CARLITE®

M-3, M-4, M-5, M-6
GRAIN-ORIENTED ELECTRICAL STEELS

Large Generators

Transformer Cores

CLEVELAND-CLIFFS GRAIN-ORIENTED ELECTRICAL STEELS are used most effectively in transformer cores having wound or sheared and stamped laminations with the magnetic flux path entirely or predominately in the rolling direction. They also are used in large generators and other apparatus when the design permits the directional magnetic characteristics to be used efficiently.

Product Description

Grain-Oriented Electrical Steels are iron-silicon alloys that were developed to provide the low core loss and high permeability required for efficient and economical electrical transformers. First produced commercially by Cleveland-Cliffs, these magnetic materials exhibit their superior magnetic properties in the rolling direction. This directionality occurs because the steels are specially processed to create a very high proportion of grains within the steel, which have similarly oriented atomic crystalline structures relative to the rolling direction.

In iron-silicon alloys, this atomic structure is cubic and the crystals are most easily magnetized in a direction parallel to the cube edges. By a combination of precise steel composition, rigidly controlled cold-rolling and annealing procedures, the crystals of these oriented electrical steels are aligned with their cube edges nearly parallel to the direction in which the steel is rolled. Consequently, they provide superior permeability and lower core loss when magnetized in this direction.

Since the inception of oriented electrical steels in 1933, our Research and Development team has continued to develop new and improved grades to provide the electrical industry with core materials for the manufacture of more efficient electrical apparatus.

FORMS AND STANDARD SIZES

Nominal Thickness
M-3: 0.009 in. (0.23 mm)
M-4: 0.011 in. (0.27 mm)
M-5: 0.012 in. (0.30 mm)
M-6: 0.014 in. (0.35 mm)

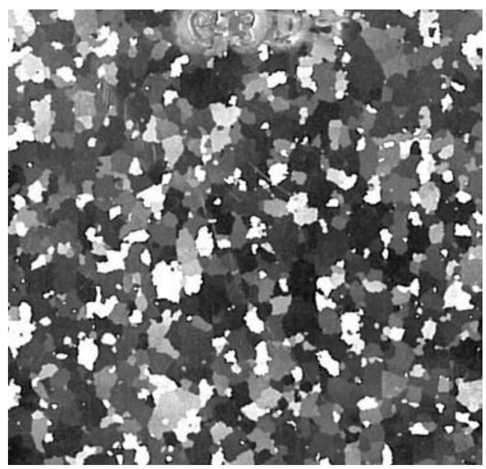
Width
Maximum: 36.22 in. (920 mm)
Minimum: 0.75 in. (19 mm)

Inside Coil Diameter
Master Coil 20.0 in. (508 mm)
Slit Width Coil 16.0 and 20.0 in. (406 and 508 mm)

CARLITE 3 SURFACE INSULATION

Cleveland-Cliffs' CARLITE® Grain-Oriented Electrical Steels (GOES) products are supplied with CARLITE 3 insulative coating, an inorganic coating equivalent to ASTM A976 C-5. CARLITE 3 insulation is ideal for materials that will be used in the form of sheared laminations for power transformers and other apparatus with high volts per turn. In addition to supplying all the benefits of C-5 insulation, CARLITE 3 provides other important advantages, which include:

- Potential for reduced transformer building factor from added resistance to elastic strain damage
- Potential for reduction of magnetostriction related transformer noise
- High stacking factor
- Easy assembly due to smoothness of coating (low coefficient of friction)



Sample chemically etched to reveal grain structure.

Specifications

In terms of maximum core loss, Cleveland-Cliffs CARLITE GOES specifications are determined at 15 kG and 17 kG at 60 Hz. Core loss grading is conducted using as-sheared single sheet test samples, which are tested in accordance with ASTM test method A804. Peak permeability is specified at 10 Oe. Permeability grading is conducted using stress relief annealed Epstein samples tested in accordance with ASTM test method A343. Samples are secured from each end of the coil and the higher core loss and lower permeability values are used for certification of conformance to product grade guarantees.

TABLE 1 – GUARANTEED CORE LOSS AND LAMINATION FACTOR

Product Name	Approximate Equivalent ASTM Grades	Nominal Thickness, in. (mm)	Assumed Density, gm/cm³	Resistivity, Ω-m, x10⁻⁸	Maximum Core Loss Watts per pound				Minimum Peak Permeability at 10 Oe	Minimum Lamination Factor, %
					50 Hz		60 Hz			
					15 kG	17 kG	15 kG	17 kG		
M-3 CARLITE	23G045 23H070	0.009 (0.23)	7.65	51	0.340	0.530	0.445	0.700	1780	94.5%
M-4 CARLITE	27G051 27H074	0.011 (0.27)			0.390	0.560	0.510	0.740	1780	95.0%
M-5 CARLITE	30G058 30H083	0.012 (0.30)			0.440	0.630	0.580	0.830	1780	95.5%
M-6 CARLITE	35G066 35H094	0.014 (0.35)			0.500	0.710	0.660	0.940	1780	96.0%

TABLE 2 – TYPICAL CORE LOSS AND LAMINATION FACTOR

Product Name	Approximate Equivalent ASTM Grades	Nominal Thickness, in. (mm)	Assumed Density, gm/cm³	Resistivity, Ω-m, x10⁻⁸	Typical Core Loss Watts per pound				Typical Peak Permeability at 10 Oe	Typical Lamination Factor, %
					50 Hz		60 Hz			
					15 kG	17 kG	15 kG	17 kG		
M-3 CARLITE	23G045 23H070	0.009 (0.23)	7.65	51	0.304	0.457	0.394	0.585	1844	96.1%
M-4 CARLITE	27G051 27H074	0.011 (0.27)			0.351	0.518	0.460	0.670	1845	96.9%
M-5 CARLITE	30G058 30H083	0.012 (0.30)			0.390	0.566	0.513	0.736	1834	97.2%
M-6 CARLITE	35G066 35H094	0.014 (0.35)			0.440	0.627	0.582	0.823	1848	97.2%

The core loss and exciting power of the Cleveland-Cliffs TRAN-COR® H grades are determined by magnetic tests performed in accordance with general procedures approved by the American Society for Testing and Materials. The following conditions apply:
1. Results for as-sheared single sheet specimens from fully processed material cut parallel to the rolling direction of the coil and tested per ASTM A804
2. Density of all grades (7.65 gm/cm³) per ASTM A343
ASTM A664 is a grade identification system for electrical steels. While this system has not been widely adopted by the manufacturers and consumers of electrical steels, it is used in ASTM A876 to designate various grades of grain oriented electrical steel.

Surface Insulation & Lamination Factor Curves

SURFACE INSULATION CURVES

Figure 1 (right) shows the variation of surface insulation resistivity versus pressure. The range of surface insulation resistivity values between the upper and lower lines are typical of those for CARLITE 3 insulated surfaces as determined by the Franklin Test method (ASTM A717). However, the user should recognize that the normally small variations in mill oxide and coating thickness within a lot necessitate allowing for test values lower, as well as higher, than those shown in the curves.

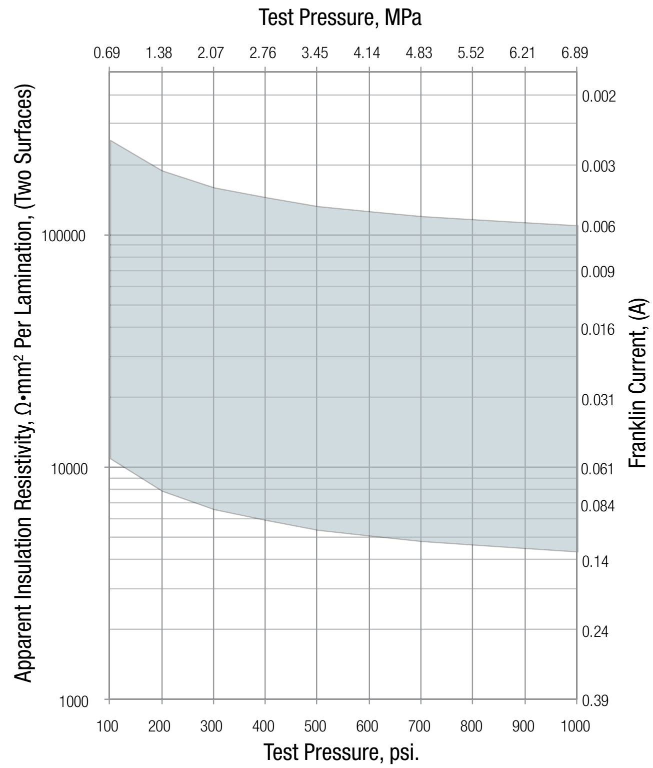
LAMINATION FACTOR

Lamination factor is the measure of compactness of an electrical steel core. This is also referred to as "stacking factor" and "space factor." Lamination factor is the ratio of the equivalent "solid" volume, calculated from weight and density of the steel, to the actual volume of the compressed pack, determined from its dimensions. Special processing gives Cleveland-Cliffs' Grain-Oriented Electrical Steels exceptionally and consistently high lamination factors.

TEST METHOD

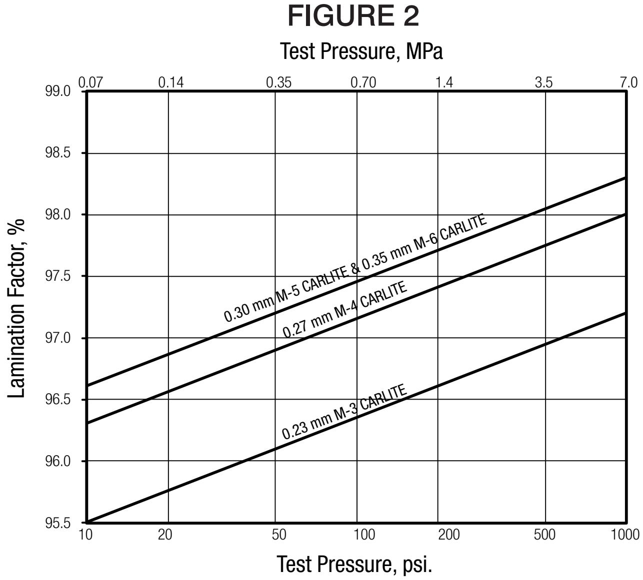
The lamination factor of electrical steels is determined from measurements of a stack of Epstein strips under known pressure, in accordance with ASTM A719. Figure 2 (below) illustrates how the ASTM lamination factor varies as a function of pressure for Cleveland-Cliffs Grain-Oriented Electrical Steels. The values shown are representative of the lamination factor determined by this test.

FIGURE 1



Typical surface insulation characteristics of Cleveland-Cliffs Grain-Oriented Electrical Steels at various pressures as determined by the Franklin Test.

FIGURE 2



Representative lamination factors for Cleveland-Cliffs Grain-Oriented Electrical Steels at various pressures.

