength at which the magnet shows an irreversible loss of 5 % of its magnetic moment.

Upon request, for all VACODYM alloys VACUUMSCHMELZE will provide the H_{D5} values at 20 °C as well as at higher operating temperatures.

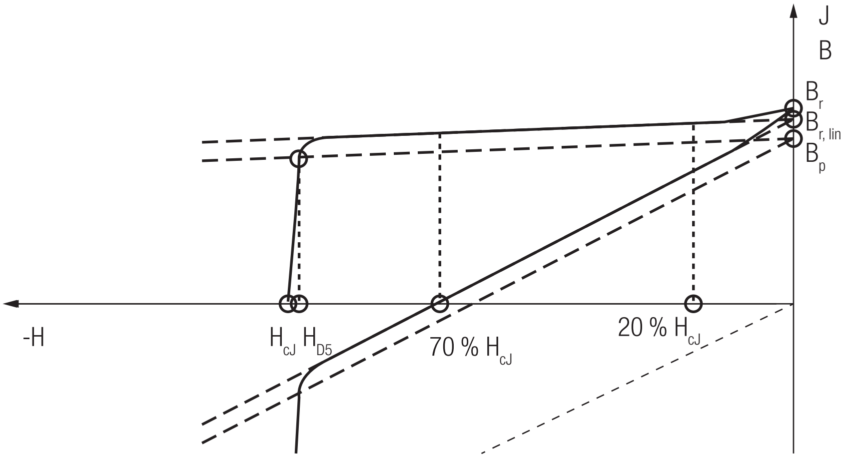


Fig. 9: B(H) and J(H) demagnetization curves with H_{D5} evaluation

7. CORROSION BEHAVIOUR, SURFACE PROTECTION AND COATINGS

7.1 CORROSION BEHAVIOUR

Rare Earth (RE) elements belong to the group of ignoble and thus highly reactive elements due to their strongly negative electrochemical standard potential ($E^0 = -2.2$ to -2.5 V).

Their chemical reactivity is similar to that of alkaline earth metals such as magnesium. Under normal conditions, the RE metals react slowly. Under conditions at higher temperatures and in the presence of water or humidity, the reaction is more rapid releasing hydrogen and RE hydroxide. The released hydrogen can then react with the free RE metal forming RE metal hydrides.

The reaction with water vapour can be signicantly suppressed by adding sufficient quantities of more noble elements such as cobalt. The speed of the reaction thereby becomes negligible.

This is the reason why only VACOMAX ($SmCo_5$ or Sm_2Co_{17}) exhibits slight surface discoloration when exposed to high humidity (e.g. > 80 % rel. humidity) and increased temperature (e.g. > 80 °C). No significant amounts of corrosion products were measured even after long exposure times (e.g. > 1000 h).

The general situation is different with Nd-Fe-B magnets. The individual magnet grains are held together and bonded to each other by the Nd-rich phase. This phase represents up to 5 % of the total volume of the material and behaves, in uncoated magnets, like pure neodymium from a chemical point of view.

Thus, an intergranular decomposition starts (see Fig. 10) with increased humidity and temperature (e.g. in the HAST test – Highly Accelerated Stress Test according to IEC 68-2-66 at 130 °C / 95 % humidity and 2.6 bar pressure). This results in volume reduction through corrosion products (e.g. Nd-hydroxide) as well as magnet dust (loose NdFeB grains). Pages 57-60 describe the options for protecting this material effectively in corrosive operating conditions.

This type of corrosion becomes negligible in the VACODYM materials 6XX, 8XX and 9XX series.

Selective addition of suitable elements (among others, cobalt) to the Nd-rich phase has significantly improved its corrosion behaviour and systematically minimized the intergranular corrosion in a warm, humid atmosphere. The corrosion behaviour of such VACODYM alloys is similar to

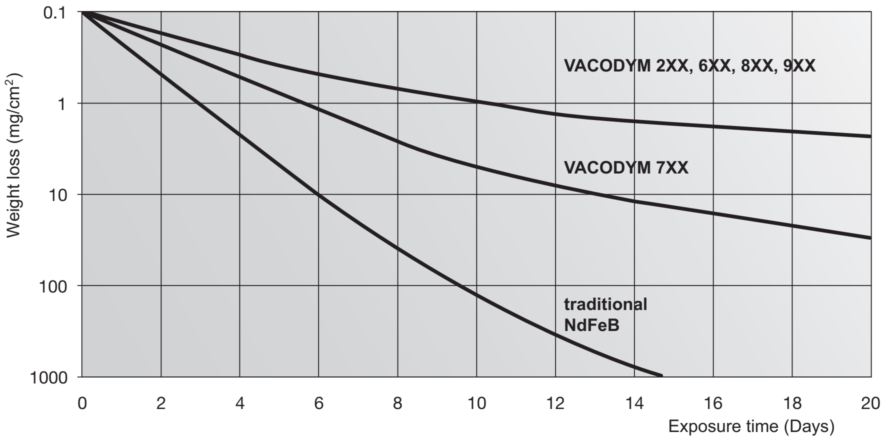


Fig. 10
Weight loss of uncoated VACODYM magnets in the HAST based on IEC 68-2-66 (130 °C; 95 % rel. humidity, water vapor 2.6 bar)

that of pure iron materials (steel). In the HAST, there is hardly any measurable reduction, even after several weeks' exposure. Only a grey-black discolouration is visible on the material surface.

Like parts made of iron, all VACODYM materials gradually begin to rust (red rust) when humidity turns to condensation. Here, the corrosion products are mainly non-magnetic metal oxides or hydroxides. We therefore recommend a coating for applications where dew formation occurs regularly (e.g. condensation of water) or if the parts are to be used in water or other corrosive media such as acids, alkaline solutions, salts, cooling lubricants or corrosive gases.

For VACODYM, high humidity, dew formation or sweat is already sufficient to cause corrosion. We therefore recommend using suitable gloves to handle VACODYM magnets in all cases.

7.2 TEMPORARY CORROSION PROTECTION AND SURFACE PASSIVATION

To protect uncoated magnets temporarily, e.g. during transport or storage, we have developed a passivation method. This protects our RE permanent magnet materials, particularly the more corrosion-sensitive VACODYM, effectively against environmental influences such as a temporary rise in humidity. With this standard protection method, our magnets can be stored under normal ambient conditions as long as condensation can be prevented.

