ATI

Technical Data Sheet

Grain-Oriented Electrical Steel

Available in the Following Thicknesses:

7-mil or 0.007"	(0.18 mm)
9-mil or 0.009"	(0.23 mm)
11-mil or 0.011"	(0.27 mm)
12-mil or 0.012"	(0.30 mm)
14-mil or 0.014"	(0.35 mm)

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GOES Technical Information
and Inside Sales
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Grain-Oriented Electrical Steel

Technical Data Sheet

Grain-Oriented Electrical Steel

ATI Allegheny Ludlum Grain-Oriented Electrical Steel (GOES) is processed under carefully controlled conditions to develop optimum magnetic characteristics in the rolling direction. GOES develops low core losses at high inductions when used as core material in designs with the flux path parallel to the rolling direction. These low losses at high inductions are attained with low exciting currents because of the excellent high induction permeability of GOES. In addition, the normal operating inductions for GOES are sufficiently below the magnetic saturation of the material to allow a comfortable margin of safety in most designs. Processing of GOES is carefully controlled in order to achieve a very high stacking factor for the core material. This stacking factor often exceeds 95 percent of the theoretical maximum. The high usable magnetic induction of GOES, along with the high stacking factor, allow compact core designs requiring the minimum amount of material to be used in the windings surrounding the core. This contributes to low losses, not only in the core (no load losses), but also allows for minimum load losses or winding losses in the transformer.

ATI Allegheny Ludlum GOES also offers low manufacturing costs for transformer cores. GOES may be processed into conventional core designs and is available in a wide variety of widths ranging from 3 inches to 34 inches (7.6 cm to 86.4 cm). GOES can be formed by conventional methods. Slitting, cutting to length, winding, and stacking may all be accomplished using conventional core processing. Stress relief annealing, where required, can also be accomplished using conventional techniques.

D-Finish for Wound Core Applications

ATI Allegheny Ludlum GOES D-Finish is a product specifically designed for use in wound core transformers. The product is a lightly coated material which offers the following benefits:

- Enhances ease of winding using automated core winding equipment allowing maximum productivity
- Resists internal oxidation during stress relief annealing
- Enhances lacing of transformer cores into windings due to reduced surface friction
- Reduces interlamination eddy current losses due to the insulating quality of the coating
- Resists the formation of surface rust on the material in storage by the presence of the coating

These factors, as well as translating into the lowest possible manufacturing costs and highest productivity lend themselves to reducing to a minimum the magnetic destruction factor encountered in the core building operation.

T-Finish for Lay-Up Applications

ATI Allegheny Ludlum's T-Finish designation for GOES has been specially processed, slit, and tested for use in stacked-core configurations. Slitting to width is accomplished while minimizing burr and retaining the magnetic characteristics. Superior insulation quality and low magnetostriction make the T-Finish steel a world-class choice for today's power transformers. T-Finish steel is delivered ready to be sheared into final lamination size for immediate stacking into the core structure.

Typical properties of GOES are shown in Table 1.

Table 1 - TYPICAL PHYSICAL PROPERTIES	
Electrical Resistivity 20°C (68°F)	48 Microhm-cm
Thermal Coefficient of Resistivity	
20-145°C (70-300°F)	0.047 Microhm-cm/°C
Thermal Conductivity	
20-600°C 70-1100°F	0.0715 Cal/cm^2•Sec•°C/cm 207.4 Btu/ft^2•Hr•°F/In
Heat Capacity	0.12 Cal/g/°C(Btu/lb/°F)
Thermal Expansion	
20-100°C	11.9•10^{-6}•cm/cm/°C
20-300°C	12.9•10^{-6}•cm/cm/°C
20-500°C	13.6•10^{-6}•cm/cm/°C
20-700°C	14.2•10^{-6}•cm/cnVC
20-900°C	14.6•10^{-6}•cm/cm/°C
20-1065°C	15.3•10^{-6}•cm/cm/°C
Density	7.65 g/cm^3 0.28 lbs/In^3
Saturation Induction	20350 Gauss 2.035 Tesla
Curie Temperature	730°C (1350°F)

TYPICAL MECHANICAL PROPERTIES

The high degree of grain orientation in GOES creates substantial differences in mechanical properties with sample orientation to the rolling direction. Typical properties are relatively insensitive to material thickness and grade.

Table 2—Typical Mechanical Properties of GOES

Property	Angle to Rolling Direction				
	0°	20°	45°	55°	90°
0.2% Offset Yield Strength ksi MPa	47.5 328	45.4 313	49.8 343	51.1 352	49.7 343
Ultimate Tensile Strength ksi MPa	52.3 361	49.0 338	54.6 376	54.4 375	58.7 405
Percent Elongation in 2"	11	13	3	4	30
Modulus of Elasticity 106 psi 103 MPa	15.5 107	17.8 123	29.5 203	29.1 201	25.3 175
Rockwell Hardness 15T	85	85	85	85	85

Table 3—TEMPERATURE DEPENDENCE of MECHANICAL YIELD STRENGTH[1]
[1]Yield Strength (0.2% Offset) is shown as ksi (MPa)Units

Temperature	Angle to Rolling Direction			
	0°		90°	
	ksi	MPa	ksi	MPa
70°F (20°C)	47.5	328	49.7	343
400°F (204°C)	36.4	251	38.1	263
600°F (317°C)	34.5	238	35.9	248
800°F (427°C)	31.5	217	33.2	229
1000°F (538°C)	18.9	130	20.8	143
1100°F (594°C)	12.1	83	13.5	93
1200°F (649°C)	7.2	50	8.7	60
1300°F (704°C)	4.1	28	4.2 2.6	30
1400°F (760°C)	2.4	17	1.7	18
1500°F (816°C)	1.4	10	1.3	12
1600°F (871°C)	1.0	7		9

STEEL COATINGS AND FINISHES

This section is included as an aid to understanding surface finishes and coatings applied by the GOES producing mill.

Producers of electrical steels found it necessary in the past to define the variety of surface conditions shipped by the mill in both oriented and non-oriented steels. To meet this demand, and to control surface requirements dictated by the customers' end uses, the AISI created the descriptions for flat rolled electrical steel insulation and core plates. Applicable surface conditions for fully processed GOES are listed in Table 4.

Table 4 - AISI ELECTRICAL STEEL INSULATIONS OR COREPLATES[1]

AISI ID	Description
C-2	This identification is for the purpose of describing an inorganic insulation which consists of a glass-like film which forms during high-temperature hydrogen annealing GOES as the result of the reaction of an applied coating of MgO and silicates on the surface of the steel. This insulation is intended for air-cooled or oil-immersed cores. It will withstand stress relief annealing temperatures and has sufficient interlamination resistance for wound cores of narrow width strip such as are used in distribution transformer cores. NOTE: Available in ATI Allegheny Ludlum GOES as S-Finish.
C-5	This is an inorganic insulation similar to C-4 but with ceramic fillers added to enhance the interlamination resistance. It is typically applied over the C-2 coating on grain-oriented electrical steel. It is principally intended for air cooled or oil-immersed cores which utilize sheared laminations and operate at high volts per turn, but find application in all apparatus requiring high levels of interlamination resistance. Like C-2, it will withstand stress-relief annealing in a neutral or slightly reducing atmosphere. NOTE: Available in ATI Allegheny Ludlum GOES as C-5, C-10 or C-10S Finishes.

[1] Core plate descriptions are from the AISI Steel Products Manual, Electrical Steels, 1983, page 16.

ATI Allegheny Ludlum Finish Terminology Compared to AISI and ASTM

Table 4 references only AISI C-2 and C-5. There are other AISI designations for surface coatings or finishes, but they are not common to fully processed GOES.

ATI Allegheny Ludlum GOES is readily available in C-5 finishes. Any other AISI finishes should be referred to the mill for technical review prior to mill order entry.

ATI Allegheny Ludlum coating terminology includes a C-10 Finish which is an equivalent to AISI C-5. This modification in designation is required by ATI Allegheny Ludlum to differentiate between two ceramic fillers required to meet unique customer applications.

For clarification, a detailed comparison of ATI Allegheny Ludlum finishes to AISI and ASTM designations is outlined in Table 5.

It should be noted that steel thickness is not a determining factor for classification of coatings. Coating chemistry, coating thickness and/or resultant Franklin surface resistance are the principle factors considered for coating description.

Table 5—ATI ALLEGHENY LUDLUM FINISH COATING CODES AND DESCRIPTIONS COMPARED TO AISI IDENTIFICATION AND ASTM CONDITION

AISI	ASTM Condition	ATI Allegheny Ludlum Finishes		General Processing Description
		Code	Identification	
C-2	NF	S	Base Glass (Scrubbed)	Anneal and Scrub Clean
C-5 over C-2	F2	D	C-10 on Base Glass	Anneal and Coat
C-5 over C-2	F5	T	C-10S on Base Glass	Anneal and Coat
C-5 over C-2	F2	Q	C-10 on Base Glass	Anneal and Coat

.