Surface Insulation & Lamination Factor Curves

TABLE 3

Ultimate Tensile Strength in rolling direction, psi. (MPa)	51,000	(352)
Yield Strength in rolling direction, psi. (MPa)	48,000	(331)
Percent Elongation in 2" in. rolling direction	9	–
Microhardness (Knoop Hardness Number, HK)	167	–
Equivalent Rockwell B Scale Hardness	81	–
Modulus of Elasticity, psi. (MPa)*		
in rolling direction	17,700,000	(122,000)
at 20° to rolling direction	20,800,000	(143,000)
at 45° to rolling direction	34,300,000	(236,000)
at 55° to rolling direction	37,500,000	(258,000)
at right angles to rolling direction	29,000,000	(200,000)

**Values may vary as much as plus or minus 5%.*

Magnetostriction

The magnetostriction coefficients are inherent to CARLITE Grain-Oriented Electrical Steel, owing to the degree of grain orientation, low residual strain after thermal flattening and high degree of residual tension imparted by the CARLITE 3 coating.

The information below, while purely comparative in nature, is considered to be representative of Cleveland-Cliffs' CARLITE Grain-Oriented Electrical Steel products.

TABLE 4 – COMPARATIVE MAGNETOSTRICTION

Grade	Nominal Thickness, in. (mm)	Magnetostriction x 10^8 60 Hz	
		15 kG	17 kG
M-3 CARLITE	0.009 (0.23)	-80	-94
M-4 CARLITE	0.011 (0.27)	-93	-116
M-5 CARLITE	0.012 (0.30)	-94	-125
M-6 CARLITE	0.014 (0.35)	-97	-124

TEST METHOD

The data is meant for comparative purposes only and was developed using Epstein specimens from representative samples which were prepared in accordance with ASTM A876. While there are no agreed upon standard testing methods for magnetostriction, the data was acquired using an accelerometer-based measurement of crossover-to-tip displacement of many individual Epstein strips which were tested at a frequency of 60 Hz at the inductions shown abo ve. The magnetostriction values are, to our best knowledge, believed to be representative of commercially produced materials.

Thickness, Width, Camber & Flatness Tolerances

TABLE 5 – THICKNESS TOLERANCES

Grade	Nominal Thickness, in. (mm)	Thickness, in. (mm)	
		Minimum	Maximum
M-3 CARLITE	0.009 (0.23)	0.0075 (0.190)	0.0100 (0.254)
M-4 CARLITE	0.011 (0.27)	0.0095 (0.241)	0.0120 (0.305)
M-5 CARLITE	0.012 (0.30)	0.0105 (0.267)	0.0130 (0.330)
M-6 CARLITE	0.014 (0.35)	0.0125 (0.318)	0.0150 (0.381)

The aim thickness values are based on the test sample weight, plus typical coating thickness, such as would be measured using a contacting micrometer. The typical coating thickness is 0.0002 – 0.0004 in. (0.005 – 0.010 mm). Thickness measured at any point on the sheet not less than 0.375 in. (10 mm) from an edge shall not deviate more than +/- 0.0010 in. (0.025 mm) from the average thickness of the test lot or coil.

TABLE 6 – WIDTH TOLERANCES

Specified Width, in. (mm)	Tolerance over, in. (mm)	Tolerance under, in. (mm)
To 4 (102) inclusive	0.005 (0.127)	0.005 (0.127)
Over 4 to 9 (102 to 229) inclusive	0.007 (0.178)	0.007 (0.178)
Over 9 to 15 (229 to 381) inclusive	0.010 (0.254)	0.010 (0.254)
Over 15 (381) inclusive	0.016 (0.406)	0.016 (0.406)

CAMBER TOLERANCES

The deviation of a side edge from a straight line over a length of 80 in. (2 m), or a fraction thereof, shall not exceed 0.1 in. (2.54 mm).

FLATNESS TOLERANCES

Because of the wide range of processing treatments employed to meet the published core loss values for the various types and classes of flat rolled electrical steels, and because ordinary supplemental flattening operations employed on other steel products cannot be used due to their effects on magnetic quality, it has not been feasible to prepare flatness tolerance tables for flat-rolled electrical steel. Some applications, and certain types of fabricating techniques for construction of magnetic cores, are tolerant of certain flatness deviations. However, it is generally recognized that sharp, short waves and buckles are objectionable and should be avoided as much as possible. The producer should determine the flatness requirements for its particular application and the suitability of this electrical steel.

Manufacturing Specifications

TABLE 7

Thickness	0.009 in. (0.23 mm) M-3 0.011 in. (0.27 mm) M-4 0.012 in. (0.30 mm) M-5 0.014 in. (0.35 mm) M-6	
Width	Master coils are available in widths up to 36.22 in. (920 mm)	
Coils-Slit	Minimum width Inside diameters	0.75 in. (19 mm) Narrower – Inquire 16.0 in. (406 mm) 20.0 in. (508 mm)
Coils-Not Slit	Inside diameter	20.0 in. (508 mm)
Approximate Coil Weight	335 lb. per in. of width (600 kg per 100 mm of width)	

Typical Values of Core Loss

At 50 and 60 Hz for Typical Specimens of Cleveland-Cliffs Oriented CARLITE Coated Electrical Steels

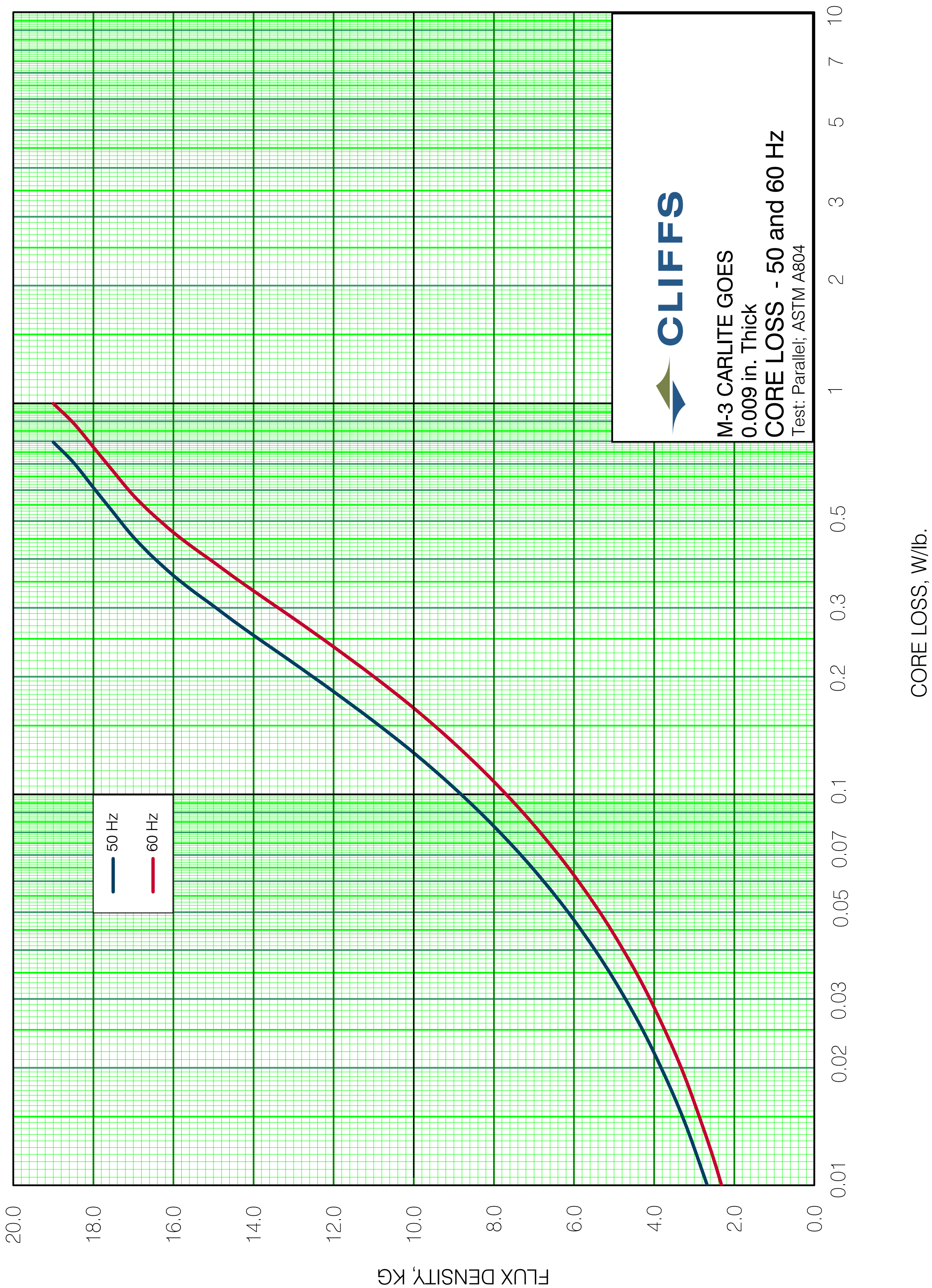
Flux Density (kG)	Core Loss (W/lb.) – ASTM A804 (Sheet Specimens)							
	0.009 in. M-3 Oriented CARLITE		0.011 in. M-4 Oriented CARLITE		0.012 in. M-5 Oriented CARLITE		0.014 in. M-6 Oriented CARLITE	
	50 Hz	60 Hz	50 Hz	60 Hz	50 Hz	60 Hz	50 Hz	60 Hz
1	0.00147	0.00192	0.00183	0.00242	0.00195	0.00259	0.00247	0.00329
2	0.00257	0.00742	0.00702	0.00928	0.00757	0.0101	0.00928	0.0124
3	0.0125	0.0163	0.0152	0.0202	0.0165	0.0220	0.0199	0.0267
4	0.0218	0.0285	0.0265	0.0347	0.0286	0.0381	0.0342	0.0458
5	0.0336	0.0438	0.0400	0.0528	0.0437	0.0580	0.0518	0.0694
6	0.0477	0.0621	0.0564	0.0742	0.0617	0.0819	0.0728	0.0973
7	0.0641	0.0834	0.0753	0.0990	0.0828	0.110	0.0971	0.130
8	0.0829	0.108	0.0968	0.127	0.107	0.142	0.125	0.166
9	0.104	0.135	0.121	0.159	0.134	0.178	0.156	0.208
10	0.128	0.166	0.148	0.195	0.165	0.218	0.191	0.254
11	0.154	0.200	0.179	0.236	0.199	0.263	0.230	0.305
12	0.183	0.238	0.214	0.281	0.238	0.314	0.273	0.363
13	0.217	0.282	0.253	0.333	0.281	0.371	0.322	0.427
14	0.255	0.331	0.298	0.391	0.330	0.435	0.376	0.498
15	0.303	0.393	0.353	0.462	0.390	0.513	0.440	0.582
16	0.363	0.467	0.418	0.546	0.462	0.605	0.517	0.683
17	0.455	0.581	0.514	0.666	0.566	0.736	0.625	0.823
18	0.609	0.773	0.658	0.845	0.719	0.930	0.776	1.02
19	0.795	0.999	0.770	0.990	0.898	1.15	0.921	1.19
	Core Loss (W/lb.) – ASTM A343 (Epstein Specimens)							
1	0.00154	0.00201	0.00189	0.00249	0.00195	0.00260	0.00251	0.00334
2	0.00581	0.00762	0.00707	0.00935	0.0075	0.0100	0.00921	0.0123
3	0.0127	0.0167	0.0153	0.0202	0.0164	0.0219	0.0197	0.0265
4	0.0222	0.0291	0.0264	0.0346	0.0285	0.0381	0.0338	0.0453
5	0.0343	0.0447	0.0402	0.0531	0.0437	0.0582	0.0513	0.0687
6	0.0489	0.0636	0.0568	0.0748	0.0620	0.0823	0.0721	0.0964
7	0.0659	0.0858	0.0761	0.100	0.0833	0.111	0.0964	0.129
8	0.0854	0.111	0.0981	0.129	0.108	0.143	0.124	0.165
9	0.107	0.140	0.123	0.162	0.136	0.180	0.155	0.207
10	0.132	0.172	0.151	0.198	0.166	0.220	0.190	0.253
11	0.159	0.207	0.182	0.239	0.201	0.266	0.229	0.305
12	0.189	0.246	0.217	0.285	0.240	0.317	0.273	0.362
13	0.223	0.291	0.255	0.336	0.283	0.374	0.321	0.425
14	0.263	0.341	0.300	0.395	0.332	0.438	0.375	0.496
15	0.311	0.402	0.354	0.463	0.390	0.513	0.437	0.578
16	0.374	0.481	0.421	0.550	0.463	0.606	0.512	0.676
17	0.468	0.598	0.520	0.673	0.563	0.733	0.612	0.806
18	0.631	0.801	0.680	0.872	0.717	0.925	0.765	1.00
19	0.824	1.03	0.845	1.090	0.895	1.15	0.943	1.22