Passivation involves the application of an ultra-thin Nd/Fe phosphate layer onto the magnet surface.

The thickness of this phosphate layer lies in the sub-µm range (typically < 0.5 µm). This is sufficient to protect the magnets against rust under normal Central European ambient conditions ($T \leq 30\,°C$, rel. humidity $< 70\,\%$).

The thickness of the phosphate layer is within the spectrum of visible light wavelengths. Minor fluctuations in thickness and light incidence cause the surface to appear in different colours. Magnets normally appear from light yellow or brownish to iridescent blue and grey. These colours are not an indication of corrosion (rust), but are the basic colours of the phosphate layers.

7.3 SURFACE PROTECTION

In many applications, the phosphate layer applied is too thin to provide reliable long-term protection for VACODYM magnets. For effective corrosion protection of magnets under complex application conditions, an additional coating is often necessary.

The type and thickness of the coating depends on the prevalent environmental influences in the application. Corrosion-proof coatings can be applied to magnets directly after production and cleaning.

Users may also choose to apply a surface protection to magnets in the finished system. Proven methods are e.g. bandaging with subsequent treatment, grouting or coating of the assembled magnets with synthetic resin or thick enclosure of the magnets, e.g. in a stainless steel casing as well as coating of the finished magnet systems with corrosion-proof layers, e.g. paints.

Depending on the application, surface coatings may also serve other purposes besides corrosion protection:

PROTECTION AGAINST MAGNETIC PARTICLES

VACODYM and VACOMAX are sintered materials, where the occurrence of loose magnetic particles and magnet dusts on the surface cannot be ruled out. In certain applications (e.g. systems with small working air gaps), loose magnetic particles may affect the function or destroy the magnet system. The coating process must therefore ensure that the magnets can be cleaned thoroughly and are free of all deposits.

HANDLING PROTECTION

Magnets are often mechanically stressed during assembly or when used in systems. Under certain circumstances, this can lead to separation of magnetic particles, particularly at sharp edges.

Each application of VACODYM and VACOMAX must therefore be evaluated to ascertain whether and how the surface should be protected. We have tested the behaviour of our permanent magnets under widely varying operating conditions and will be pleased to advise you on the selection of the appropriate surface protection for your application.

7.4 TYPES OF COATINGS

The coatings can be divided into metallic and organic coatings. To meet special requirements and on request, double coatings of metal/metal & metal/organic, and a number of special coatings are available.

METALLIC COATINGS

As a rule, galvanic processes are used for applying metallic coatings. Apart from our standard nickel and tin coatings, we also offer a double coating of nickel + tin on request. In addition, IVD (Ion Vapour Deposition) aluminium coating is also possible (see page 60 Special coatings).

When selecting the type of metallic coating, the possibility of a galvanic element formation in the finished system must be taken into account where condensation cannot be excluded.

In addition, all galvanic coating processes generate a small amount of hydrogen as a side reaction to metal deposition. This hydrogen is absorbed by the surface magnetic material and may lead to irreversible losses in NdFeB alloys, depending on the geometry.

In this context, unsuitable parts are miniature parts (weight < 0.5 g), thin-walled rings and ultra-thin magnets (thickness < 1.5 mm). In these cases, other coating processes such as spray-coating should be selected instead of galvanic deposition.

ORGANIC COATINGS

Here, we offer different spray coatings with excellent corrosion protection characteristics. Our newly developed VACCOAT epoxy resin coatings are particularly useful cost-effective alternatives to metallic coatings.

This is especially applicable for large magnets from approx. 25 g upwards. These must usually be rack-coated when metallic coatings are selected. Here, the painting processes offer significant advantages in terms of costs, coating quality and resistance in corrosive environments.

7.5 DESCRIPTION OF THE COATINGS

Most applications can be served by our VACCOAT spray coatings as well as the "galvanic tin" and "galvanic nickel" coatings. The coatings feature complementary properties.

VAC carries out all galvanic coating processes and the spray coatings in-house. The described properties can only be achieved in a carefully controlled system incorporating the magnet structure, its mechanical processing, as well as cleaning and coating. The TiN and IVD aluminium coatings are provided via selected sub-contractors carefully qualified by VAC. Appropriate quality assurance measures ensure consistent high quality in series production.

All other coatings are applied at VAC in-house cost-effectively and with high reproducibility and quality using the latest automated technology.

EPOXY SPRAY COATING VACCOAT

This coating is an in-house development that sets new standards regarding the combination of corrosion protection, temperature resistance, coating application and the subsequent further processing of the coated magnets into systems. When cured, VACCOAT 20011 provides high-grade corrosion protection for VACODYM. At the same time, the coating film can also serve as a high-strength adhesive before curing. During the baking of the coating, a high-strength adhesive bond forms giving a typical shear strength of > 15 N/mm^2.

At the same time, the coating effectively protects the system against corrosion. The baked coating has a pencil hardness of at least 4H and can be thermally stressed to approx. 200 °C. In a single operation, visually high-quality layers of between 5 µm and 40 µm can be applied. The colour of the coating is adjustable (standard colour: black). The coating is abrasion-resistant and exhibits excellent electrical insulation behaviour. The layers can be applied to the magnets either in a continuous automatic process or a barrel-coating process.

VACCOAT was developed further especially for small barrel-coated magnets (< 10 g) and offers optimized corrosion protection and productivity with VACCOAT 20021.
The newest VACCOAT generation, VACCOAT 30033, was developed to achieve the highest corrosion protection for RE magnets. In a salt spray test according to DIN EN ISO 9227, as well as in the autoclave test at 130 °C / 100 % humidity / 2.7 bar, VACODYM magnets protected with this baked coating achieve corrosion-free aging times of over 1,000 hours. These long resistance times in both tests cannot be matched by previously used spray coatings or by metallic protective layers such as galvanic nickel or tin. The other properties (mechanical parameters, temperature and chemical resistance) are comparable with VACCOAT 20011. This coating type is only available for continuous automatic processing, and thus only for magnets with a weight of > 5 g.

ALUMINIUM SPRAY COATINGS VACCOAT 10047

The stove-enamel filled with aluminium flakes exhibits good resistance to climatic and salt spray tests similar to the epoxy spray coating VACCOAT 200XX. Even from a thickness of 5 µm onwards, the magnets withstand long-term autoclave and salt spray tests without any problems.