Table 6—TYPICAL ATI ALLEGHENY LUDLUM COATING THICKNESSES, INSULATION AND END USES

ATI Allegheny Ludlum Code	Thickness/Side Inch (mm)	Insulation/Side Average Franklin Values	Typical End Uses
S	.00007 (0.0018)	0.75 - 0.95 amp @ 300 psi (2.1 MPa)	Current Transformer, Distribution Transformer
D	.00009 (0.0023)	0.40 -0.85 amp @ 300 psi (2.1 MPa)	Distribution Transformer
T	.00014 (0.0035)	0.00 - 0.30 amp @ 300 psi (2.1 MPa)	Power Transformer, Pad
Q	.00010 (0.0025)	0.40 - 0.85 amp @ 300 psi (2.1 MPa)	Distribution Transformer Sheared Lamination

NOTE: The values of Table 6 are typical and should not be interpreted as guarantees.

LAMINATION or STACKING FACTOR

Lamination factor is sometimes referred to as stacking factor. It may also be called space factor.

By definition, *lamination factor* is the ratio of calculated volume to measured volume at a given lamination stack pressure expressed as a percentage. Calculations assume solid volumes at measured or theoretical material densities.

Typical *lamination factor* values at 50 psi for GOES, in a variety of thickness and finish combinations, are shown in Table 7.

Table 7—TYPICAL STACKING FACTOR VALUES OF GOES

Nominal Thickness Inches (mm)	Finish	Product	ASTM Cond.	Lamination Factor @ 50psi
0.007 (0.18)	S-Finish D-Finish	GOES GOES	NF F2	95.5% 95.0%
0.009 (0.23)	S-Finish D-Finish T-Finish	GOES GOES GOES	NF F2 F5	96.0% 95.6% 95.2%
0.011 (0.27)	S-Finish D-Finish T-Finish	GOES GOES GOES	NF F2 F5	96.8% 96.5% 96.2%
0.014 (0.35)	S-Finish Q-Finish T-Finish	GOES GOES GOES	NF F2 F5	98.0% 97.4% 96.6%

STRESS-RELIEF ANNEALING

Requirements

Stress-relief annealing is designed to:

1. Reduce mechanical stress in the steel to a minimum to yield optimum magnetic properties.
2. Prevent contamination of the steel with oxygen and/or carbon.
3. Retain or enhance the insulation quality of the steel coating.

These qualities are generally achieved by annealing at temperatures in the 1400 to 1550°F (760 to 845°C) range, preferably in the 1450 to 1500°F range, with a protective atmosphere. The protective atmosphere most widely used is pure, dry nitrogen which will protect the steel from oxidation. To insure the annealing atmosphere is non-oxidizing, hydrogen up to 20% is sometimes added to the dry nitrogen.

An exothermic gas is an alternate atmosphere that is generated by partially combusting natural gas (usually 7.5 to 1 air-gas ratio) or similar hydrocarbons. The atmosphere produced in an exothermic generator from natural gas will contain relatively equal amounts of carbon monoxide, carbon dioxide (6-8%), nitrogen (about 75%) and hydrogen (about 10%) at a dew point of +40/+45°F after refrigeration. Auxiliary equipment can be used to modify the exothermic atmosphere by removing carbon monoxide, carbon dioxide and water vapor. Because the high quality of GOES depends in part upon the steel having very low carbon and oxygen levels (each about 0.0030% or less) the generation of exothermic atmospheres must be carefully controlled so as to produce the recommended percentage of constituents.

ATI Allegheny Ludlum supplies its GOES with a mill-anneal finish (forsterite) or with a phosphate-based insulative coating. The forsterite finish is very heat resistant and chemically stable, and can be stress relief annealed in atmospheres of hydrogen, nitrogen or mixtures of both without impairing the magnetic or insulative qualities of the steel. Steels with insulative coating will provide improved insulative qualities if annealed in a neutral or slightly oxidizing atmosphere, thus making "pure" nitrogen an ideal atmosphere.

During the course of stress-relief annealing, heating and cooling rates are very critical with regard to inducing thermal stresses within the steel cores. Transformer core assemblies that have large cross sections are more vulnerable to internal stresses due to rapid heating and cooling rates where the full magnetic quality may be impaired. Cooling rates below 700°F (370°C) are not critical, and at these lower temperatures, the protective atmosphere is no longer necessary.

Furnace Types and Operating Principles

There are two general categories of furnaces: the batch furnace and the continuous furnace. The batch furnace is advantageous when core sizes vary considerably and when production is intermittent or the quantity of cores being annealed is small. The continuous furnace is advantageous for high production rates of reasonably uniform-sized cores.

The continuous furnace has other technical advantages. The temperature conditions are held reasonably constant in the respective zones of the furnace. Each core of nearly the same size moving through the furnace is exposed to virtually the same thermal cycle and the same flow of atmosphere over its surfaces making use of the counter-flow principal. While some continuous furnaces are capable of high productivity, excess exposure of steel cores to rapid heating and cooling rates can lead to large thermal gradients and physical distortion of the cores. Continuous furnaces require entry and exit vestibules in order to maintain the integrity of the atmosphere in the furnace. Maintenance of the seals in these vestibules is critical if the back diffusion of oxygen and water vapor into the furnace is to be minimized. To further assure the integrity of the atmosphere in a continuous annealing furnace, turnover rates of at least ten volumes per hour are recommended. The atmosphere flow rates are generally high for continuous furnaces when compared to flow rates for batch furnaces of equal volume.

The batch furnaces allow for greater flexibility in production planning although with large loads it is not possible to provide each and every core with the same thermal cycle and atmosphere exposure even with recirculating fans. Such furnaces generally have inner covers with sand seals that provide for a tightly sealed system and relatively small atmosphere volume. This combination of small volume and tight seals means that lower flow rates can be used and still provide adequate atmosphere protection. Initial atmosphere flow rates should be at approximately 10 volumes per hour turnover in order to purge the furnace of oxygen and water vapor. Subsequently 5 volumes per hour of atmosphere flow rate is sufficient for the balance of the cycle.

When compared to continuous furnaces, batch furnaces are unlikely to induce high heating and cooling rates. Nonetheless, caution should be exercised to avoid heating or cooling that cause thermal distortion. During the initial stages of the cooling cycle, the furnace should not be removed. It should remain in place with power off until the cooling rate has slowed perceptibly (generally, below 1000°F [540°C]). Following removal of the furnace, the inner cover should remain in place with the protective atmosphere flowing until the temperature has decreased to less than 700°F (370°C).

Load Preparation

To optimize the thermal cycle and atmosphere exposure to the wound cores, it is important to plan the preparation of the loads for batch and continuous furnaces. It is a basic principle that heat transmission through cores is greatest along the plane of the strip. Transmission of heat perpendicular to the plane of the strip is much slower because of the insulating effect of the forsterite and/or phosphate coating in conjunction with a gas layer between the convolutions of the wound core through which the heat must travel. Therefore, the cores should be configured so that strip edges are exposed directly to the source of radiated heat. It is important to minimize the "shadowing" of cores from the direct heat by other cores. Some shadowing is unavoidable in many loads, particularly in batch furnaces, so recirculation fans are particularly important in these furnaces to improve the uniformity of heat delivery to all cores in the load.

Anneal Cycle Duration

The duration of any cycle is determined by the coldest spot in the load. This cold spot must reach a minimum temperature of 1400°F (760°C) or preferably 1450°F (788°C) for at least one hour before starting the cooling cycle. Since core designs vary and the relative extent of plastic and elastic damage done to the steel during core forming varies, some experimentation may be required to establish the maximum temperature to thoroughly recover the potential magnetic quality. In no case, however, are temperatures below 1400°F (760°C) recommended, nor are temperatures in excess of 1550°F (845°C). In the special case of annealing individual laminations on a conveyor-belt furnace, the annealing cycle may involve only a few minutes, in which case, the annealing atmosphere may be air.

Steel Distortion

There are some guiding principles for avoiding distortion of the steel during stress-relief annealing that can be of assistance when optimizing anneal conditions. The lamination geometry required in the assembled transformer should be the same configuration as the annealed core. For example, if the steel is to be used in a stacked-core-design transformer, each lamination should approach perfect flatness in order to avoid the introduction of stresses that arise as non-flat laminations are piled one upon the other. This requires that during the stress-relief anneal, the laminations be rigidly supported on a very flat-base plate. It is further recommended that the load not be rapidly heated causing large thermal gradients which may induce plastic deformation to the exposed edges. A wavy edge is one symptom of such a condition. Edge waves can lead to poor stacking of the transformer core which when clamped will result in damaging compressive stresses.

In the case of wound cores, the fixturing should be rigid and provide the exact geometry required in the final application. To assure the maintenance of the proper geometry, the cores should rest upon very flat support bases. Extreme heating and cooling rates should be avoided. As in the case of flat laminations, very fast heating of the wound core lamination edges may cause excessive physical expansion differentials that will deform the steel. Equally important, excessive cooling rates in wound cores can result in "hoop" stresses that can stretch and distort the steel.