Typical Values of RMS Exciting Power

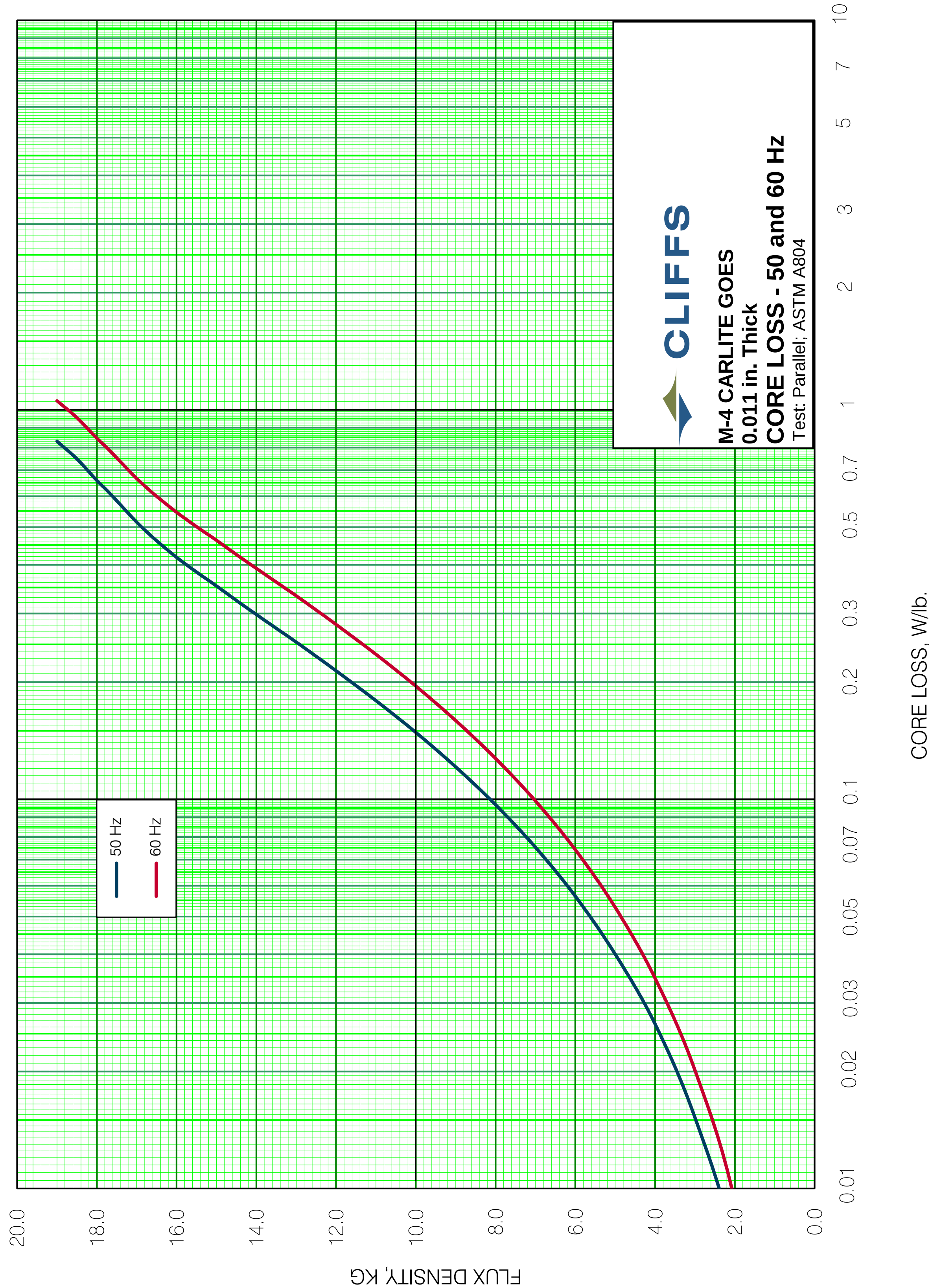
At 50 and 60 Hz for Typical Specimens of Cleveland-Cliffs Oriented CARLITE Coated Electrical Steels

Flux Density (kG)	Exciting Power (rms VA/lb.) - ASTM A804 (Sheet Specimens)							
	0.009 in. M-3 Oriented CARLITE		0.011 in. M-4 Oriented CARLITE		0.012 in. M-5 Oriented CARLITE		0.014 in. M-6 Oriented CARLITE	
	50 Hz	60 Hz	50 Hz	60 Hz	50 Hz	60 Hz	50 Hz	60 Hz
1	0.00458	0.00560	0.00472	0.00583	0.00418	0.00521	0.00406	0.00516
2	0.0152	0.0186	0.0154	0.0192	0.0138	0.0174	0.0134	0.0173
3	0.0300	0.0369	0.0305	0.0381	0.0275	0.0348	0.0270	0.0350
4	0.0479	0.0592	0.0488	0.0613	0.0447	0.0567	0.0443	0.0576
5	0.0683	0.0846	0.0699	0.0881	0.0650	0.0827	0.0651	0.0848
6	0.0910	0.113	0.0937	0.118	0.0882	0.112	0.0893	0.116
7	0.116	0.144	0.120	0.152	0.114	0.147	0.117	0.153
8	0.143	0.179	0.149	0.189	0.144	0.185	0.148	0.193
9	0.173	0.217	0.181	0.231	0.177	0.228	0.183	0.239
10	0.207	0.259	0.218	0.277	0.215	0.276	0.222	0.290
11	0.244	0.306	0.258	0.329	0.258	0.331	0.266	0.348
12	0.288	0.360	0.306	0.389	0.309	0.396	0.318	0.414
13	0.343	0.429	0.365	0.463	0.372	0.476	0.379	0.493
14	0.410	0.511	0.437	0.553	0.456	0.580	0.456	0.591
15	0.521	0.645	0.552	0.694	0.582	0.733	0.571	0.734
16	0.687	0.843	0.711	0.883	0.783	0.975	0.761	0.965
17	1.20	1.45	1.25	1.53	1.45	1.78	1.38	1.71
18	3.19	3.84	3.50	4.25	4.11	4.99	4.16	5.01
19	11.7	14.1	12.4	15.1	13.8	16.8	15.2	18.2
	Exciting Power (rms VA/lb.) - ASTM A343 (Epstein Specimens)							
1	0.00413	0.00504	0.00424	0.00524	0.00398	0.00496	0.00393	0.00499
2	0.0139	0.0171	0.0141	0.0176	0.0135	0.0171	0.0132	0.0169
3	0.0279	0.0343	0.0283	0.0354	0.0274	0.0347	0.0267	0.0346
4	0.0449	0.0555	0.0457	0.0574	0.0448	0.0569	0.0440	0.0572
5	0.0645	0.0799	0.0659	0.0831	0.0652	0.0831	0.0648	0.0844
6	0.0862	0.107	0.0887	0.112	0.0887	0.113	0.0889	0.116
7	0.110	0.137	0.114	0.145	0.115	0.147	0.116	0.152
8	0.136	0.170	0.142	0.181	0.145	0.186	0.147	0.193
9	0.165	0.206	0.173	0.221	0.178	0.229	0.182	0.238
10	0.196	0.246	0.208	0.265	0.215	0.277	0.221	0.288
11	0.232	0.291	0.248	0.316	0.259	0.332	0.264	0.345
12	0.274	0.343	0.294	0.374	0.309	0.396	0.314	0.409
13	0.325	0.406	0.351	0.445	0.371	0.474	0.372	0.484
14	0.392	0.489	0.424	0.537	0.452	0.575	0.444	0.575
15	0.494	0.612	0.533	0.669	0.572	0.722	0.544	0.699
16	0.683	0.839	0.726	0.901	0.788	0.980	0.713	0.904
17	1.17	1.41	1.24	1.52	1.34	1.65	1.16	1.43
18	3.24	3.90	3.72	4.52	3.76	4.57	3.43	4.13
19	14.7	17.7	16.4	20.0	14.7	18.0	14.4	17.2