When compared to conventional coatings, this coating is characterized by an extremely good edge protection. The coating is suitable for applications with operating temperatures of up to 180 °C and exhibits very good chemical resistance.

Thanks to the excellent hardness (typically 6-8 H pencil hardness), the coating is not sensitive to mechanical damage.

This coating is particularly beneficial for barrel-coating of small parts. The built-in aluminum flakes provide very good edge coverage. In connection with excellent substrate adherence, edge damage is effectively prevented during the coating process.

GALVANIC TIN

Galvanic tin plating provides good corrosion protection against atmospheric influences, humidity and weak acids and alkaline solutions. The tin plating applied at VAC is dense and free of interconnected pores. The typical plating thickness range for magnets is 15 - 30 µm. The finish of the tin plating is silvery-white and slightly glossy.

No phase transitions occur in the temperature range from -40 °C to the melting point +232 °C. The deposition process is optimized by VAC for RE magnets, especially to prevent hydrogen damage to the surface of the magnet during plating.

Small parts can be plated economically in a barrel. Larger parts are galvanized in a rack. The decision whether to use barrel or rack method is governed by the weight of the part or the part geometry (typical guide value: < 25 g barrel; > 25 g rack).

The galvanic tin platings are characterized particularly by their high resistance to environmental influences in a humid-warm climate (e.g. 85 °C / 85 % rel. humidity), as generally specified for electronic applications. Tin is highly ductile and is almost free of internal stresses over a wide range of plating thickness and can be deposited with high process reliability. There is no risk of cracking or flaking of the plating. Mechanical stress does not lead to chipping but merely to deformation of the tin plating, so that the magnetic material is still protected safely.

The tin plating is free of all residues when cleaned thoroughly and thus provides an ideal surface for many adhesives.

GALVANIC NICKEL

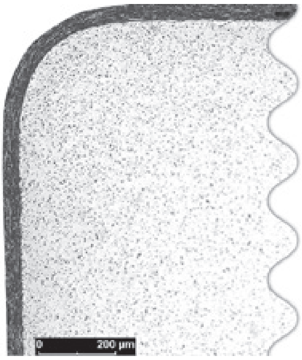
Galvanic nickel platings can be used as an alternative to tin or as a double plating in combination with tin.

On VACODYM, it provides superior protection against a comparable plating thickness of tin. The minimum plating thickness that we recommend for protection against corrosion is 10 µm for nickel plating as compared to 15 µm for tin plating.

Galvanic nickel platings are hard, abrasion-proof and easy to clean without residues. These platings have thus established themselves today particularly for cleanroom applications.

VAC uses a special nickel plating process which ensures visually attractive silk-matt platings.

Galvanic nickel platin is magnetically soft and therefore must be considered due its flux carrying properties.



Micrograph of edge coverage with VACCOAT

CHARACTERISTICS OF DIFFERENT COATINGS

Table 5 compares the properties of the most important coatings and should be used as a guideline when selecting surface protection for a certain application. It specifies the minimum layer thickness of the various coatings and ensures adequate corrosion protection in the majority of applications.

To meet more stringent requirements on corrosion protection, the layer thickness must be adjusted accordingly. Please also note that improper handling may affect the integrity of the coating.

Table 5: SURFACE COATINGS

Surface	Method	Minimum layer thickness for corrosion protection	Colour	Hardness	Resistance to	Temperature range	Typical application examples
Epoxy spray coating VACCOAT 20011/20021	Automatic spray coating	> 10 µm	black	> 4H1)	Humid atmosphere, spray test, toxic gas test, solvents	< 200 °C	Segmented magnet systems, electric motors, linear motors, motor vehicles
Epoxy spray coating VACCOAT 30033	Automatic spray coating	> 10 µm	green	> 4H1)	Humid atmosphere, salt spray test, toxic gas test, solvents	< 200 °C	Applications with highest corrosion protection
Aluminium spray coating VACCOAT 10047	Automatic spray coating	> 5 µm	yellow semi-bright	> 4H1)	Humid atmosphere, spray test, toxic gas test, solvents	< 180 °C	Electric motors, generators, sensor technology, linear motors, motor vehicles
Tin (Sn)	galvanic	> 15 µm	silver bright	HV 102)	Humid atmosphere, solvents	< 160 °C	Electric motors, sensor technology, mechanical
Nickel (Ni)	galvanic	> 10 µm	silver semi-bright	HV 3502)	Humid atmosphere, solvents, cooling lubricants	< 200 °C	Clean-rooms, small-sized motors, linear motors, UHV undulators

1) Pencil hardness

2) Vickers hardness (guide values)

7.6 SPECIAL COATINGS

As well as our standard coatings, we offer a number of special coatings for special applications, which are applied in-house at VAC or by selected subcontractor.

IVD (= **I**on **V**apour **D**eposition) aluminium coatings provide effective corrosion protection for our VACODYM and VACOMAX permanent magnets. Thanks to the cathodic protection, IVD aluminium coatings offer good corrosion protection in connection with the condensed water phase and particularly in the presence of salt solutions. This coating variant has proven itself particularly for aerospace applications. Since the coating is applied in a dry process, hydrogen damage to the magnets is ruled out. Prerequisites are a minimum quantity of magnets to be coated as well as a suitable part geometry. IVD aluminium coatings are successfully used, among others, for magnets in beam guiding systems (wigglers, undulators) under Ultra-High Vacuum conditions (UHV).

However, for UHV applications, in which the shortest pump-down times are important, the titanium nitride coating (TiN) must be preferred over IVD aluminum. This coating is deposited on the magnets in a thinner layer (2 - 6 µm) using the sputter method. This process that has been especially developed for our VACODYM and VACOMAX magnets, as well as for soft magnetic pole plates made of VACOFLUX, gives a firmly adhering and thick protective coating with high wear resistance. Upon request, we can clean and pack the parts in an additional process in a UHV-compatible manner.

Another special coating, particularly for VACOMAX magnets, is the galvanically applied double coating of nickel and gold. This surface is normally used for applications in medical technology and is sterilizable. The coating is available for small parts (barrel plating) and small batch sizes.