MAGNETOSTRICTION

Definition and Causes

Magnetizing a core material usually changes its dimensions by a few parts per million. This dimensional change is called magnetostriction. Longitudinal magnetostriction is the dimensional change in the direction of magnetization and may be positive or negative. It is generally considered the most significant dimensional change of the core material. Its magnitude depends on the core material and the angle between the direction of magnetization and the rolling direction.

Under the cyclic excitation, magnetostriction causes core vibration which creates noise. During cyclic excitation, this vibration has a fundamental frequency twice the excitation frequency. Since the magnetostriction does not vary linearly with induction level, higher frequency harmonics are also generated.

Although there are other sources of noise in transformers, magnetostriction makes a significant contribution. The noise amplitude increases with core size as well as induction level and is a function of core design. Configuration, clamping, and other constructional features of the complete transformer can also have a large effect on noise levels.

Noise Reduction

Grain orientation combines low magnetostriction and many other highly desirable magnetic characteristics when the flux is parallel to the rolling direction. In this direction, magnetostriction and core losses are lowest (magnetostriction is near zero) and permeability is highest. Magnetostriction at 90° to the rolling direction (cross-grain flux) is significantly higher.

Lower noise levels in power transformers at high inductions are extremely difficult to achieve even with a core material of low magnetostriction due largely to stress sensitivity. Compressive stresses are far more damaging than tensile stresses. Bending of laminations can result in significant increases in magnetostriction. The application of tensile stress-reducing coatings such as C-10S (T-Finish) builds a tensile-stress "cushion" affording some protection against damage by compressive stresses. This results in a simpler magnetic domain pattern at the sheet surface which may reduce the magnetostriction 50% at normal operating inductions.

Extremely low values of magnetostriction are not easily retained in transformer cores since it is impractical to fabricate a large core without adding stresses to the material. Meticulous core fabrication and producing very flat laminations which are less subject to strain during assembly will result in magnetostriction values which are the lowest.

MAGNETIC GRADING

Components of Core Loss

Two components comprise the majority of core loss in grain-oriented electrical steels:

1. Hysteresis loss which varies with frequency and is a function of the induction.
2. Eddy current loss which increases with the square of induction, frequency, and linearly with steel thickness.

The eddy current contribution to core loss does, to some degree, vary with service temperature, as does the excitation characteristic. This should be considered when designing equipment to critical specifications. The traditional division or separation of losses in electrical steels generally consists of measuring the hysteresis loss (D.C. Loop loss multiplied by the frequency of excitation), and assuming the remainder of the total loss to be eddy current losses. The hysteresis loss data contained herein were obtained using a computer-controlled, solid-state D-C hysteresigraph conforming to the D-C loop test specifications of ASTM Method A 773 for D-C Magnetic Properties with Electronic Hysteresigraphs. The unit features an automatic demagnetizing routine and self-centering of the loop.

Table 8 shows the typical eddy current contribution as a percent of total loss at 60 hertz.

Table 8—EDDY CURRENT CONTRIBUTION AS A PERCENT OF TOTAL LOSS @ 60 HERTZ

	13 kG	15 kG	17 kG
0.007" (0.18 mm) Method 1	45%	53%	51%
0.009" (0.23 mm) Method 1	59%	57%	54%
0.011" (0.27 mm) Method 1	71%	71%	67%
0.014" (0.35 mm) Method 1	78%	76%	76%

Temperature Dependence of Core Loss

The eddy current portion of the total power losses is an important factor when considering the effect of temperature rise on the core loss of equipment at service temperatures. Eddy current losses are inversely proportional to the resistivity of the material, which increases with temperature.

The core loss values in Table 9 were obtained on typical samples of GOES measured at the temperature using the ASTM Epstein method (ASTM A 343).

Table 9—TEMPERATURE CONTRIBUTION TO TOTAL CORE LOSS OF GOES

Ratio of Core Loss at 185°F (85°C) to Core Loss at 77°F (25°C)

Thickness Inches (mm)	(W @ 85°C/W @ 25°C) at Induction (Kilogausses) of:			
	10 kG	13 kG	15 kG	17 kG
0.007" (0.18)	.957	.960	.963	.978
0.009" (0.23)	.955	.958	.963	.977
0.011" (0.27)	.953	.956	.962	.977
0.014" (0.35)	.953	.957	.964	.978

Magnetic Grading Methods

GOES is graded by two criteria:

1. Thickness
2. Maximum core loss at a given induction

Core losses are determined by magnetic testing in conformance to applicable ASTM specifications generally those set forth in the sections of Specification A-34. Grading of GOES products is generally done in conformance to applicable portions of the AISI Electrical Steel Products Manual, or in accordance with applicable ASTM Specifications A-665 or A-725. These core loss specifications are based on parallel grain Epstein test specimens which are stress relief annealed, unless otherwise specified. The maximum specific core loss will be guaranteed at either 15 or 17 kilogausses (1.5 or 1.7 Tesla). Values at other induction levels may be reported for informational purposes upon request.

The GOES products maximum core losses are guaranteed on the basis of maximum core loss at one specified induction. Data representative of typical products are given in the Design Data section of this brochure. GOES products are processed to provide the lowest core loss using strict chemistry and process controls. Proper fabrication techniques are required to retain the optimum magnetic performance in the finished product.

Tables 10 and 11 show the gauge and dimensional tolerances, respectively, of ATI Allegheny Ludlum GOES.

Table 10 – Gauge Tolerance of GOES

Nominal Thickness		Range by Contact Caliper	
Inches	Millimeters	Inches	Millimeters
.007	.18	.0060 to .0080	.15 to .20
.009	.23	.0075 to .0100	.19 to .25
.011	.27	.0095 to .0120	.24 to .30
.014	.35	.0125 to .0150	.32 to .38

Table 11 —DIMENSIONAL TOLERANCE OF GOES

	Width		Tolerances (+/-)	
	Inches	Millimeters	Inches	Millimeters
To	4 incl.	102 incl.	.005	0.127
Over	4 to 9 incl.	102 to 229 incl.	.007	0.178
Over	9 to 15 incl.	229 to 381 incl.	.010	0.254
Over	15	381	.016	0.406

Guaranteed Magnetic Properties

The guaranteed core loss properties for GOES steels are shown in Table 12. Magnetic grading is based on the core loss within the given steel thickness.

Table 12—GUARANTEED CORE LOSSES (ENGLISH AND METRIC SYSTEMS)

Core Loss @ 60 Hz (English)

Grade	Nominal Thickness Inch	15kG-Induction Watt/lb (Watt/Kg)		17kG-Induction Watt/lb (Watt/Kg)	
M-2	0.007	0.400	(0.90)	-	-
M-3	0.009	0.445	(1.01)	0.710	(1.57)
M-4	0.011	0.510	(1.17)	0.740	(1.63)
M-5	0.012	0.580	(1.28)	0.830	(1.83)
M-6	0.014	0.660	(1.46)	0.930	(2.05)

Core Loss @ 50 Hz (Metric)

Grade	Nominal Thickness mm	1.5 Tesla Induct Watt/Kg	1.7 Tesla Induct Watt/Kg
M-2	0.18	0.668	-
M-3	0.23	0.743	1.18
M-4	0.27	0.850	1.24
M-5	0.30	0.970	1.39
M-6	0.35	1.100	1.55

Comparative Magnetic Data By Thickness

Tables 13 through 15 compare typical magnetic data of the GOES products by strip thickness.

Table 13—EXPECTED MEAN CORE LOSS, BY THICKNESS (TYPICAL)

Core Loss in Watts per Pound (WPP) at 60 Hz

Induction Kilogauss	7-Mil M-2 WPP	9-Mil M-3 WPP	11-Mil M-4 WPP	14-Mil M-6 WPP
10	.161	.170	.203	.262
11	.195	.206	.246	.315
12	.231	.243	.293	.373
13	.272	.286	.345	.438
14	.321	.337	.405	.513
15	.382	.395	.475	.600
16	.470	.473	.561	.708
17	.601	.600	.686	.856
18	.820	.810	.830	1.080

Core Loss in Watts per Kilogram (WPKg) at 50 Hz

Induction Tesla	0.18mm M-2 WPKg	0.23mm M-3 WPKg	0.27mm M-4 WPKg	0.35mm M-6 WPKg
1.0	.268	.283	.338	.437
1.1	.325	.343	.410	.525
1.0	.385	.405	.488	.622
1.3	.453	.477	.575	.730
1.4	.535	.562	.675	.855
1.5	.638	.658	.792	1.000
1.6	.785	.790	.935	1.180
1.7	1.004	1.002	1.144	1.427
1.8	1.369	1.353	1.386	1.800