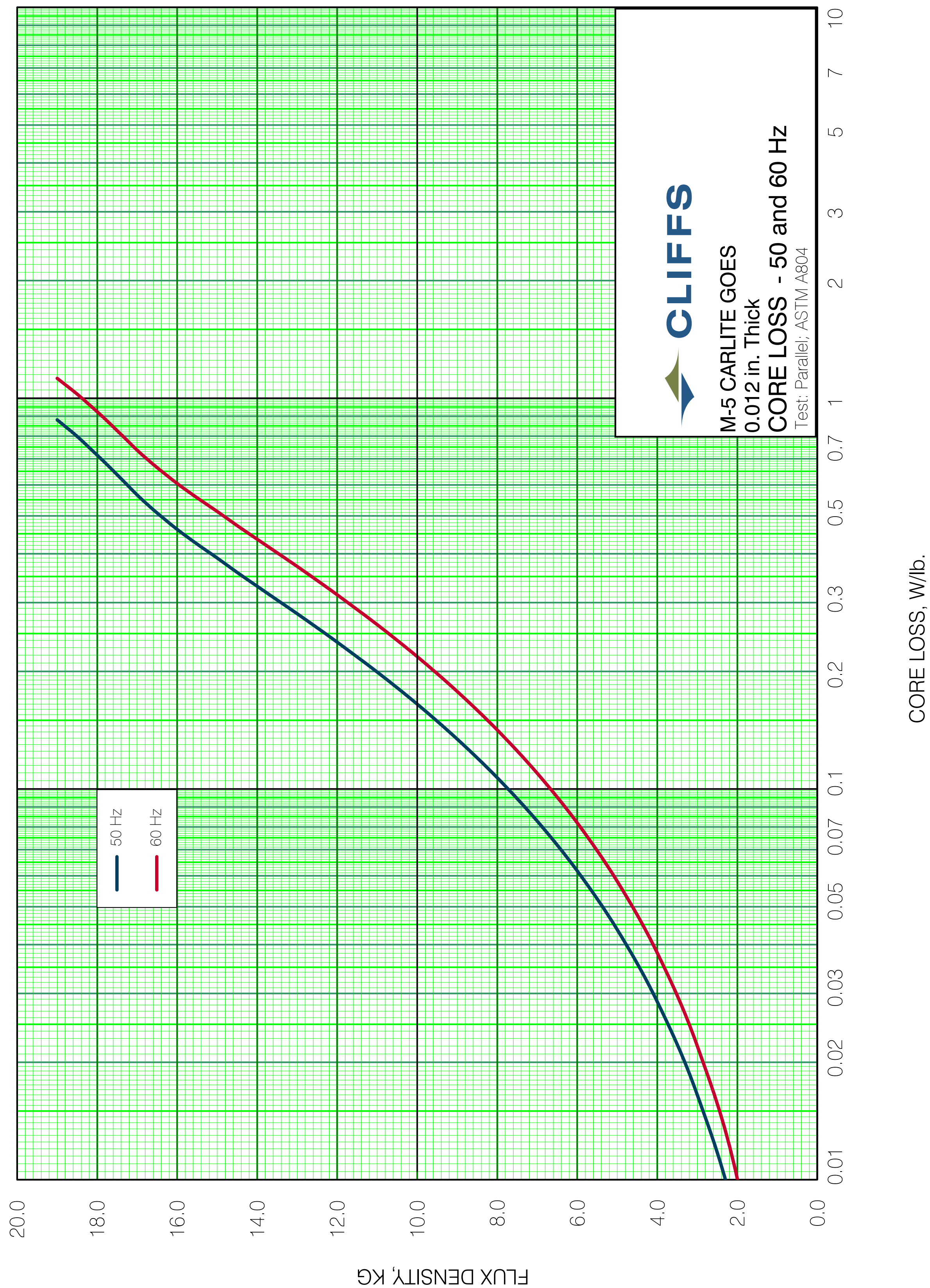
Core Loss Curve – M-3 CARLITE



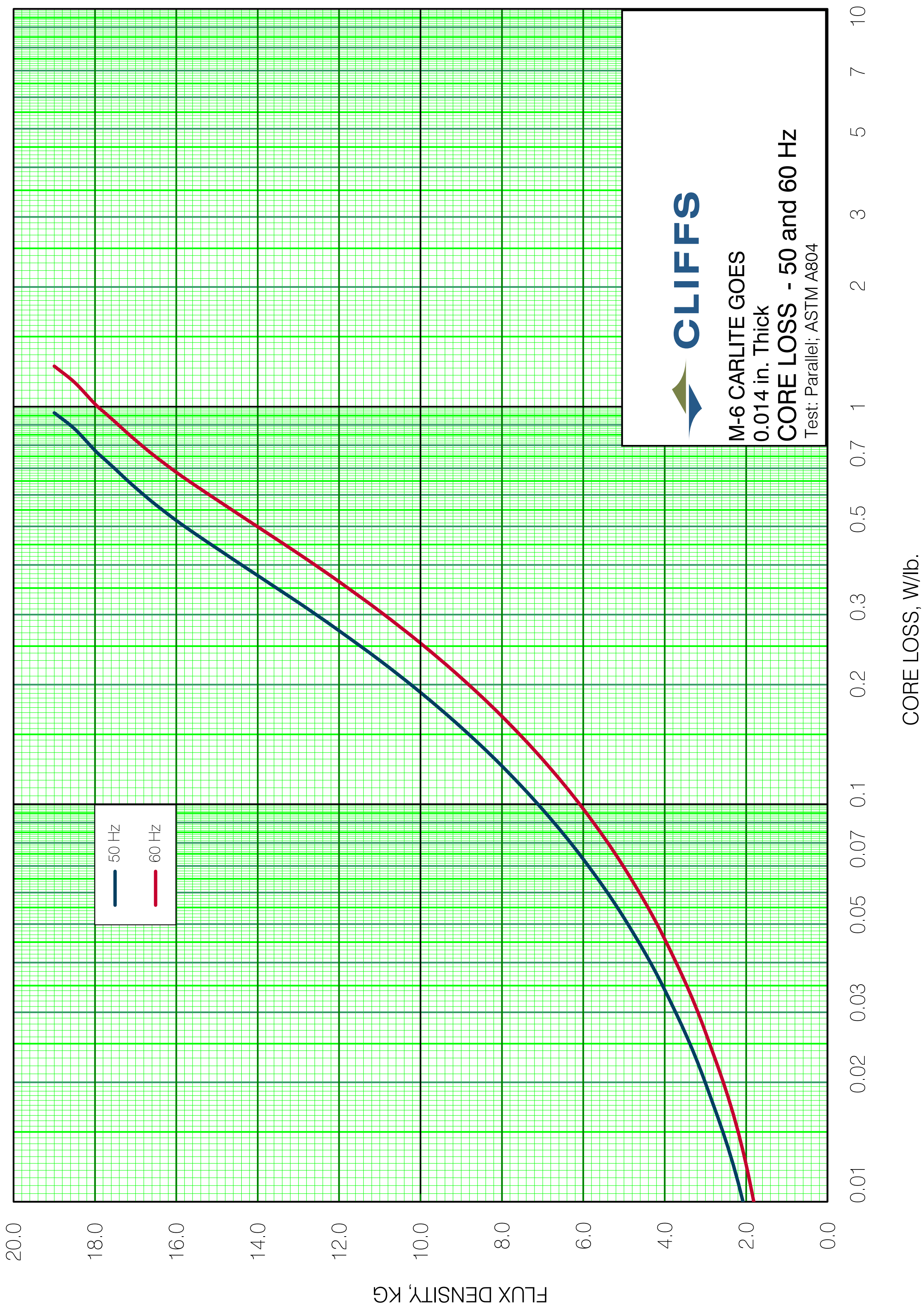
Core Loss Curve – M-4 CARLITE



Core Loss Curve – M-5 CARLITE



Core Loss Curve – M-6 CARLITE



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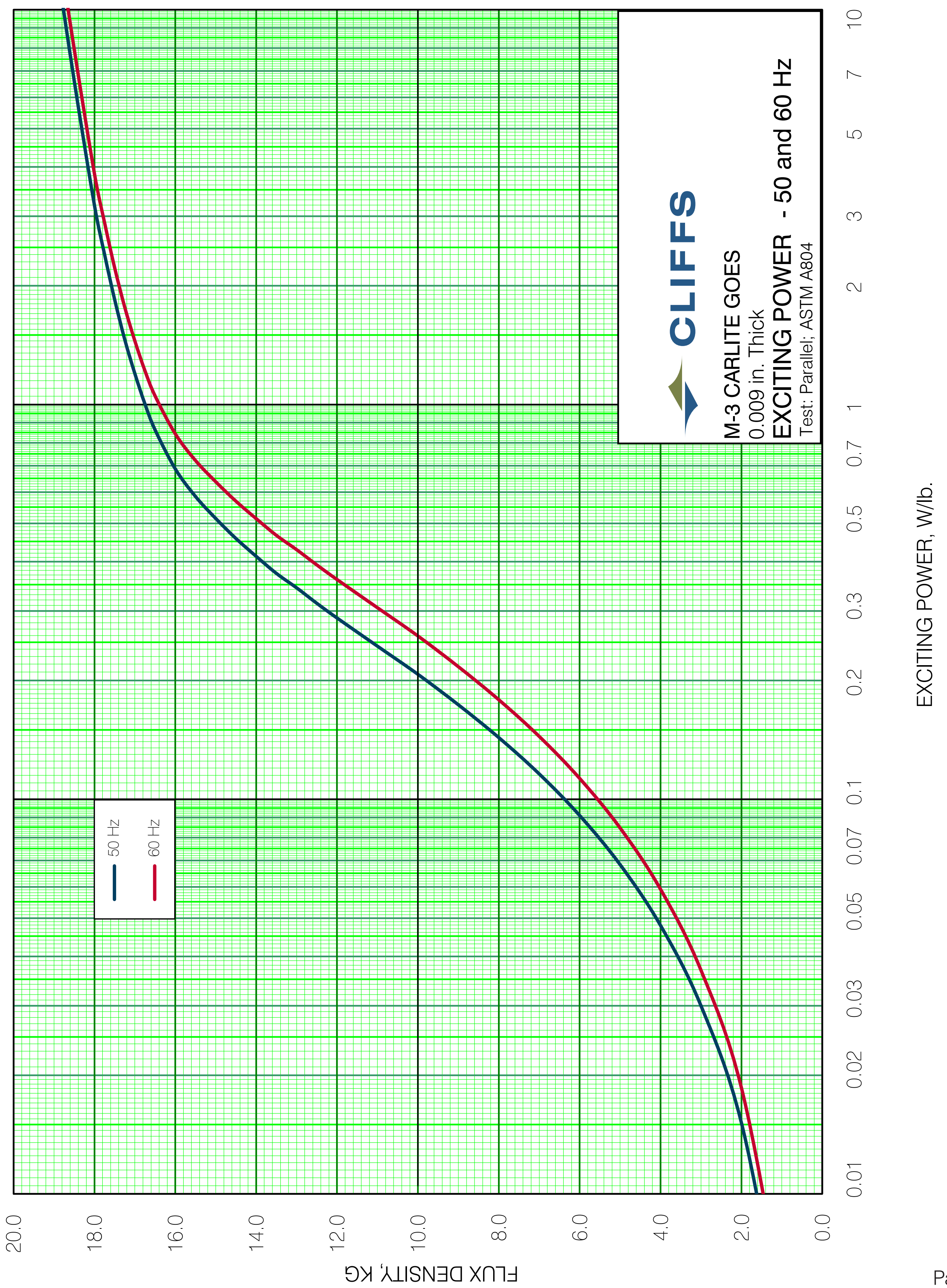
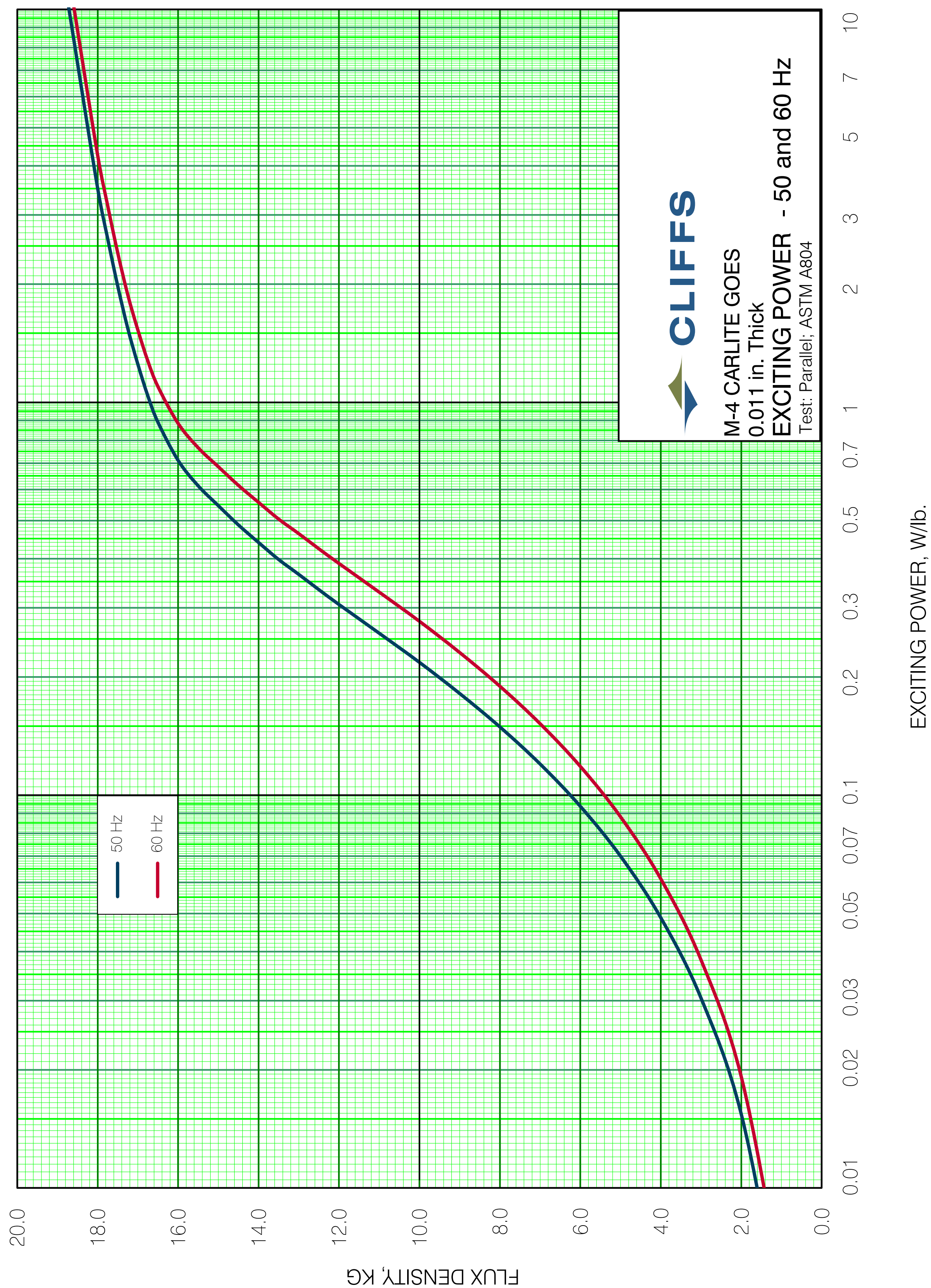
CARLITE®