Moreover for extreme corrosion protection requirements, double coatings such as nickel + tin or nickel and/or tin + VACCOAT are also possible.

8. FORMS OF SUPPLY

8.1 TYPES OF MAGNETIZATION

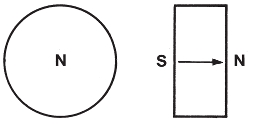
Magnets made of VACODYM and VACOMAX can be supplied in the magnetized as well as in the non-magnetized state. Normally, the poles are not marked on individual magnets.

Owing to the magnetic anisotropy of VACODYM and VACOMAX, the magnetization takes place along the preferred direction aligned during the production process. The most common pole configurations are shown below.

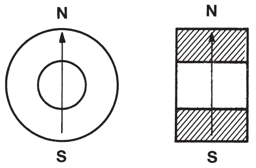
Our experts with extensive experience on the subject are available to answer all of your questions of magnetization technology. To supply magnetized parts, we have developed different packaging methods which can be modified if necessary taking into account the strict IATA rules for transport by air freight in a customised manner. For further processing at the customers site, we recommend discussion of packaging with our experts.

Pole arrangements:

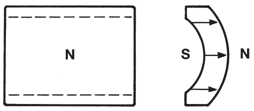
Top view Side view



for disks and rings: axial



for rings/disks: diametral



for segments: diametral

8.2 DIMENSIONS AND DIMENSIONAL TOLERANCES

The pole surfaces of die-pressed sintered magnets made of VACODYM or VACOMAX usually need to be ground. The tolerance after grinding is normally ± 0.05 mm; from case to case, values up to ± 0.02 mm are possible.

The dimensions perpendicular to the direction of pressing are largely determined by the dies and these surfaces normally remain unworked (as sintered). Typical ″press tolerances″ of such side dimensions:

Perpendicular (mm)*	Nominal dimension pressing direction (mm)
up to 7	±0.10 … ±0.20
7-15	±0.15 … ±0.30
15-25	±0.25 … ±0.40
25-40	±0.30 … ±0.60
40-60	±0.45 … ±0.90
60-100	±0.80 … ±1.50
100-150	±1.50 … ±2.50

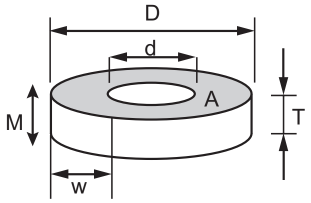
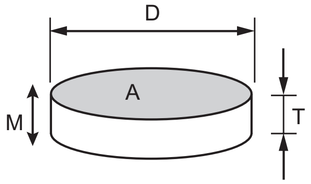
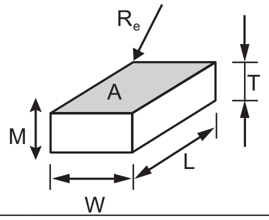
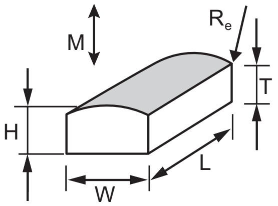
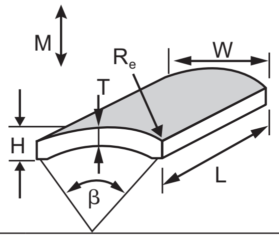
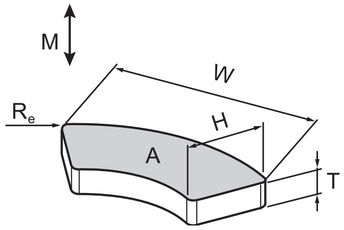
* precise data on request

If these surfaces need to be processed, general tolerances as per DIN EN 2768 mK in connection with tolerance principle as per DIN ISO 8015 can usually be adhered to. For shaped parts with more complex geometry, a maximum and minimum envelope curve is usually specified, wherein the contour of the pressed part lies. For parts cut from blocks (TP or HR quality), the length tolerances are ± 0.1 mm. Upon agreement, even tighter length tolerances can be met by grinding. If no dimensional tolerances are specified, we typically supply according to DIN ISO 2768 mK.

NETSHAPE PARTS

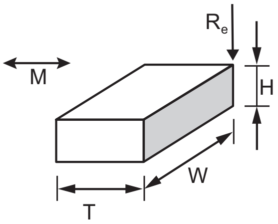
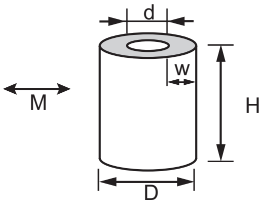
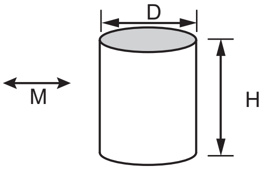
By leaving out the grinding process, competitively priced magnets with a pole surface of up to approx. 6 cm^2 can be die-pressed. Perpendicular to the direction of pressing, these netshape magnets have the aforementioned tolerances. Owing to special die-pressing and sintering processes in the direction of pressing, thickness tolerances of typically ± 0.2 mm can be met without subsequent grinding. Preferred shapes are cuboids and arc segments with typical thicknesses in the range of 2.2 to 8.0 mm. Our experts will gladly assist in the layout of the magnet geometry and the tolerances of netshape magnets.