Table 14—EXPECTED MEAN APPARENT LOSS BY THICKNESS FOR GOES				
Apparent Loss in Volt-Amps per pound				
Induction Kilogauss	7-Mil VA/lb	9-Mil VA/lb	11-Mil VA/lb	14-Mil VA/lb
2	0.021	0.011	0.012	0.014
3	0.035	0.034	0.032	0.039
4	0.050	0.049	0.049	0.059
5	0.070	0.065	0.069	0.083
6	0.095	0.087	0.095	0.114
7	0.126	0.115	0.126	0.152
8	0.160	0.148	0.162	0.198
9	0.194	0.184	0.201	0.249
10	0.229	0.221	0.242	0.302
11	0.266	0.259	0.286	0.361
12	0.309	0.299	0.335	0.431
13	0.368	0.350	0.394	0.513
14	0.456	0.423	0.473	0.611
15	0.594	0.538	0.585	0.750
16	0.809	0.722	0.751	0.985

Table 15— EXPECTED MEAN PEAK PERMEABILITY BY THICKNESS FOR GOES				
Peak Permeability				
Induction Kilogauss	7-Mil	9-Mil	11-Mil	14-Mil
2	21010	26248	25816	23029
3	24850	29770	28860	24637
4	29120	32233	31128	26123
5	32530	34212	32887	27426
6	34710	36068	34379	28551
4	36000	37971	35799	29539
8	37050	39924	37269	30435
9	38330	41789	38816	31262
10	39970	43316	40356	31986
11	41300	44164	41661	32487
12	42090	43930	42345	32532
13	39810	42173	41839	31738
14	33990	38441	39366	29549
15	26120	32295	33921	25199
16	18620	23335	24249	17688

Typical Magnetic Test Results

Tables 16 through 19 show typical magnetic test results from ATI Allegheny Ludlum's computerized test equipment. Each table represents a different strip thickness.

Table 16—TYPICAL EPSTEIN TEST RESULTS FOR MAGNETIC PROPERTIES OF 0.007” ASTM TEST METHOD A-343 (EPSTEIN METHOD)

7-Mil or 0.007" (0.18mm) M-2 GOES	
Peak Permeability @ 10 Oersted	1845
Peak Permeability @ 200 Gausses	12495
Watt/lb Core Loss - 60 Hz:	
@ 1.0 Tesla	.161
@ 1.3 Tesla	.270
@ 1.5 Tesla	.382
@1.7 Tesla	.601
Volt - Amp/lb Exciting Power - 60 Hz:	
@1.0 Tesla	.225
@1.3 Tesla	.370
@1.5 Tesla	.572
@1.7 Tesla	1.488

Table 18—TYPICAL EPSTEIN TEST RESULTS FOR MAGNETIC PROPERTIES OF 0.011” ASTM TEST METHOD A-343 (EPSTEIN METHOD)

11 -Mil or 0.011" (0.27 mm) M-4 GOES	
Peak Permeability @ 10 Oersted	1850
Peak Permeability @ 200 Gausses	12050
Watt/lb Core Loss - 60 Hz:	
@1.0 Tesla	.204
@ 1.3 Tesla	.349
@ 1.5 Tesla	.476
@1.7 Tesla	.686
Volt - Amp/lb Exciting Power - 60 Hz:	
@1.0 Tesla	.243
@ 1.3 Tesla	.409
@1.5 Tesla	.608
@ 1.7 Tesla	1.430

Table 17—TYPICAL EPSTEIN TEST RESULTS FOR MAGNETIC PROPERTIES OF 0.009” ASTM TEST METHOD A-343 (EPSTEIN METHOD)

9-Mil or 0.009" (0.23mm) M-3 GOES	
Peak Permeability @ 10 Oersted	1850
Peak Permeability @ 200 Gausses	13860
Watt/lb Core Loss - 60 Hz:	
@ 1.0 Tesla	.166
@ 1.3 Tesla	.284
@ 1.5 Tesla	.395
@1.7 Tesla	.604
Volt - Amp/lb Exciting Power - 60 Hz:	
@1.0 Tesla	.221
@1.3 Tesla	.371
@1.5 Tesla	.550
@1.7 Tesla	1.308

Table 19—TYPICAL EPSTEIN TEST RESULTS FOR MAGNETIC PROPERTIES OF 0.014” ASTM TEST METHOD A-343 (EPSTEIN METHOD)

14-Mil or 0.014" (0.35mm) M-6 GOES	
Peak Permeability @ 10 Oersted	1840
Peak Permeability @ 200 Gausses	13860
Watt/lb Core Loss - 60 Hz:	
@1.0 Tesla	.265
@ 1.3 Tesla	.440
@ 1.5 Tesla	.600
@1.7 Tesla	.856
Volt - Amp/lb Exciting Power - 60 Hz:	
@1.0 Tesla	.306
@1.3 Tesla	.517
@1.5 Tesla	.769
@ 1.7 Tesla	1.775

Table 20—ASTM SPECIFICATIONS: GRAIN-ORIENTED ELECTRICAL STEEL
Partial Listing of ASTM Specifications for GOES Manufactured by ATI Allegheny Ludlum

Specification No.	Description
MATERIALS:	
A 876	Standard Specification for Flat-Rolled, Grain-Oriented, Silicon-Iron, Electrical Steel, Fully Processed Types
TEST METHODS:	
A 34	Testing and Sampling Procedures
A 343	Magnetic Testing Procedure with Epstein Packs (Peak I)
A 712	Electrical Resistivity
A 717	Surface Insulation Resistivity; Single Strip (Franklin)
A 719	Lamination Factor (Stacking Factor)
A 720	Ductility (Flex Bend); Commonly applied to Non-Oriented
A 721	Ductility (Brake Bend)
A 804	Magnetic Testing Procedure with Single Sheet

CONVERSION TABLES

CORE LOSS

$$\mathit{RMS\ Ampere\,Turns\ per\ Centimeter} = \frac{49.62^{*} \times \mathit{Specific\ Gravity} \times \mathit{RMS\ Volt\ Amperes\ per\ Pound}}{\mathit{Induction,\ Kilo\,gausses} \times \mathit{Frequency,\ Hertz}}$$

$$\mathit{RMS\ Volt\ Amperes\ per\ Pound} = \frac{\mathit{RMS\ Ampere\,Turns\ per\ Centimeter} \times \mathit{Induction,\ Kilo\,gausses} \times \mathit{Frequency,\ Hertz}}{49.62^{*} \times \mathit{Specific\ Gravity}}$$

$$\mathit{RMS\ Ampere\,Turns\ per\ Inch} = \frac{126.04^{*} \times \mathit{Specific\ Gravity} \times \mathit{RMS\ Volt\ Amperes\ per\ Pound}}{\mathit{Induction,\ Kilo\,gausses} \times \mathit{Frequency,\ Hertz}}$$

$$\mathit{RMS\ Volt\ Amperes\ per\ Pound} = \frac{\mathit{RMS\ Ampere\,Turns\ per\ Inch} \times \mathit{Induction,\ Kilo\,gausses} \times \mathit{Frequency,\ Hertz}}{126.04^{*} \times \mathit{Specific\ Gravity}}$$

*The numerical coefficients in the above contain the factors necessary to balance the formulas for length, weight, and volt

TO CONVERT	TO	MULTIPLY BY
	80 Hertz—10 KILOGAUSSES—SPECIFIC GRAVITY 7.55	.6244
RMS VA/lb	RMS AT/cm	1.586
RMS VA/lb	RMS AT/inch	1.602
RMS AT/cm	RMS VA/lb	.6305
	60 Hertz—15 KILOGAUSSES—SPECIFIC GRAVITY 7.55	
RMS VA/lb	RMS AT/cm	.4163
RMS VA/lb	RMS AT/inch	1.057
RMS AT/cm	RMS VA/lb	2.402
RMS AT/inch	RMS VA/lb	.9458
	60 Hertz—10 KILOGAUSSES—SPECIFIC GRAVITY 7.65	
RMS VA/lb	RMS AT/cm	.6327
RMS VA/lb	RMS AT/inch	1.607
RMS AT/cm	RMS VA/lb	1.581
RMS AT/inch	RMS VA/lb	.6223
	60 Hertz—15 KILOGAUSSES—SPECIFIC GRAVITY 7.65	
RMS VA/lb	RMS AT/cm	.4218
RMS VA/lb	RMS AT/inch	1.071
RMS AT/cm	RMS VA/lb	2.371
RMS AT/inch	RMS VA/lb	.9334
	60 Hertz—10 KILOGAUSSES—SPECIFIC GRAVITY 7.75	
RMS VA/lb	RMS AT/cm	.6409
RMS VA/lb	RMS AT/inch	1.628
RMS AT/cm	RMS VA/lb	1.560
RMS AT/inch	RMS VA/lb	.6142
	60 Hertz—15 KILOGAUSSES—SPECIFIC GRAVITY 7.75	
RMS VA/lb	RMS AT/cm	.4273
RMS VA/lb	RMS AT/inch	1.085
RMS AT/cm	RMS VA/lb	2.340
RMS AT/inch	RMS VA/lb	.9214