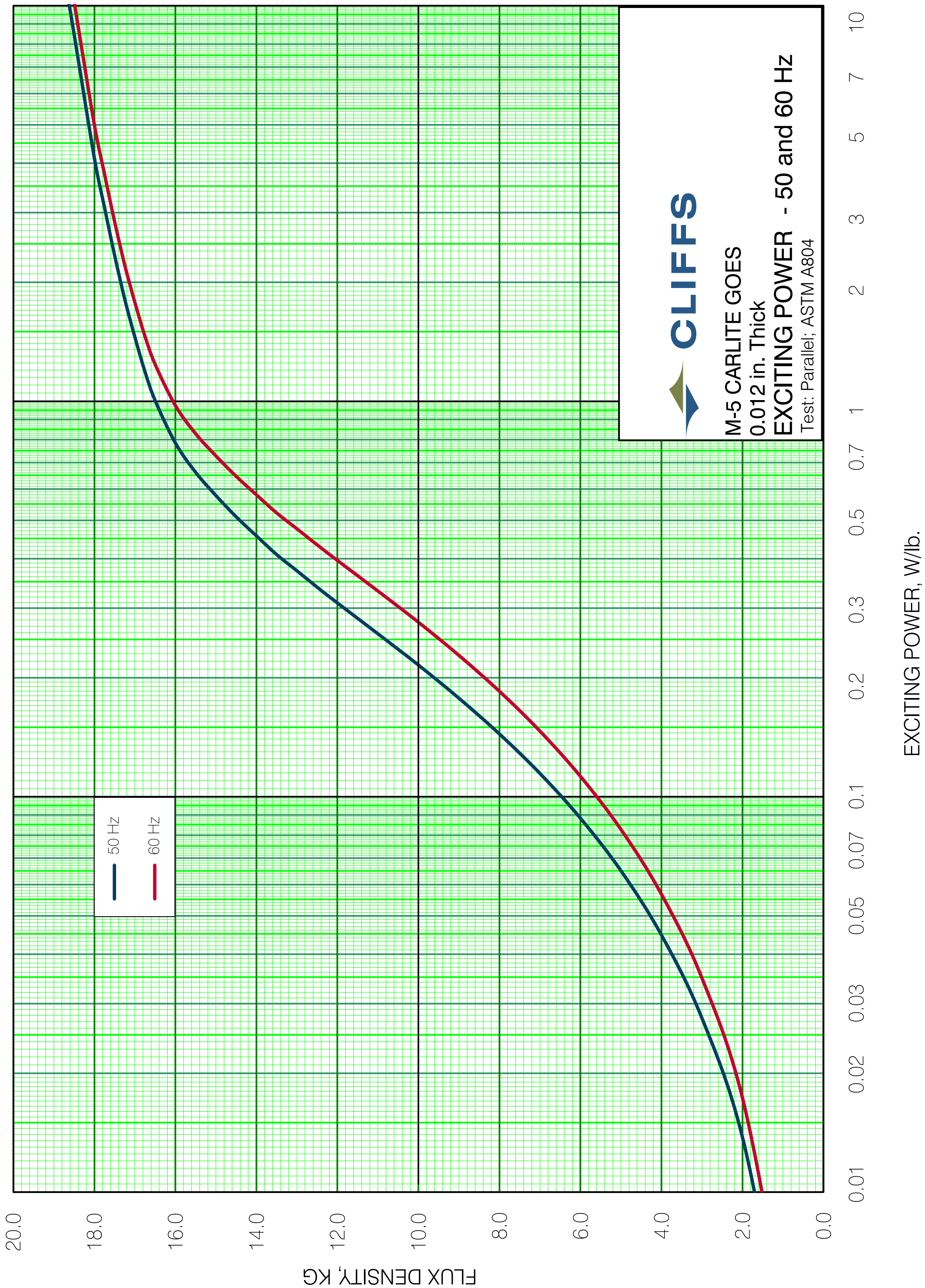
Exciting Power Curve – M-3 CARLITE



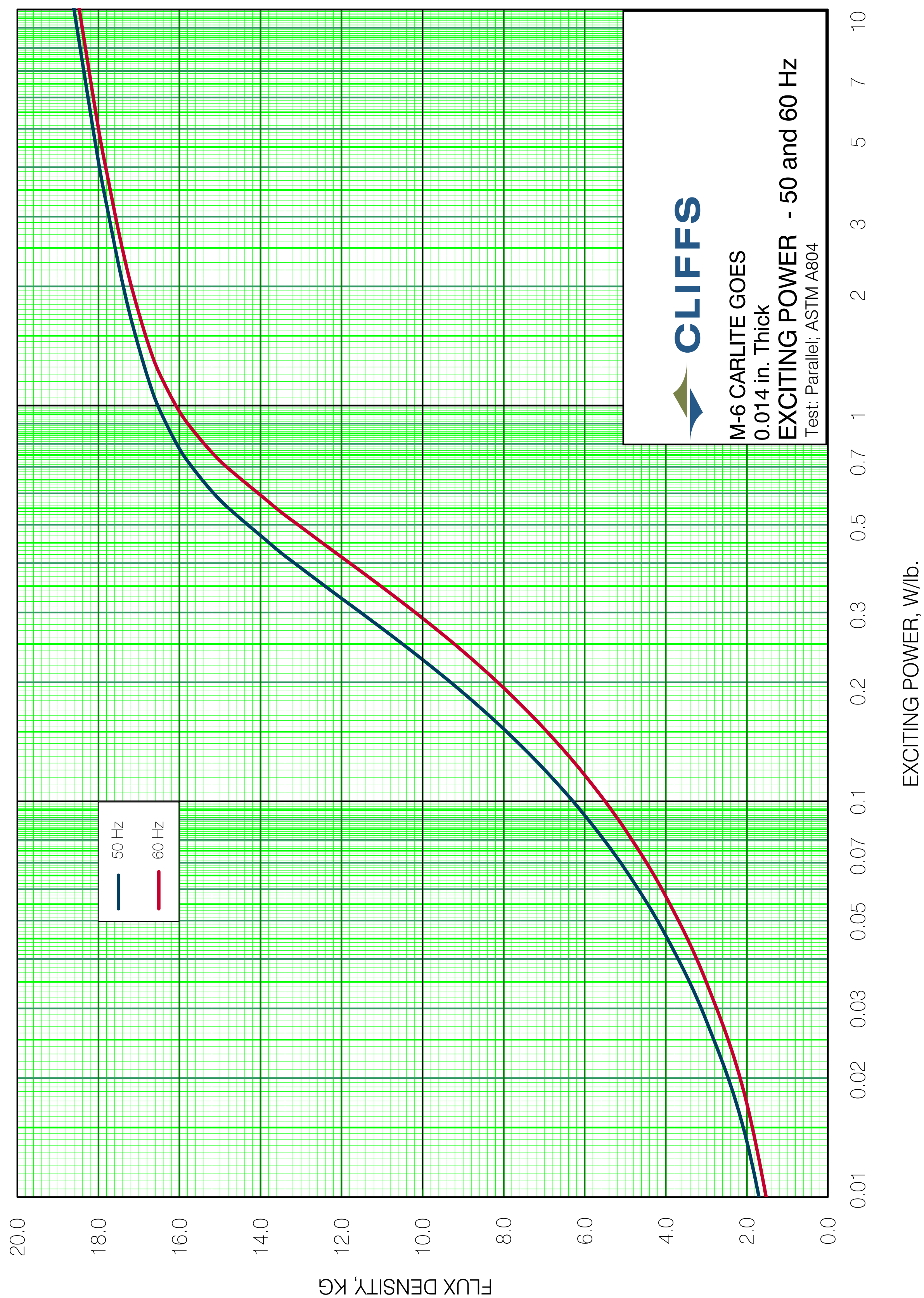
Exciting Power Curve – M-4 CARLITE



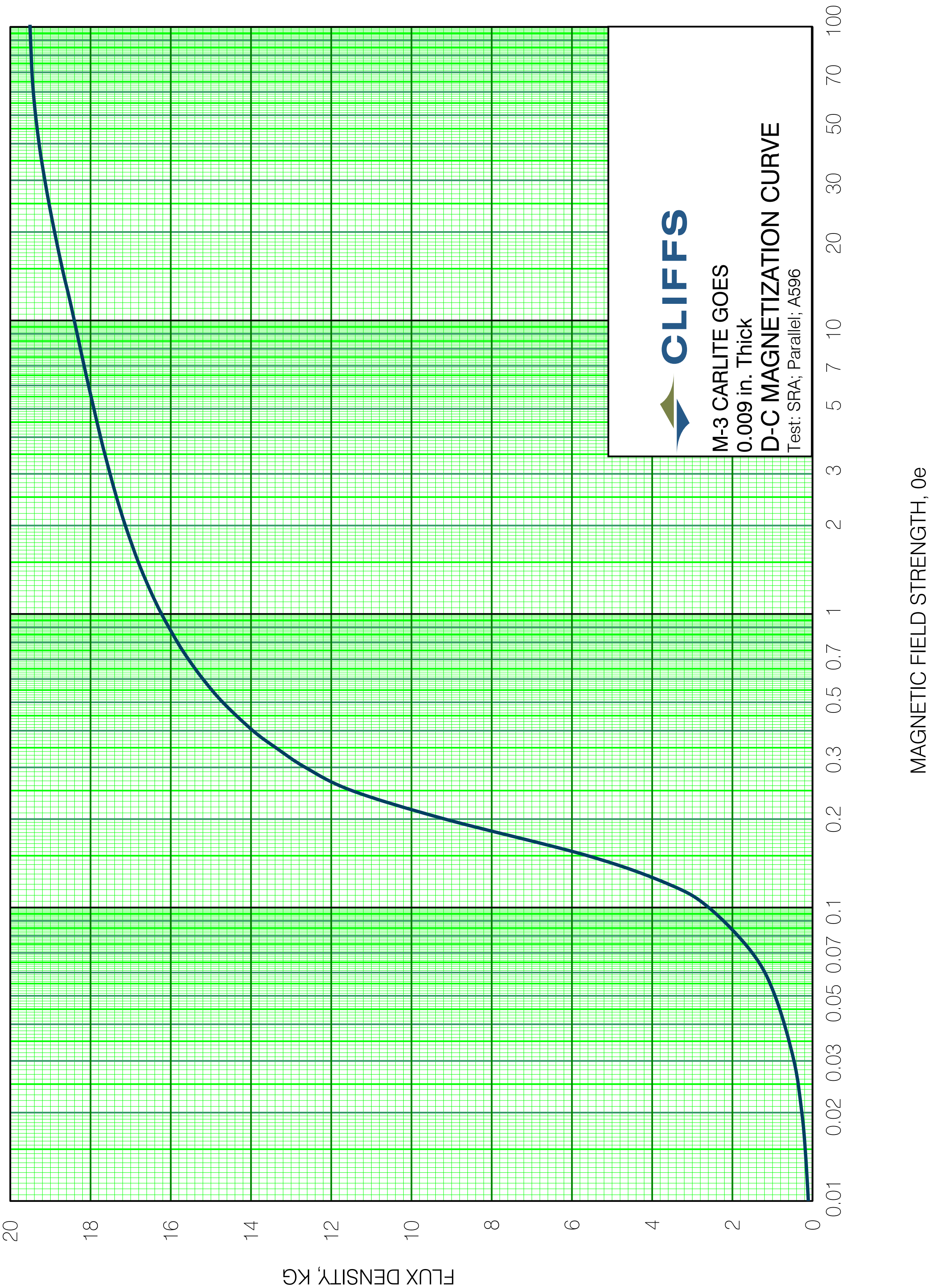