DIMENSIONS OF DIE-PRESSED VACODYM AP-MAGNETS (AXIAL FIELD PRESSED) CRITERIA FOR ECONOMICAL MAGNET GEOMETRIES

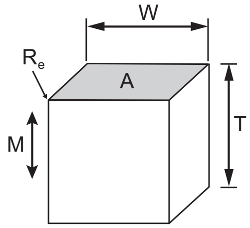
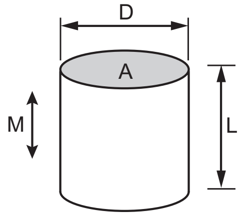
Shape	Type	Sketch	Dimensions economical	Dimensions possible	Remarks economical
Ring	AP		$D \le 120$ mm $d \ge 3$ mm $(D-d)/2 = w \ge 3$ mm $d/D \le 0.6$ $D/10 \le T \le D/2$ $A < 9{,}500$ mm^2	$D \le 180$ mm 1 mm $\le T \le$ 70 mm $A < 15{,}000$ mm^2	only thickness T ground
Disk	AP		$D \le 100$ mm $D/10 \le T \le D/2$	$D \le 140$ mm 1 mm $\le T \le$ 70 mm	only thickness T ground
Cuboid	AP		$L \le 120$ mm $LxW \le 9{,}500$ mm^2 $T \le 55$ mm $T \ge 0.15\sqrt{(LxW)}$ $L/W \le 5$ $0.5 \le R_e \le 5.0$ mm	$L \le 150$ mm $LxW \le 15{,}000$ mm^2 1 mm $\le T \le$ 70 mm	only thickness T ground
Loaf	AP		$L \le 120$ mm $W \le 50$ mm $T \ge 0.6\,H$ 2 mm $\le H \le$ 20 mm $0.5 \le L/W \le 5$ $0.5 \le R_e \le 5.0$ mm	$L \le 150$ mm 2 mm $\le H \le$ 55 mm	thickness T and width W ground
Seg-ment	AP		$L \le 120$ mm $W \le 50$ mm 2 mm $\le T \le$ 20 mm $ß \le 80°$ $0.5 \le L/W \le 3$ $0.5 \le R_e \le 5.0$ mm	$L \le 150$ mm 1.5 mm $\le T \le$ 50 mm $ß \le 150°$ $W \le 70$ mm	thickness T and width W ground
Shaped part	AP		$W \le 45$ mm $H \le 35$ mm $A \le 1{,}500$ mm^2 $W/H \le 3$ 1.5 mm $\le T \le$ 30 mm $T \ge 0.1\sqrt{A}$ $0.5 \le R_e \le 5.0$ mm	$H, W \le 150$ mm $A \le 15{,}000$ mm^2 1 mm $\le T \le$ 70 mm	only thickness T ground

R_e: Corner radius in the pressing direction defined by pressed tool

DIMENSIONS OF DIE-PRESSED VACODYM TP MAGNETS
(TRANSVERSE FIELD PRESSED)
CRITERIA FOR ECONOMICAL MAGNET GEOMETRIES

Shape	Type	Sketch	Dimensions economical	Dimensions possible	Remarks economical
Cuboid	TP		W ≤ 70 mm 2 mm ≤ T ≤ 100 mm 10 mm ≤ H ≤ 55 mm W/H ≤ 2.5 R_e ≤ 0.5 mm	W ≤ 120 mm 1 mm ≤ T ≤ 140 mm TxW ≤ 13,000 mm^2 H ≤ 80 mm	only thickness ground
Ring (diametral)	TP		8 mm ≤ D ≤ 70 mm d ≥ 3 mm (D-d)/2 = w ≥ 2 mm 0.1 ≤ d/D ≤ 0.65 3 mm ≤ H ≤ 55 mm H ≤ 5 w	6 mm ≤ D ≤ 120 mm d ≥ 1 mm w ≥ 1.5 mm 0.1 ≤ d/D ≤ 0.8 2 mm ≤ H ≤ 80 mm H ≤ 8 w	only thickness ground
Disk (diametral)	TP		5 mm ≤ D ≤ 70 mm 3 mm ≤ H ≤ 55 mm H ≥ D/4	5 mm ≤ D ≤ 120 mm 2 mm ≤ H ≤ 80 mm	only thickness ground

DIMENSIONS OF ISOSTATICALLY-PRESSED VACODYM HR MAGNETS
(RAW MAGNETS, UNPROCESSED)
CRITERIA FOR ECONOMICAL MAGNET GEOMETRIES

Shape	Type	Sketch	Dimensions economical	Dimensions possible	Remarks economical
Cuboid	HR		W ≤ 110 mm T ≤ 250 mm A ≤ 7,000 mm^2	W ≤ 110 mm T ≤ 800 mm A ≤ 7,000 mm^2	unprocessed with contour tolerance of 6 mm ø, R_e approx. 5 mm
Disk, rod	HR		D ≤ 70 mm L ≤ 250 mm	D ≤ 90 mm L ≤ 800 mm	unprocessed with contour tolerance of 6 mm ø

Similar shapes and dimensions also available in VACOMAX with moderate restrictions (appropriate to the magnet quality).

9. GLUING OF RARE EARTH MAGNETS

The majority of RE permanent magnets produced by VAC are assembled into magnet systems using adhesives. For a magnet system, the following framework conditions must be considered:

- Static and dynamic load of the adhesive (strength requirements)
- Thermal load (time-span/frequency/ temperature range) of the adhesive
- Thermal expansion coefficients of the adhesive partners
- Size of adhesive area
- Corrosive load of the adhesive (resistance of the adhesive to atmosphere and chemicals)
- Quality of the surfaces (coating, roughness, etc.)
- Material matching regarding electrochemical potentials (corrosion due to galvanic element formation)
- Thickness of the adhesive gap

Based on our longstanding experience in assembling RE permanent magnet systems, we can offer our customers the following tips on the gluing of magnets:

a) Adhesives with an acid content must not be used with RE magnets, particularly not with VACODYM. These products, in connection with humidity, lead to rapid decomposition of the magnet material at the adhesive-magnet interface and can damage the bond. The use of such adhesives is not recommended, even in the case of coated magnets, particularly painted magnets.

b) When bonding large surfaces with iron or other substrates, the thermal expansion coefficients of the RE magnet materials must be taken into account. In particular, in connection with VACODYM, which has a negative thermal expansion coefficient (-1×10^{-6}/K) perpendicular to the direction of magnetization (and thus, normally parallel to the gluing surface), stresses build up due to strains resulting from fluctuations in temperature, which the glue must absorb. Our team of experts will be pleased to advise you on this matter.

c) When preparing for the gluing, sand blasting for the pre-treatment of RE magnets should be avoided. This processing step might lead to loosening of the microstructure on the surface of the sintered magnet.

Our permanent magnets are supplied in a ready-for-gluing state. The passivation applied after cleaning provides a suitable base for most adhesives. However, if a pre-treatment step directly prior to glueing is considered important, we recommend cleaning the glueing surface with a solvent such as acetone or benzene.

d) An adhesive selected for an uncoated magnet is not necessarily suitable for a coated magnet. Particularly for surfaces which are difficult to glue, e.g. galvanic nickel, the market offers tailor-made adhesives. In the case of coated magnets, it must be ensured that the adhesive does not attack the coating chemically or cause a swelling. VAC has in-depth experience with a large number of adhesives and the most commonly used surfaces. We will be pleased to help our customers select the right adhesive for their application.