CONVERSION TABLES

TO CONVERT	TO	MULTIPLY BY
Gausses	Lines per square inch	6.4516
Gausses	Webers per square meter (Tesla)	10^{-4}
Gausses	Webers per square inch	$6.4516x10^{-8}$
Lines per square inch	Gausses	0.15500
Lines per square inch	Webers per square meter	$1.5500x10^{-5}$
Lines per square inch	Webers per square inch	10^{-8}
(Tesla) Webers per square meter	Gausses	10^{4}
(Tesla) Webers per square meter	Lines per square inch	$6.4516x10^{4}$
(Tesla) Webers per square meter	Webers per square inch	$6.4516X10^{-4}$
Webers per square inch	Gausses	$1.5500x10^{7}$
Webers per square inch	Lines per square inch	10^{8}
Webers per square inch	Webers per square meter (Tesla)	1550.0

MAGNETIZING FORCE

Oersteds	Ampere turns per inch	2.0213
Oersteds	Ampere turns per centimeter	.79577
Oersteds	Ampere turns per meter	79.577
Ampere turns per inch	Oersteds	.49474
Ampere turns per inch	Ampere turns per centimeter	.39370
Ampere turns per inch	Ampere turns per meter	39.370
Ampere turns per centimeter	Oersteds	1.2566
Ampere turns per centimeter	Ampere turns per inch	2.5400
Ampere turns per centimeter	Ampere turns per meter	100
Ampere turns per meter	Oersteds	.012566
Ampere turns per meter	Ampere turns per inch	.025400
Ampere turns per meter	Ampere turns per centimeter	10^{-2}

PERMEABILITY

Gauses per oersted	Lines per ampere-turn inch	3.1918
Gausses per oersted	Webers (Tesla) per ampere-turn meter	$1.2566x10^{-6}$
Gausses per oersted	Webers (Tesla) per ampere-turn inch	$3.1918X10^{-8}$
Lines per ampere-turn inch	Gausses per oersted	.31330
Lines per ampere-turn inch	Webers per ampere-turn inch	10^{-8}
Lines per ampere-turn inch	Webers per ampere-turn meter	$39.370x10^{-8}$
Webers (Tesla) per ampere-turn meter	Gausses per oersted	$7.9577x10^{5}$
Webers (Tesla) per ampere-turn meter	Lines per ampere-turn inch	$2.500x10^{6}$
Webers (Tesla) per ampere-turn meter	Webers per ampere-turn inch	.025400
Webers per ampere-turn inch	Gausses per oersted	$3.133x10^{7}$
Webers per ampere-turn inch	Lines per ampere-turn inch	10^{8}
Webers per ampere-turn inch	Webers (Tesla) per ampere-turn meter	39.370

CONVERSION TABLE

CORE LOSS

WATTS @ 60 HERTZ	TO	MULTIPLY BY
Watts per pound	Watts per kilogram	2.2046
Watts per kilogram	Watts per pound	.45359
Watts per pound	Watts per cubic inch (Specific Gravity 7.65)	.27638
Watts per cubic inch	Watts per pound (Specific Gravity 7.65)	3.6169

WATTS @ 50 HERTZ	TO	MULTIPLY BY
Watts per pound	Watts per kilogram	1.67
Watts per kilogram	Watts per pound	.60

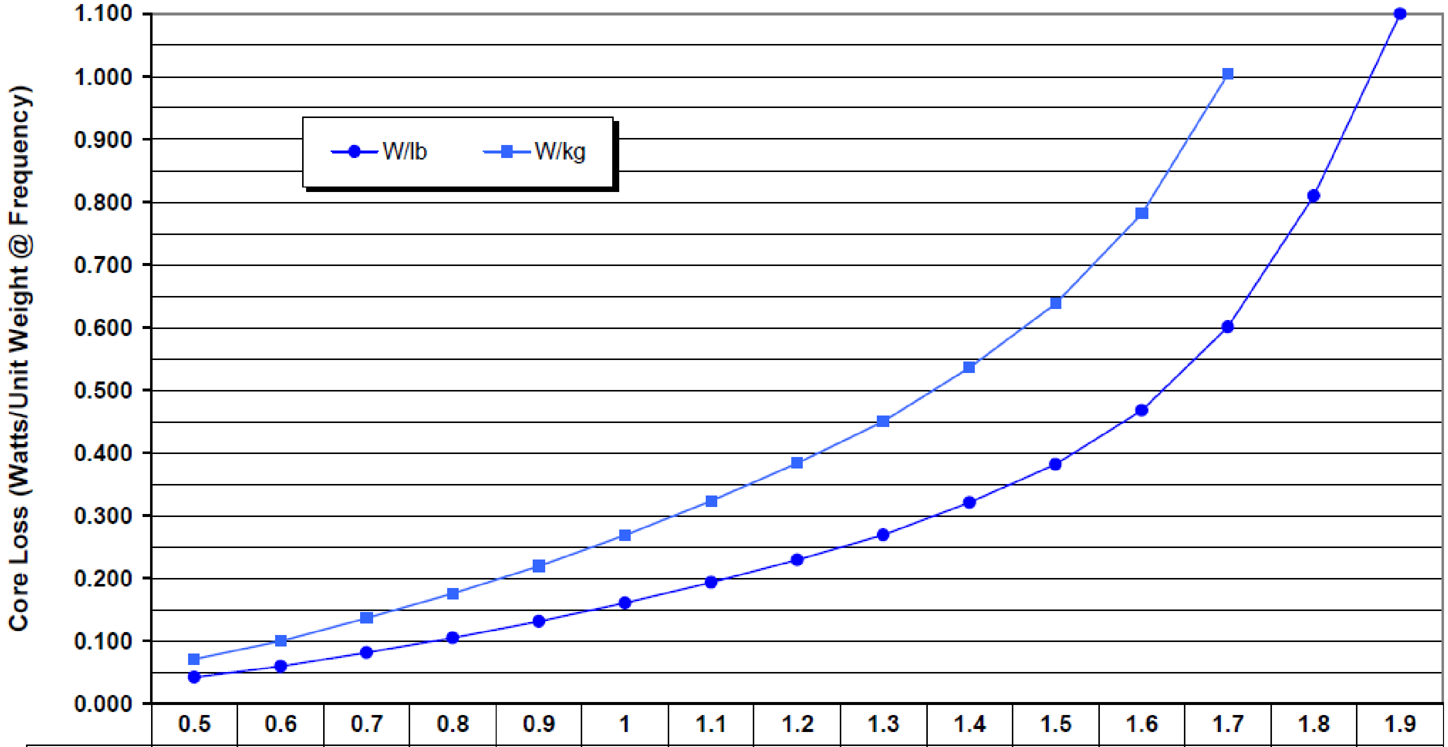
Glossary of Electrical and Magnetic Terms

Symbol	Term
B	Magnetic induction Normal induction Magnetic flux density
B_m	Maximum induction in a hysteresis loop
B_r	Residual induction
B_Δ	Incremental induction
H	Magnetizing force Magnetic field strength
H_Δ	Incremental magnetizing force
H_m	Maximum magnetizing force in a hysteresis loop
L	Self inductance
L_m	Mutual inductance
ρ	Electrical resistivity
P_c	Total core loss
$P_{c\Delta}$	Incremental core loss
μ	Permeability Normal permeability (D-C)
μ_Δ	Incremental permeability
$\mu_{\Delta p}$	Incremental peak permeability
μ_p	Peak permeability
μ_z	Impedance permeability
μ_L	Inductance permeability

Transformer Design Data

Nominal 0.007 in. / 0.18 mm M-2 GOES

Typical Core Loss (W/lb. at 60 Hertz) and (W/kg at 50 Hertz)



	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9
W/lb	0.043	0.060	0.082	0.106	0.132	0.161	0.194	0.230	0.270	0.321	0.382	0.468	0.601	0.810	1.100
W/kg	0.072	0.100	0.137	0.176	0.220	0.269	0.324	0.384	0.450	0.536	0.638	0.782	1.004		