Exciting Power Curve – M-5 CARLITE



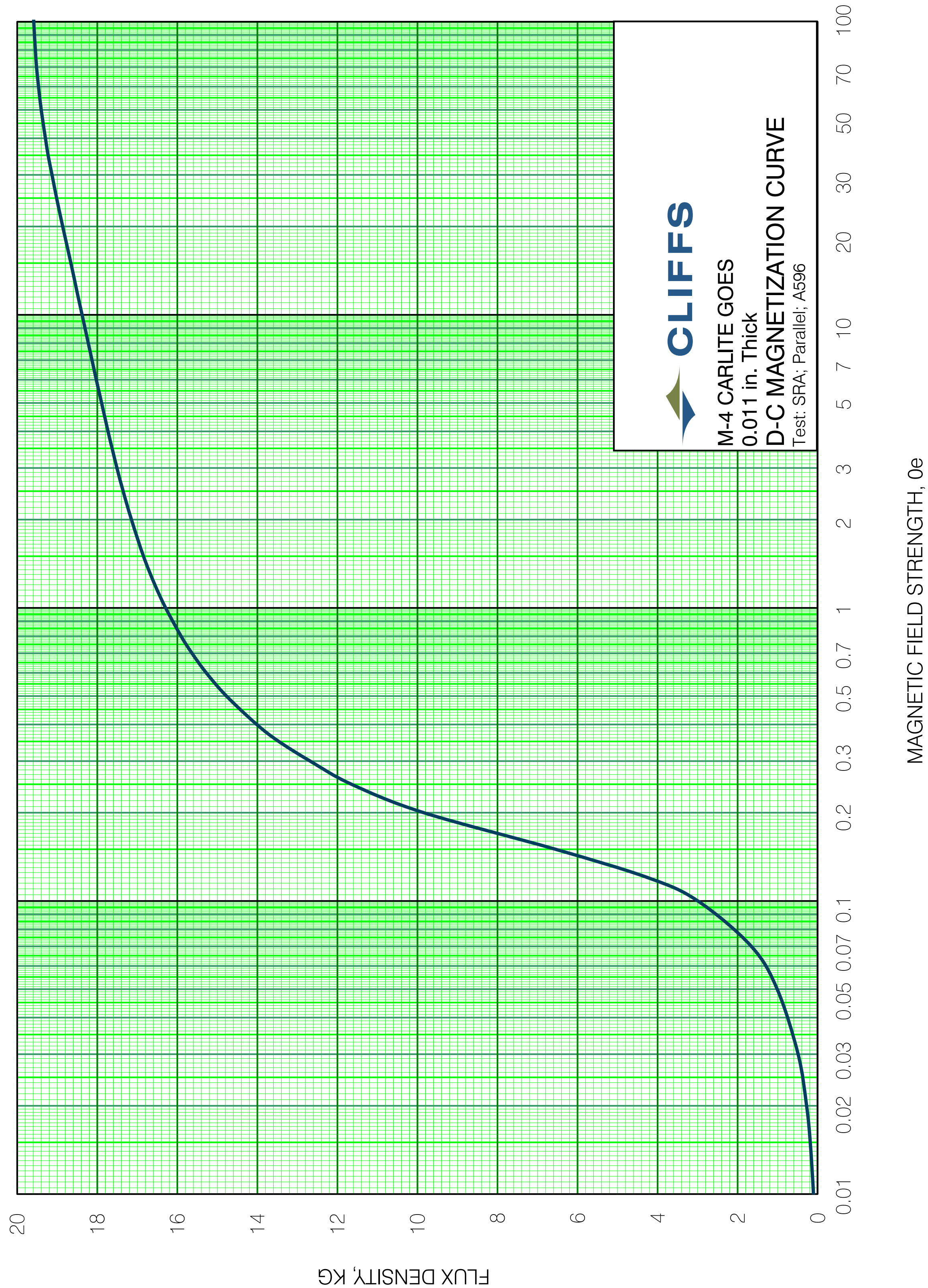
Exciting Power Curve – M-6 CARLITE



D-C Magnetization Curve – M-3 CARLITE



D-C Magnetization Curve – M-4 CARLITE