Here, we would like to point to our magnet system production. We have, in addition, tailor-made patented gluing processes and adhesives, which we have developed, tested and qualified. For further information, please refer to our brochure "Magnet Systems".

10. INTEGRATED MANAGEMENT SYSTEM

Documentation of the quality, environmental and industrial safety management system was integraded into a joint management system (integrated management system) in 2003. It is currently based on the following set of standards in their respective up-to-date versions:

- ISO 9001
- ISO/TS 16949
- ISO 14001
- OHSAS 18001
- DIN EN ISO/IEC 17025

10.1 QUALITY MANAGEMENT

Quality is an essential aspect of our corporate policy. In order to reliably realize the high quality of our products and services based on a quality management system certified in accordance with ISO 9001 and ISO/TS 16949 , we give priority to close cooperation of all operational divisions. Our Total Quality Management (TQM) process has undergone continuous improvement since its introduction in as early as 1994 and is based on business excellence models and our corporate goals.

The most important objective of our quality management measures is fulfilling all customer expectations and achieving high customer satisfaction, both externally as well as internally. To further optimize VAC-internal processes – with the primary objective of further cost reduction – the Six-Sigma analysis system was introduced in all our operations in 2002.

We achieve the product quality demanded by our customers by defining and implementing targeted QM measures in product and process planning, strictly controlling raw material procurement, and integrating test sequences into processes using a statistical process control system (SPC). Standard features of our quality management system include compliance with relevant process feasibilities (cpk values) and documentation of essential magnetic and geometric properties. For complex tasks or especially rigorous requirements, we work with our clients to define a tailored quality assurance program. By providing qualified technical advice, we help to design and implement high-quality and cost-effective products and services; we also make quality assurance agreements (QAA) upon request.

We see that our core competence lies in the production of materials with special, high-quality magnetic properties. We therefore attach importance to accordingly securing our magnet values in the field of magnetic measuring technology. Since 2006, VACUUMSCHMELZE is DAkkS-accredited as a calibration laboratory in compliance with DIN EN ISO/IEC 17025 for magnetic flux density.

10.2 TECHNICAL TERMS AND CONDITIONS OF SALE

Like most other permanent magnet materials, sintered magnets made of RE alloys are brittle. Although VACODYM is mechanically more stable than VACOMAX, it is impossible to rule out fine hairline cracks or chipped edges, even in magnets of this material. These however have a negligible effect on the magnetic and mechanical properties of the parts.

In serial production, exchange of limiting samples has proved of value in the testing and definition of the visual quality of magnets. Unless we have special agreements with our customers, our quality inspection allows mechanical surface damage (flaking, edge and corner chips) up to a total of max. 2 % per pole surface. For small magnets, for magnets whose a pole surface is the smallest surface of the part, and for diametral disks, the permissible extent of chipping must be defined jointly with the customer and with the help of limiting samples. Fine hairline cracks are not considered to be a justification for complaint. Mechanical stability of the magnet is deemed satisfactory if a hairline crack covers less than one third of the related cross sectional area of the magnet.
Under normal manufacturing conditions, slight amounts of magnetic dust and material debris may adhere to uncoated and particularly, to magnetized parts. If this is not acceptable, a coating and/or special packaging of the magnets is to be provided.

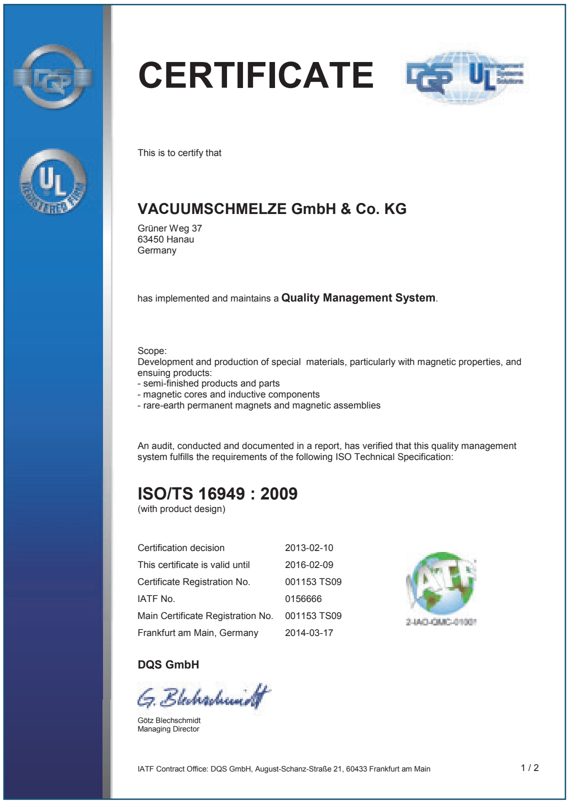
The final inspection of our magnets and magnet systems is normally based on standardized sampling systems. Unless otherwise agreed upon with customers, the sampling scopes for the mechanical and magnetic tests are conducted in accordance with DIN ISO 2859-1 with the acceptance criteria c = 0. By consistently employing the latest quality assurance techniques, we are often able to agree to even higher quality requirements upon request of the customer. For instance, products for the automotive industry require an additional process capability value of cpk ≥ 1.33 for the agreed features.

Acceptance conditions for special magnetic properties call for clearly defined test procedures and reference samples. A further prerequisite, in particular for VACOMAX, is that the parts are supplied in the magnetized state.

For miniature magnets with an edge length below approx. 2 mm, reduced magnetization is to be expected owing to surface effects and depending on the position of the working point. If you require more information, please contact our experts.

10.3 ENVIRONMENTAL AND SAFETY MANAGEMENT

VAC is committed to protecting the environment and to using the available natural resources as economically as possible. This principle applies to our production processes as well as to our products. We evaluate potential damage to the environment right from the development stage of our products. We aim at avoiding or minimizing any harmful environmental effects by implementing precautions that frequently exceed those stipulated by law. Our environmental management ensures that our environmental policy according to ISO 14001 is effectively put into practice. Technical and organizational means for this purpose are regularly audited and are subject to continuous improvement. A further goal in the design of our products, processes and workplaces is the health and safety protection of our staff and our partners based on OHSAS 18001. Here, the applicable laws, standards and regulations are taken into account together with assured expertise on occupational medicine and industrial science.