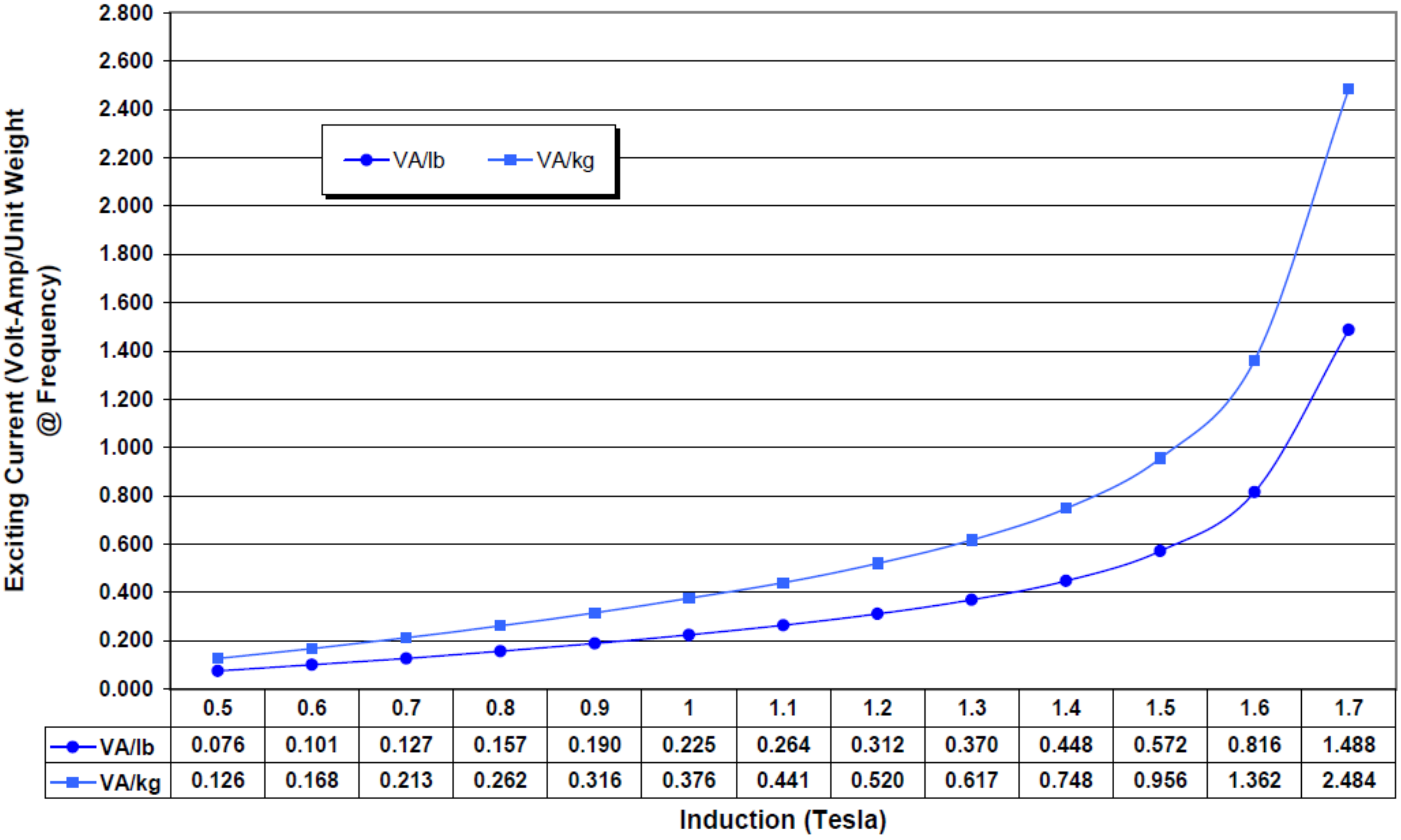
Induction (Tesla)

Allegheny Ludlum

Transformer Design Data

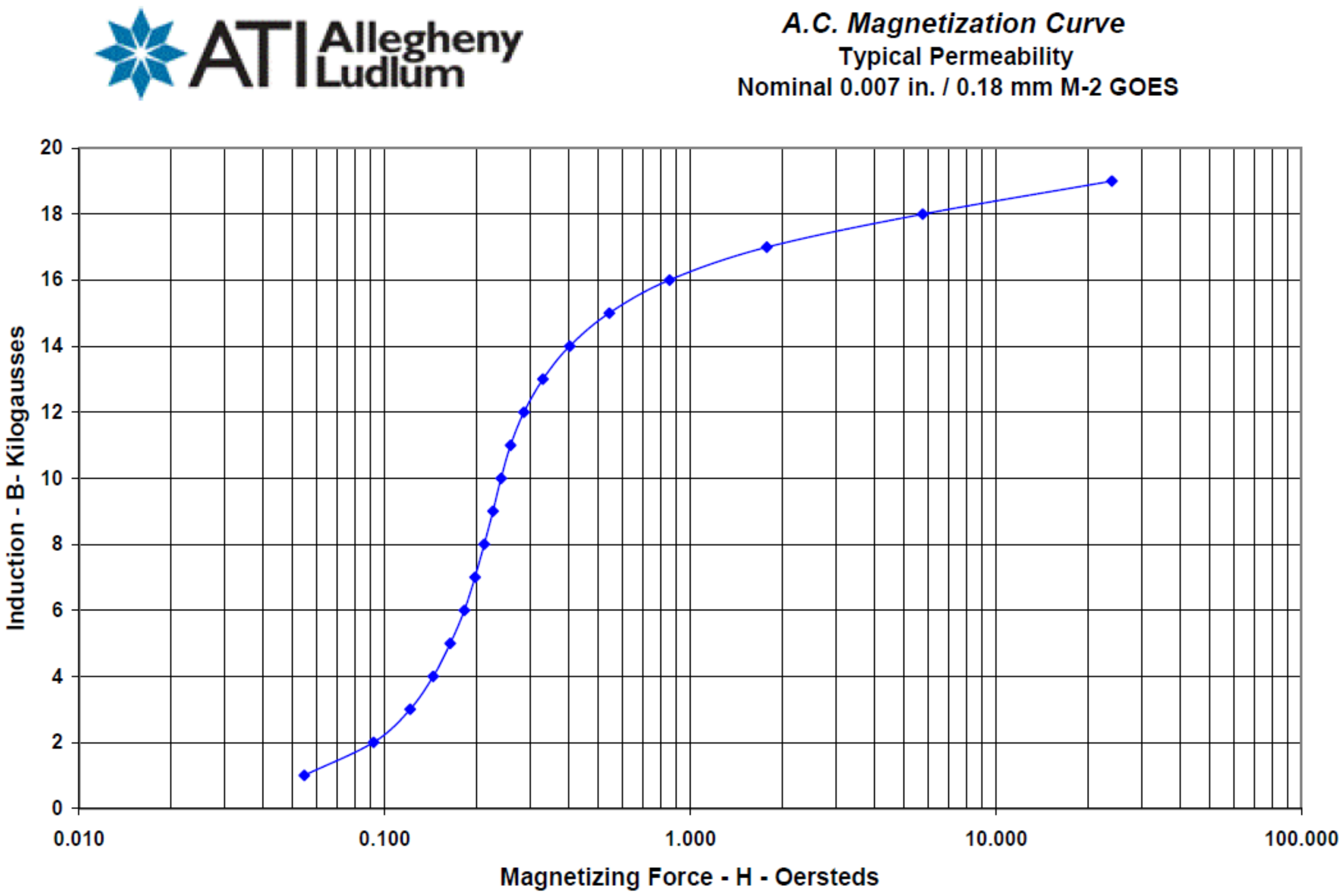
Nominal 0.007 in. / 0.18 mm M-2 GOES

Typical Apparent Loss (VA/lb. at 60 Hertz) and (VA/kg at 50 Hertz)



	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5	1.6	1.7
● VA/lb	0.076	0.101	0.127	0.157	0.190	0.225	0.264	0.312	0.370	0.448	0.572	0.816	1.488
■ VA/kg	0.126	0.168	0.213	0.262	0.316	0.376	0.441	0.520	0.617	0.748	0.956	1.362	2.484

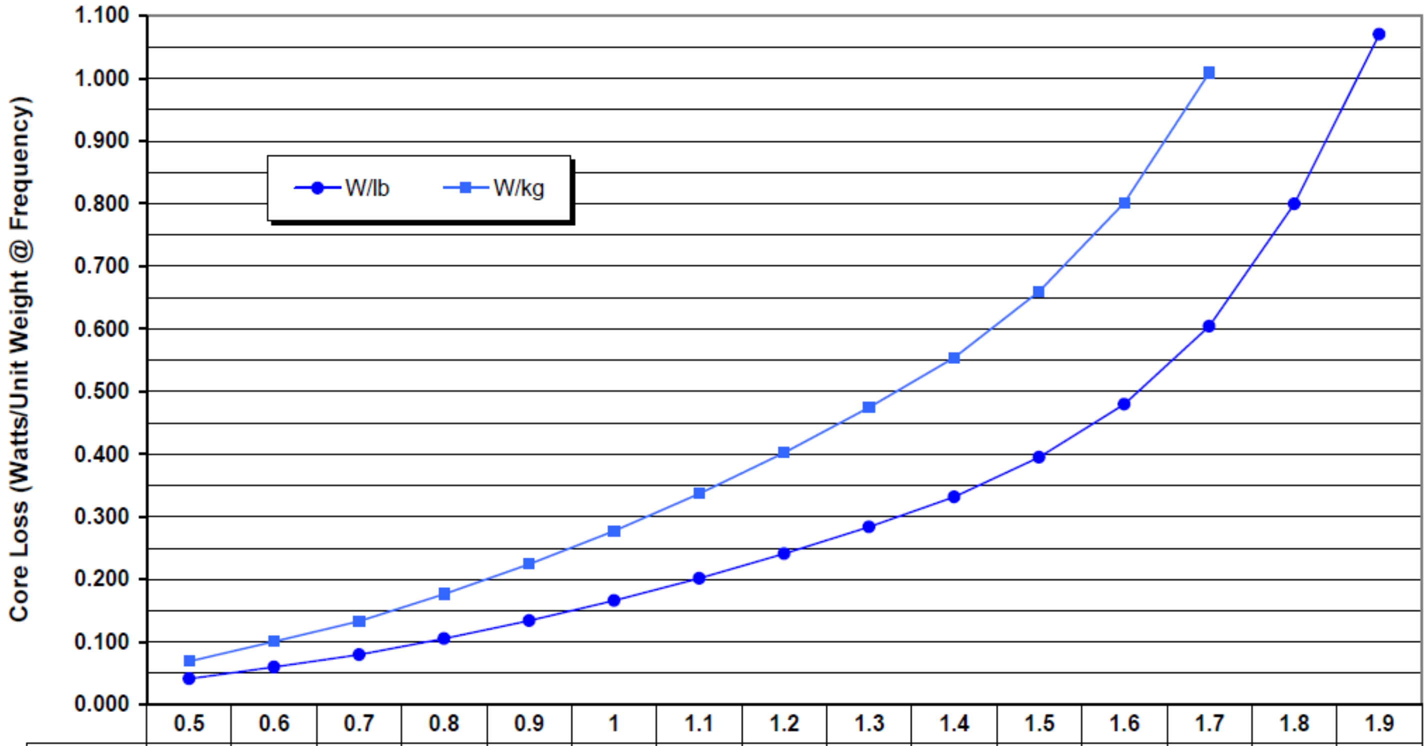
Induction (Tesla)