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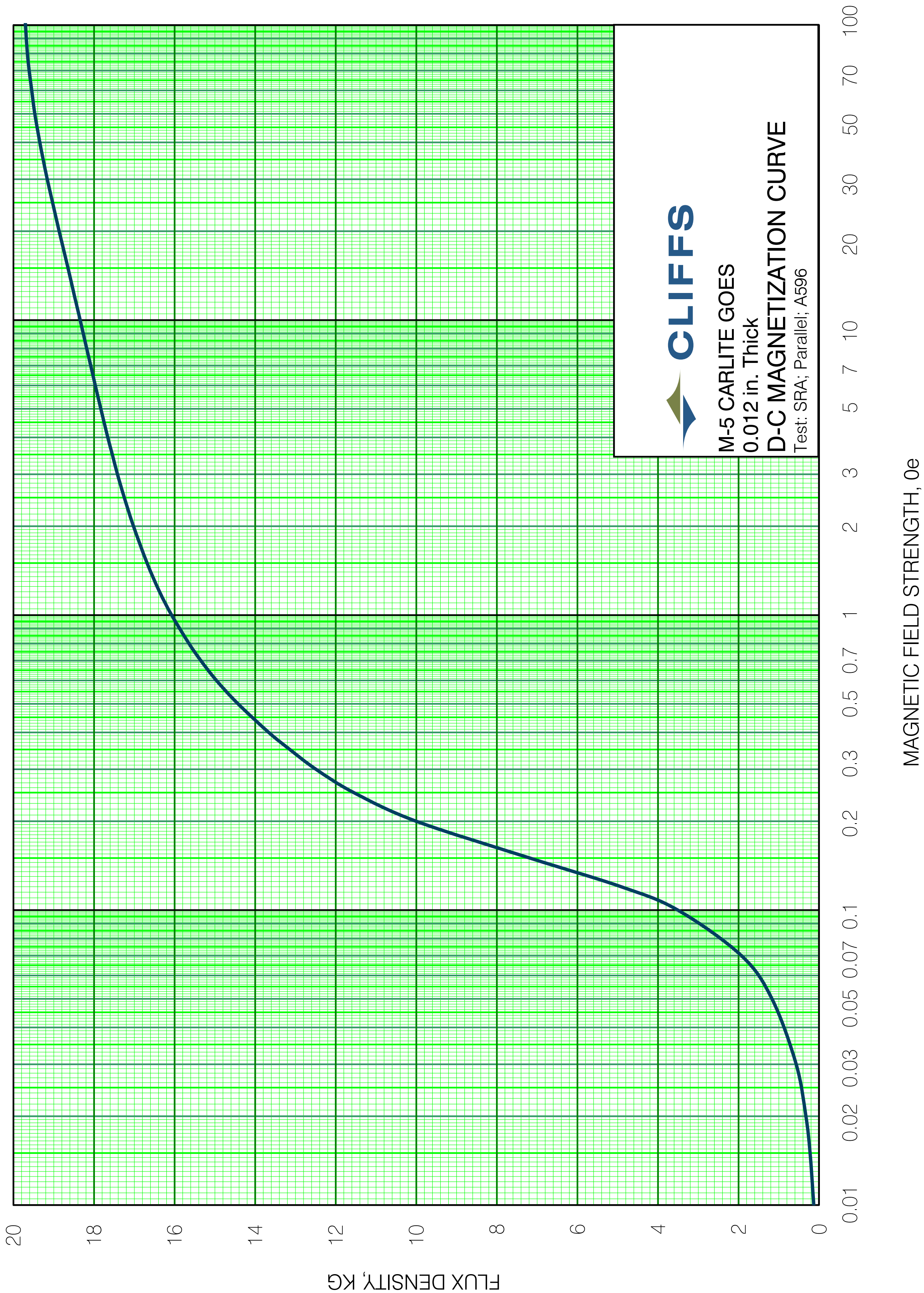
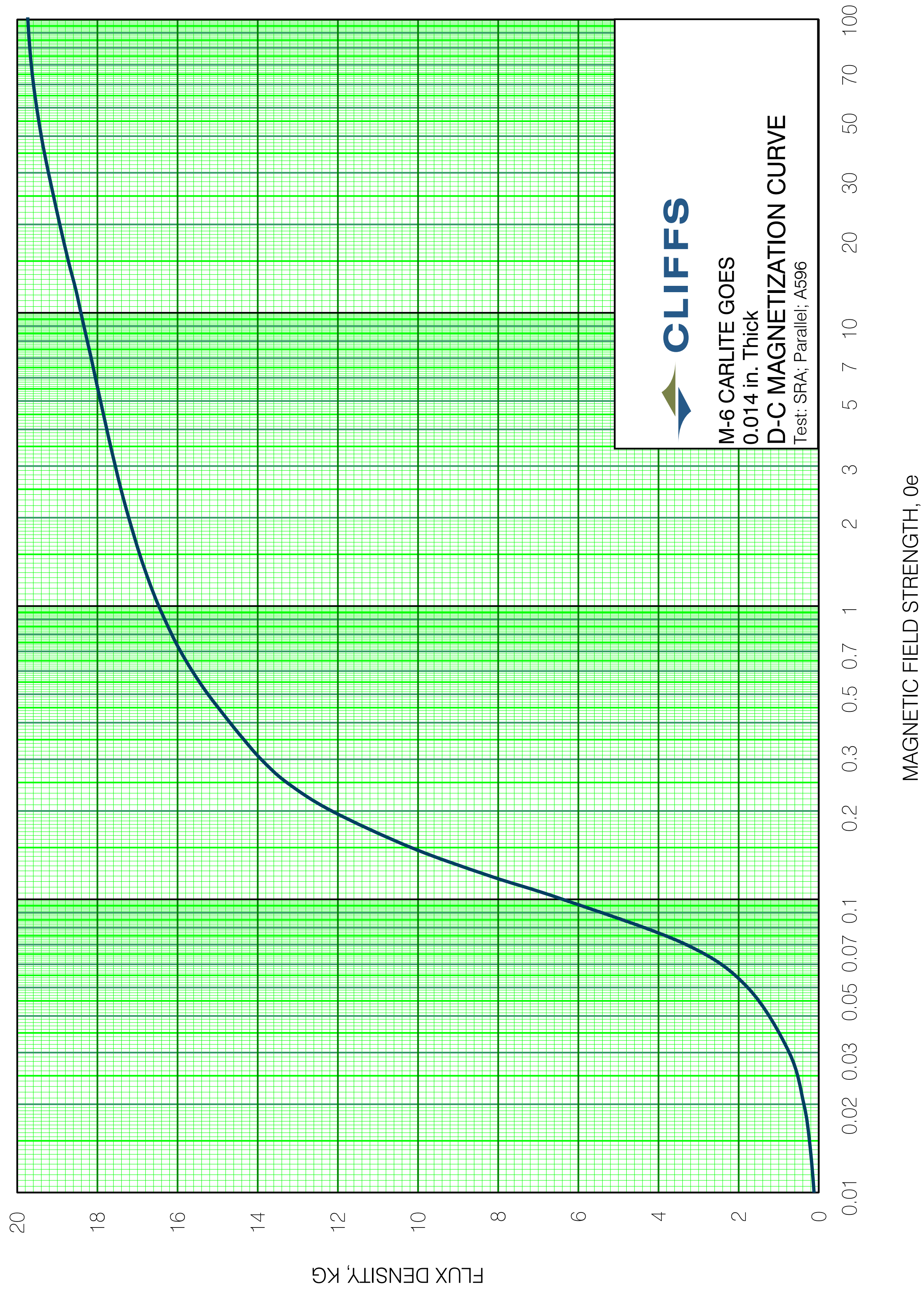
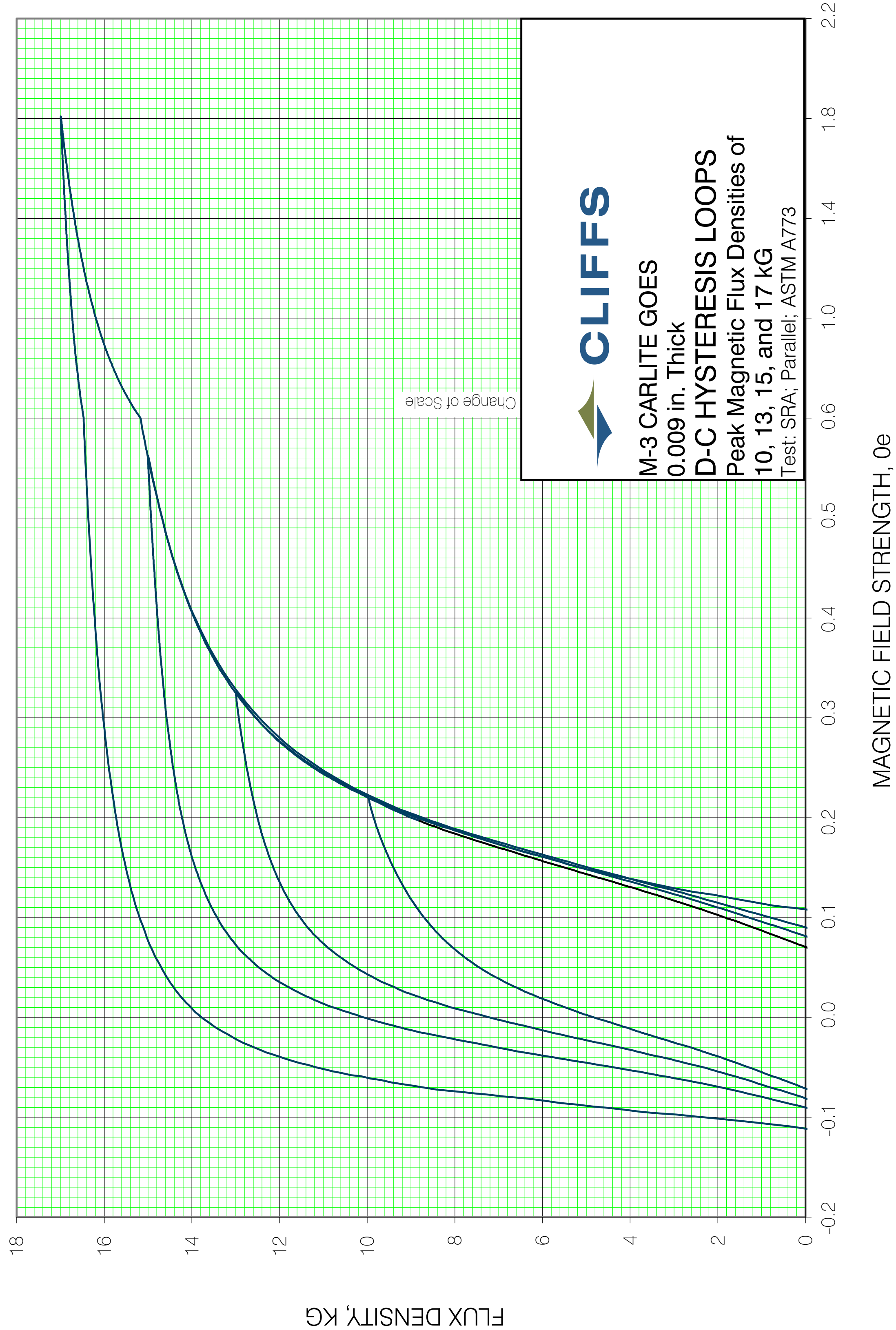
D-C Magnetization Curve – M-5 CARLITE