CERTIFICATE

This is to certify that

VACUUMSCHMELZE GmbH & Co. KG

Grüner Weg 37
63450 Hanau
Germany

has implemented and maintains a **Quality Management System**.

Scope:
Development and production of special materials, particularly with magnetic properties, and ensuing products:
- semi-finished products and parts
- magnetic cores and inductive components
- rare-earth permanent magnets and magnetic assemblies

An audit, conducted and documented in a report, has verified that this quality management system fulfills the requirements of the following ISO Technical Specification:

ISO/TS 16949 : 2009
(with product design)

Certification decision	2013-02-10
This certificate is valid until	2016-02-09
Certificate Registration No.	001153 TS09
IATF No.	0156666
Main Certificate Registration No.	001153 TS09
Frankfurt am Main, Germany	2014-03-17

DQS GmbH

G. Blechschmidt
Götz Blechschmidt
Managing Director

IATF Contract Office: DQS GmbH, August-Schanz-Straße 21, 60433 Frankfurt am Main

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11. SAFETY GUIDELINES

Magnetized rare-earth magnets made of VACODYM and VACOMAX exhibit high magnetic field strengths and exert strong, attractive forces on iron and other magnetic parts in their vicinity. Consequently, they must be handled with care by qualified and trained operators to avoid damage. Owing to their strong magnetic forces, there is a risk of injury when handling larger magnets. They should always be handled individually or with the aid of separators. We recommend wearing suitable personal protective equipment also for handling uncoated VACOMAX and nickel-coated parts. This is applicable particularly for people with allergies to metals. The high magnetic field strengths can change or damage the calibration of sensitive electronic devices and measuring instruments in the vicinity. In particular, magnetized magnets must be kept at a safe distance (e.g. over 2 m) from computers, monitors and all magnetic data storage media (such as credit cards, audio and video tapes etc.) as well as from pacemakers. RE magnets may generate large sparks on impact. Never handle them in an explosive atmosphere.

Unprotected VACODYM and VACOMAX magnets must not be exposed to hydrogen. Hydrogen deposits destroy the microstructure and lead to disintegration of the magnet. In these cases, the only effective protection is gas-proof encapsulation of the magnets. If magnets must be processed further, special safety precautions must be taken when handling the accumulating grinding debris. For VACOMAX in particular, legal regulations regarding the handling of cobalt-containing dust must be observed.

Further important information for safe handling of VACODYM / VACOMAX magnets can be found and downloaded in our alloy specific information sheets under following link:
http://www.vacuumschmelze.com/en/the-company/quality/information-sheets-msds.html
If you have any further questions please contact us. Our contact data is on the rear cover of the brochure.

12. APPENDIX – TECHNICAL BASICS AND TERMS

12.1 HYSTERESIS LOOP

The behaviour of a magnetic material in the magnetic field is characterized by the correlation between magnetic flux density (induction) B or magnetic polarization J and magnetic field strength H, the B(H) or J(H) hysteresis loop (Fig. 11). The flux density B and the polarization J are given by

$$B = \mu_0 H + J$$

The first quadrant of the hysteresis loop describes the magnetization behavior of the material: when applying a magnetic field H, the flux density B of a non-magnetized material varies along the initial curve (see Fig. 11).

When all magnetic moments are oriented parallel to the external magnetic field, the polarization J is at its maximum value, the saturation polarization J_s ($J = J_s =$ const.). The flux density B however continues to increase linearly with the field strength H.

The minimum field strength required to attain the saturation polarization is referred to as the saturation field strength H_s. If – in the magnetized state – the magnetic field strength is reduced, the flux density changes in accordance with the hysteresis loop and attains, at $H = 0$, the residual flux density (remanence) B_r (intersection of the hysteresis loop with the ordinate).

In the strongly anisotropic RE permanent magnets described here, the remanence B_r is in the same order of magnitude as the saturation polarization J_s:

$$B_r \approx J_s$$

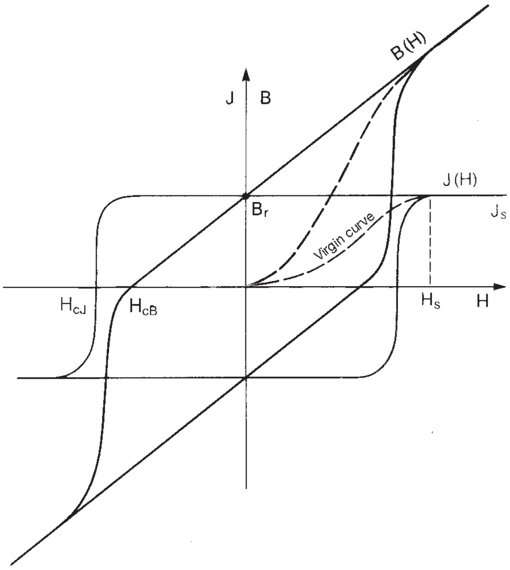

Fig. 11

12.2 DEMAGNETIZATION CURVE

The second quadrant of the hysteresis loop describes the demagnetization behaviour of the material: For permanent magnets, which are operated exclusively in opposing fields (see "working point" for further details), the most important characteristic terms are determined by the demagnetization curve.

The most important characteristic terms of a permanent magnet are:

– Remanence

This is obtained, as described above, from the intersection of the hysteresis loop and the ordinate (at $H=0$, we have $B_r=J_r$)

– Coercivity

The field strengths, at which the flux density B or the polarization J reach zero are referred to as coercivities of the flux density H_{cB} or of the polarization H_{cJ} respectively (intersections of the hysteresis loops B(H) and J(H) with the abscissa)

– Energy density

The product of the related values from flux density B and field strength H can be attained from any point along the demagnetization curve (see Fig. 12). This product represents the energy density and passes through a maximum value between remanence and coercivity, the maximum energy density $(BH)_{max}$. As a rule, this value is used to grade permanent magnet materials.