ATI Allegheny Ludlum
A.C. Magnetization Curve
Typical Permeability
Nominal 0.007 in. / 0.18 mm M-2 GOES
Induction - B- Kilogausses
0
2
4
6
8
10
12
14
16
18
20
0.010
0.100
1.000
10.000
100.000
Magnetizing Force - H - Oersteds

Transformer Design Data

Nominal 0.009 in. / 0.23 mm M-3 GOES

Typical Core Loss (W/lb. at 60 Hertz) and (W/kg at 50Hertz)



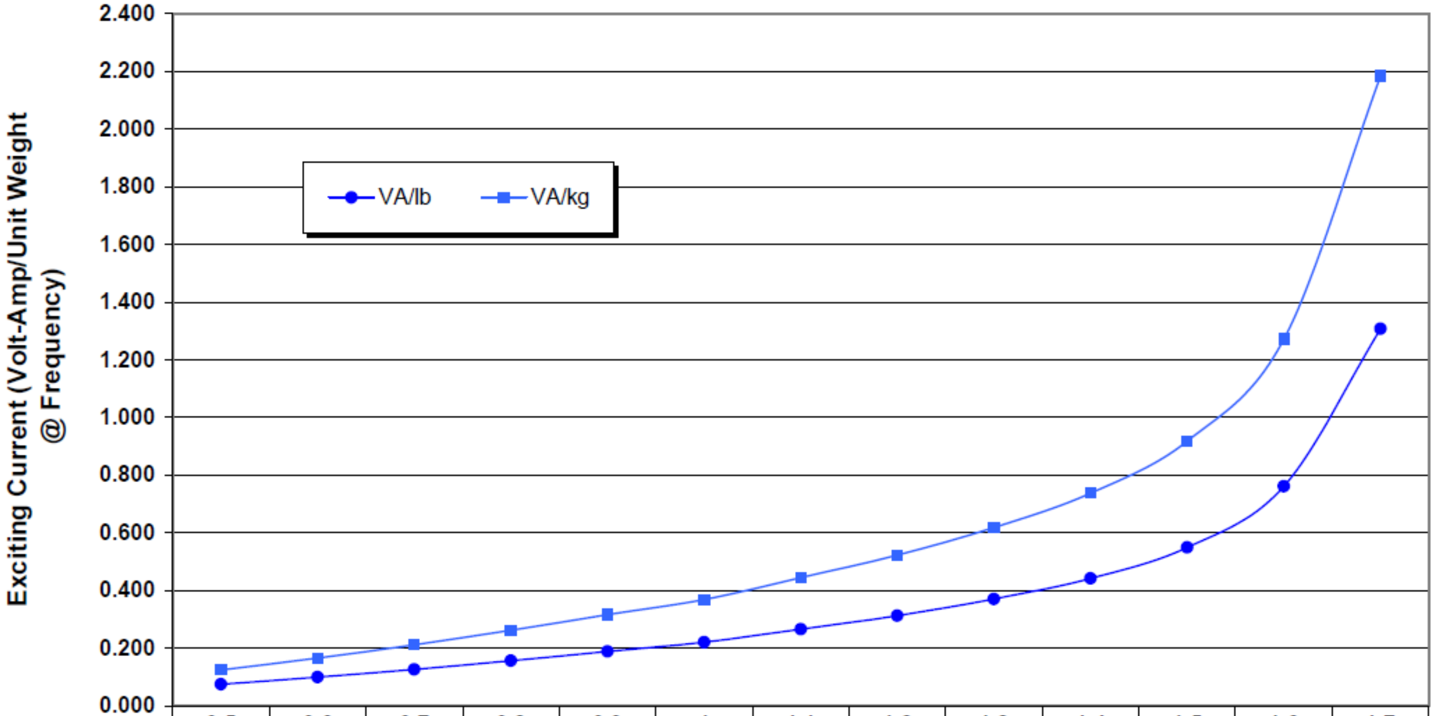
	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9
● W/lb	0.042	0.060	0.080	0.106	0.134	0.166	0.202	0.241	0.284	0.332	0.395	0.480	0.604	0.800	1.070
■ W/kg	0.069	0.101	0.134	0.177	0.224	0.278	0.337	0.403	0.475	0.554	0.660	0.801	1.009		

Induction (Tesla)

Transformer Design Data

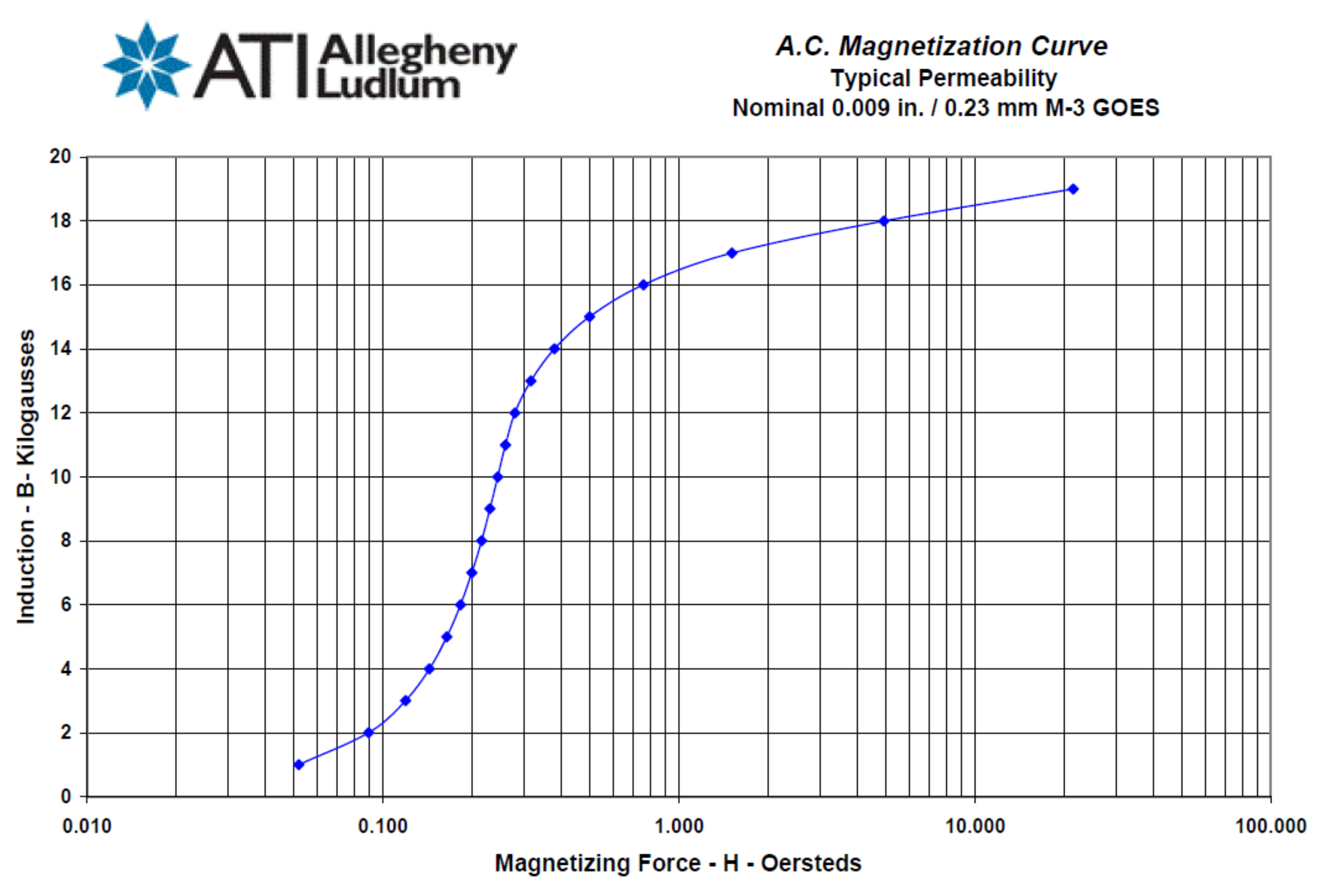
Nominal 0.009 in. / 0.23 mm M-3 GOES

Typical Apparent Loss (VA/lb. at 60 Hertz) and (VA/kg at 50 Hertz)