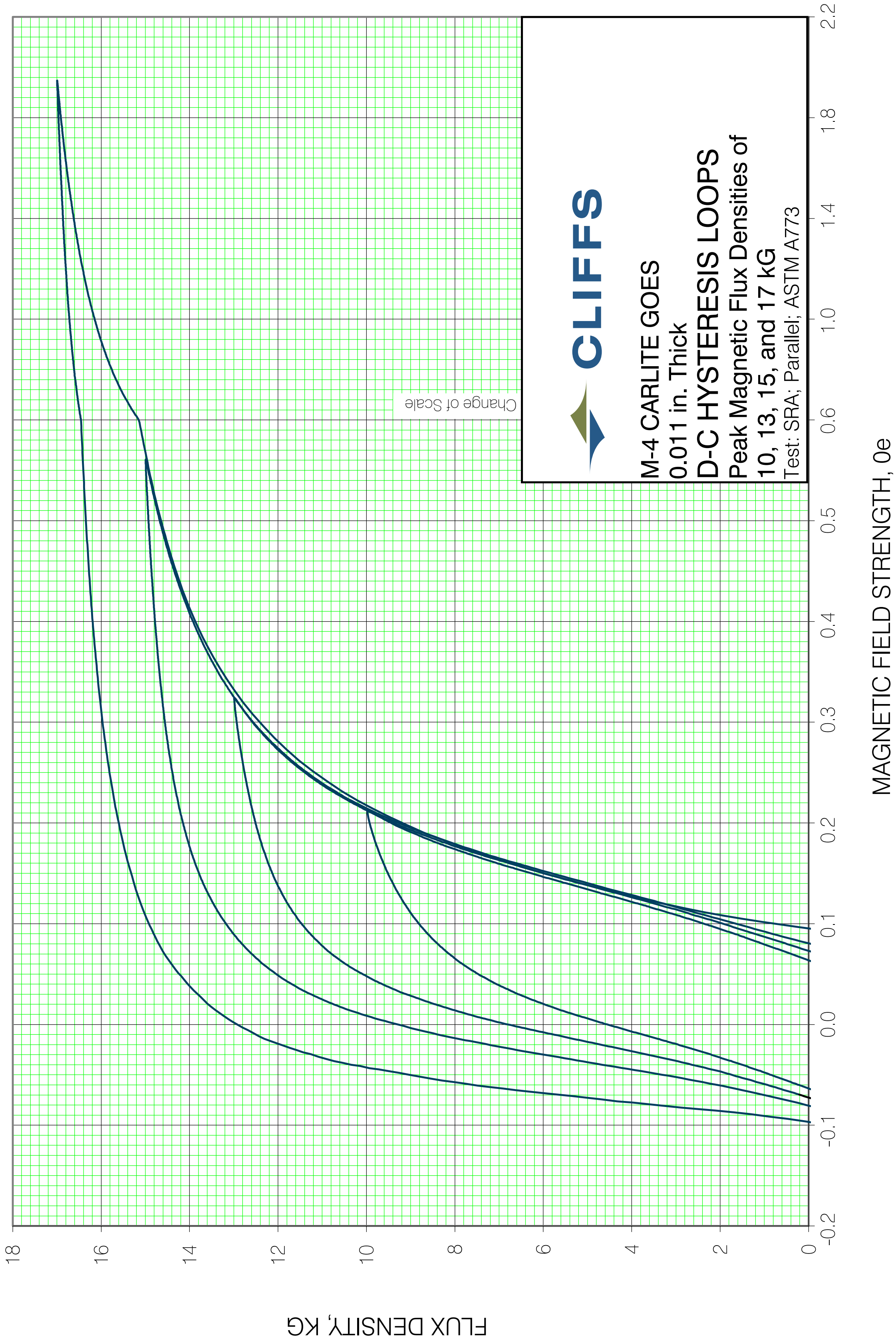
D-C Magnetization Curve – M-6 CARLITE



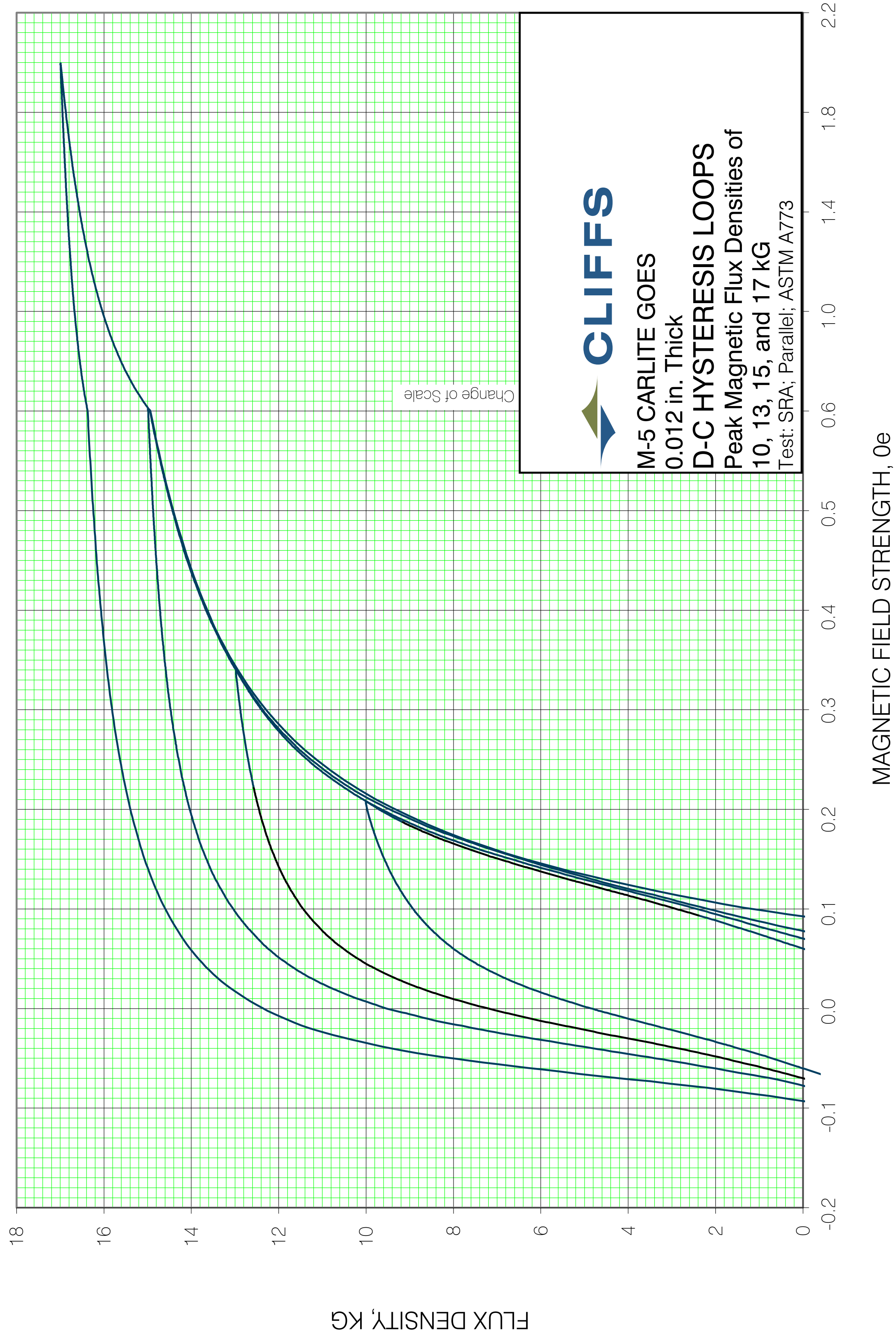
D-C Hysteresis Loops – M-3 CARLITE



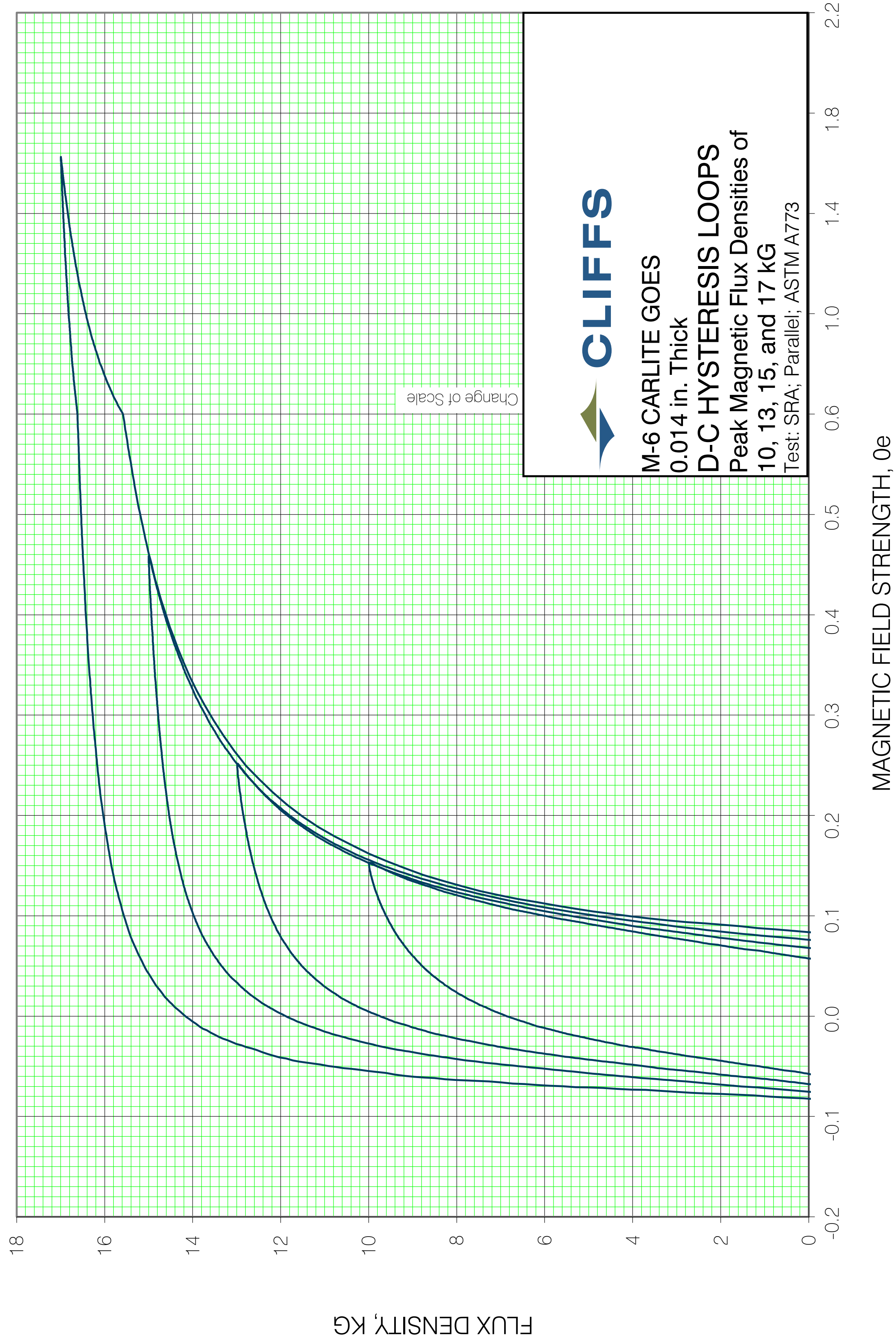
D-C Hysteresis Loops – M-4 CARLITE



D-C Hysteresis Loops – M-5 CARLITE



D-C Hysteresis Loops – M-6 CARLITE



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About Cleveland-Cliffs Inc.

Cleveland-Cliffs is the largest flat-rolled steel producer in North America. Founded in 1847 as a mine operator, Cliffs also is the largest manufacturer of iron ore pellets in North America. The Company is vertically integrated from mined raw materials and direct reduced iron to primary steelmaking and downstream finishing, stamping, tooling, and tubing. The Company serves a diverse range of markets due to its comprehensive offering of flat-rolled steel products and is the largest steel supplier to the automotive industry in North America. Headquartered in Cleveland, Ohio, Cleveland-Cliffs employs approximately 25,000 people across its mining, steel and downstream manufacturing operations in the United States and Canada.

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