– Working point

The magnetic field originating from the poles of a permanent magnet has a demagnetizing effect as it is in the opposing direction to the polarization J. The operational state of a permanent magnet is consequently always in the range of the demagnetization curve. The pair of values (B_a, H_a) applying to the relevant operational state is referred to as working point P. The position of P depends on the geometry of the magnet or, in magnetic circuits with soft magnetic flux conductors, on the ratio of air-gap length to magnet length. P is obtained from the intersection of the working or shearing lines with the B(H) curve (see Fig. 13)

The most effective use of a permanent magnet in static systems is when the working point P lies in the $(BH)_{max}$ point. In practice, shearing in the magnetic circuit should be selected such that the working point is at exactly this position or, preferably, just above it, i.e. is in slightly lower opposing field strengths.

In dynamic systems with changing operating straight lines (e.g. motors), shearing should be selected such that the working point of the permanent magnet always remains within the straight line range of the demagnetization curve in order to ensure high stability with respect to external field and temperature influences (compare Fig. 13):

If the air gap in a magnet system is increased, the working point shifts to higher opposing field strengths, e.g. from P1 to P2. If the change is reversed, the original working point P1 can only be attained if P2 is within the linear section of the demagnetization curve.

However, if P2 is, as shown in Fig. 13, below the "knee" of the demagnetization curve, this results in irreversible losses. The working point shifts to P3 on an inner return path with a correspondingly lower flux density. The rise of this return path is referred to as permanent permeability.

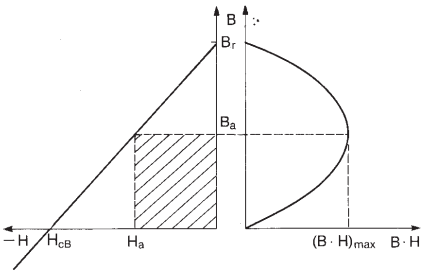

Fig. 12

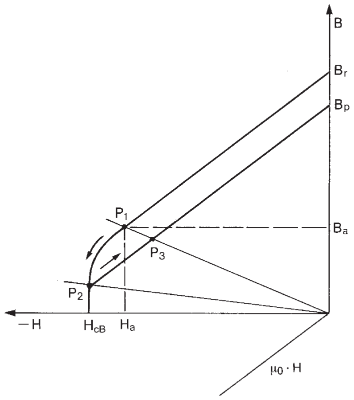

Fig. 13

12.3 INFLUENCE OF TEMPERATURE

The demagnetization curves of permanent magnets are temperature-dependent.

This dependency is marked by the temperature coefficients of the remanent flux density TK(B_r) and the coercivity TK(H_{cJ}):

$$TC(B_r) = \frac{1}{B_r} \times \frac{dB_r}{dT} \times 100\ (\%/K)$$

$$TC(H_{cJ}) = \frac{1}{H_{cJ}} \times \frac{dH_{cJ}}{dT} \times 100\ (\%/K)$$

A change in temperature causes the working point to shift on the working line (see fig. 14).
As long as the working point remains within the linear region of the demagnetization curve, the changes in the flux density are reversible, i.e. after cooling, the flux density returns to its original value. In all other cases, any change in the flux density is irreversible (irreversible magnetic losses) and can only be reversed by remagnetization.

To avoid irreversible changes in the flux density through temperature fluctuations, the working point must remain within the linear section of the demagnetization curve over the entire temperature range in which the magnet is used.

A permanent magnet can be completely demagnetized by heating to temperatures above the Curie temperature T_c. After cooling to the initial temperature, the former state of magnetization can be reproduced by remagnetizing provided heating has not caused any changes in the microstructure (see page 48). In contrast, thermal demagnetization may not be performed on magnets made of VACOMAX, because the range of Curie temperature in these alloys is substantially higher and at temperatures greater than 700 °C, phase transitions occur, which may destroy the permanent magnet properties irreversibly.

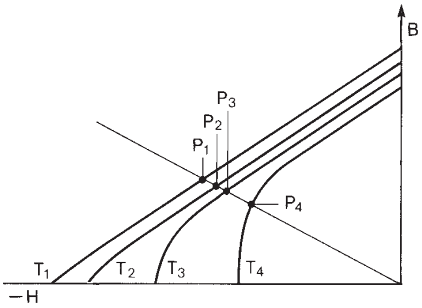

Fig. 14

MAGNETIC TERMS AND UNITS

The most important magnetic terms, their units and conversions are given in the following table:

Term and symbol	SI units[1]	Conversion table
Flux density B Induction	T (Tesla)	1 T = 1 Vs/m^2 = 10 kG (Kilogauss)
Polarization J	T (Tesla)	see flux density B
Magnetic field strength H	A/m	1 A/cm = 0,4 π Oe ≈ 1,257 Oe (Oersted)
Energy density $(BH)_{max}$ (energy product)	kJ/m^2	1 kJ/m^3 = 0,126 MGOe
Magnetic flux ϕ	Wb (Weber)	1 Wb = 1 Vs = 10^8 Mx (Maxwell)

[1] Basic units in SI systems: meter, kilogram, second, ampere. The units Gauss, Oested or Maxwell in the conversion table refer to the cgs or Gaussian system with the basic units centimeter, gram and second.

VACUUMSCHMELZE GMBH & CO. KG
GRÜNER WEG 37
D 63450 HANAU / GERMANY
PHONE +49 6181 38 0
FAX +49 6181 38 2645
INFO@VACUUMSCHMELZE.COM
WWW.VACUUMSCHMELZE.COM

VAC SALES USA LLC
2935 DOLPHIN DRIVE
SUITE 102
ELIZABETHTOWN, KY 42701
PHONE +1 270 769 1333
FAX +1 270 765 3118
INFO-USA@VACUUMSCHMELZE.COM

VACUUMSCHMELZE SINGAPORE PTE LTD
1 TAMPINES CENTRAL 5, #06-10/11
CPF TAMPINES BUILDING
SINGAPORE 529508
PHONE +65 6391 2600
FAX +65 6391 2601
VACSINGAPORE@VACUUMSCHMELZE.COM

VACUUMSCHMELZE CHINA MAGNETICS
SHANGHAI SALES OFFICE
ROOM 06, 19F
ZHONGRONG HENGRUI INTERNATIONAL PLAZA
620 ZHANGYANG ROAD, PUDONG DISTRICT
SHANGHAI, PRC 200122
PHONE +86 21 58 31 98 37
FAX +86 21 58 31 99 37
VAC_CHINA@VACUUMSCHMELZE.COM

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ADVANCED MATERIALS – THE KEY TO PROGRESS