	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5	1.6	1.7
● VA/lb	0.075	0.100	0.127	0.157	0.190	0.221	0.266	0.313	0.371	0.442	0.550	0.762	1.308
■ VA/kg	0.125	0.167	0.212	0.263	0.316	0.369	0.445	0.523	0.619	0.738	0.919	1.272	2.185

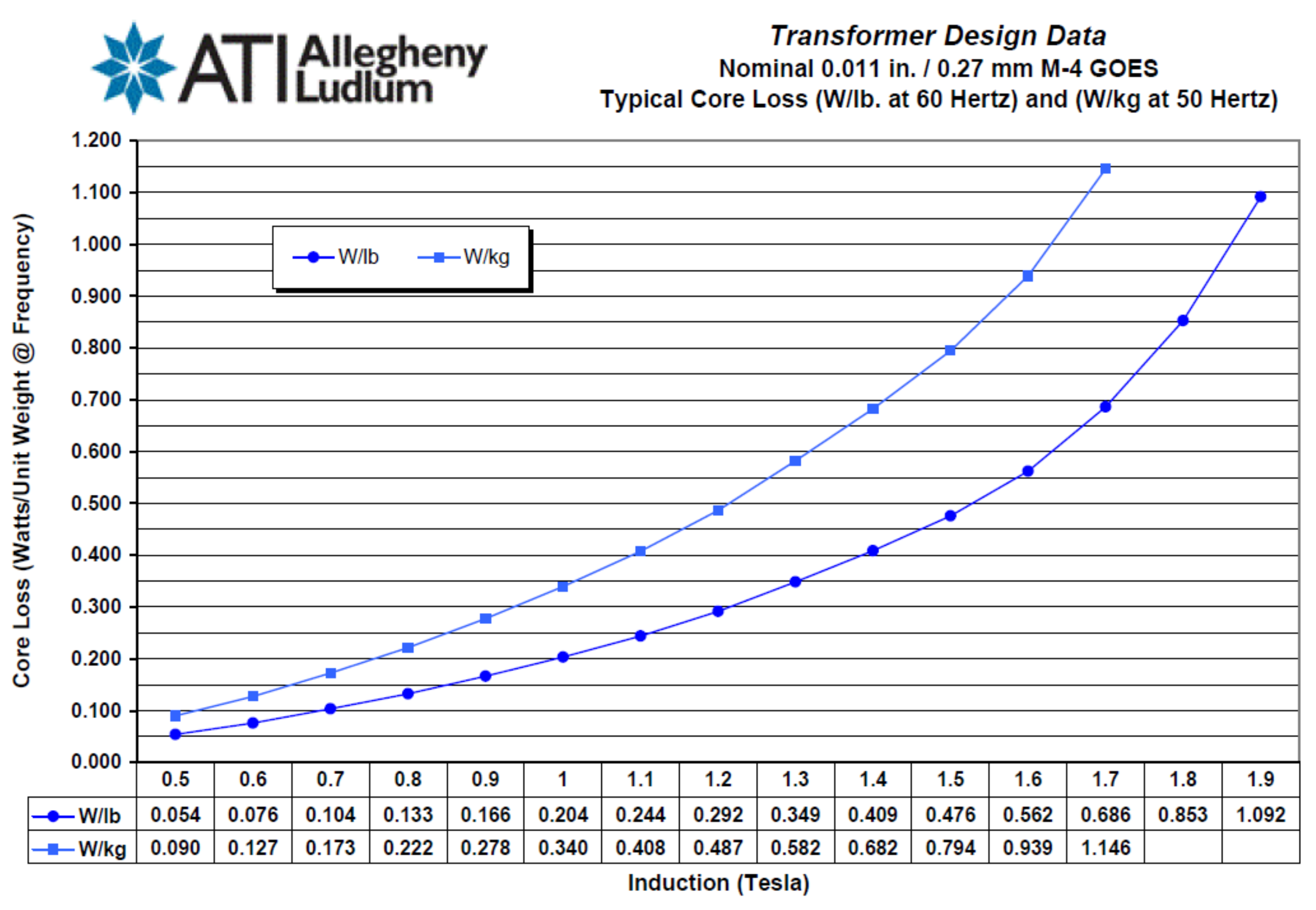
Induction (Tesla)



A.C. Magnetization Curve

Typical Permeability

Nominal 0.009 in. / 0.23 mm M-3 GOES



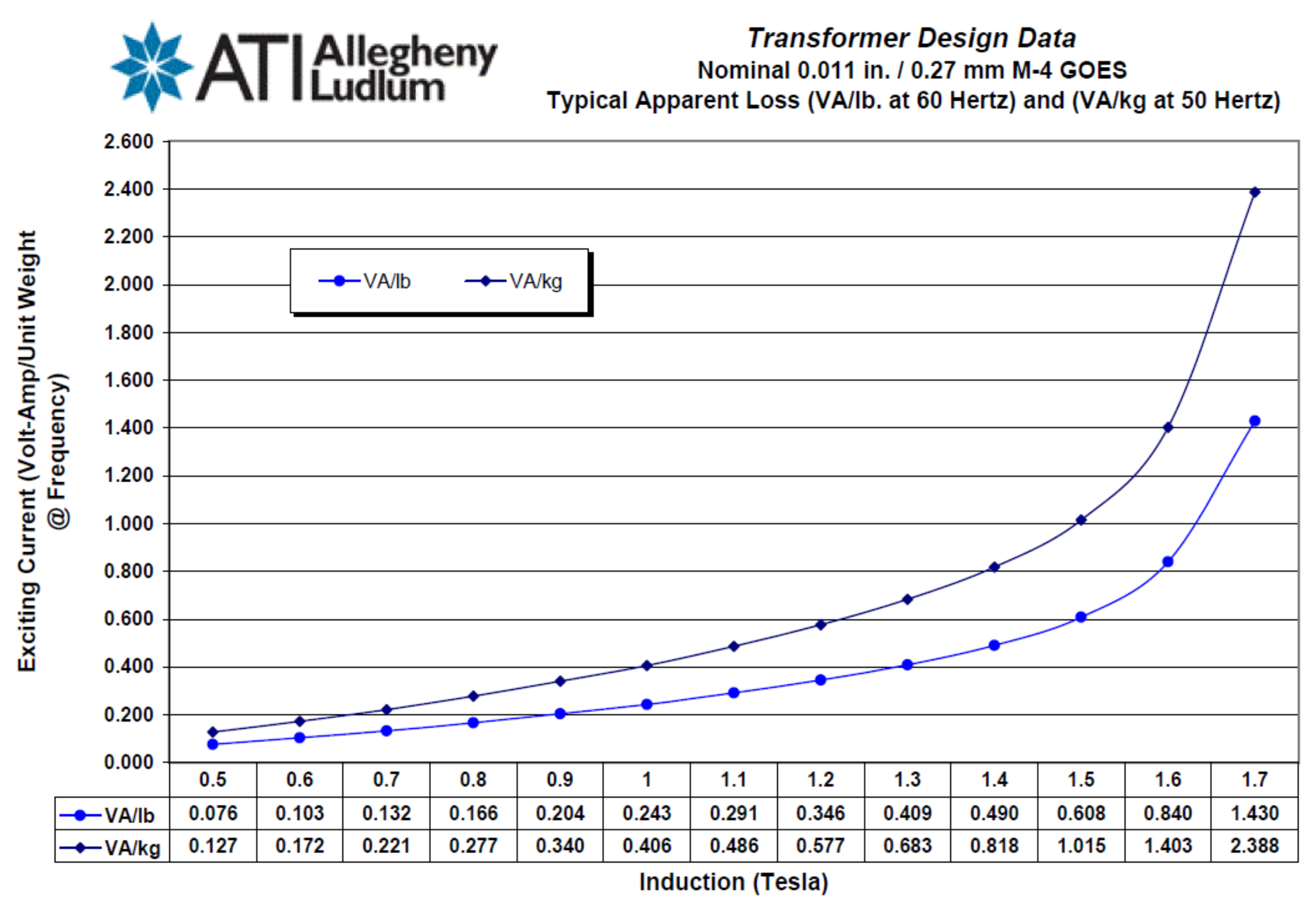
Transformer Design Data

Nominal 0.011 in. / 0.27 mm M-4 GOES

Typical Core Loss (W/lb. at 60 Hertz) and (W/kg at 50 Hertz)

	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9
W/lb	0.054	0.076	0.104	0.133	0.166	0.204	0.244	0.292	0.349	0.409	0.476	0.562	0.686	0.853	1.092
W/kg	0.090	0.127	0.173	0.222	0.278	0.340	0.408	0.487	0.582	0.682	0.794	0.939	1.146		

Induction (Tesla)



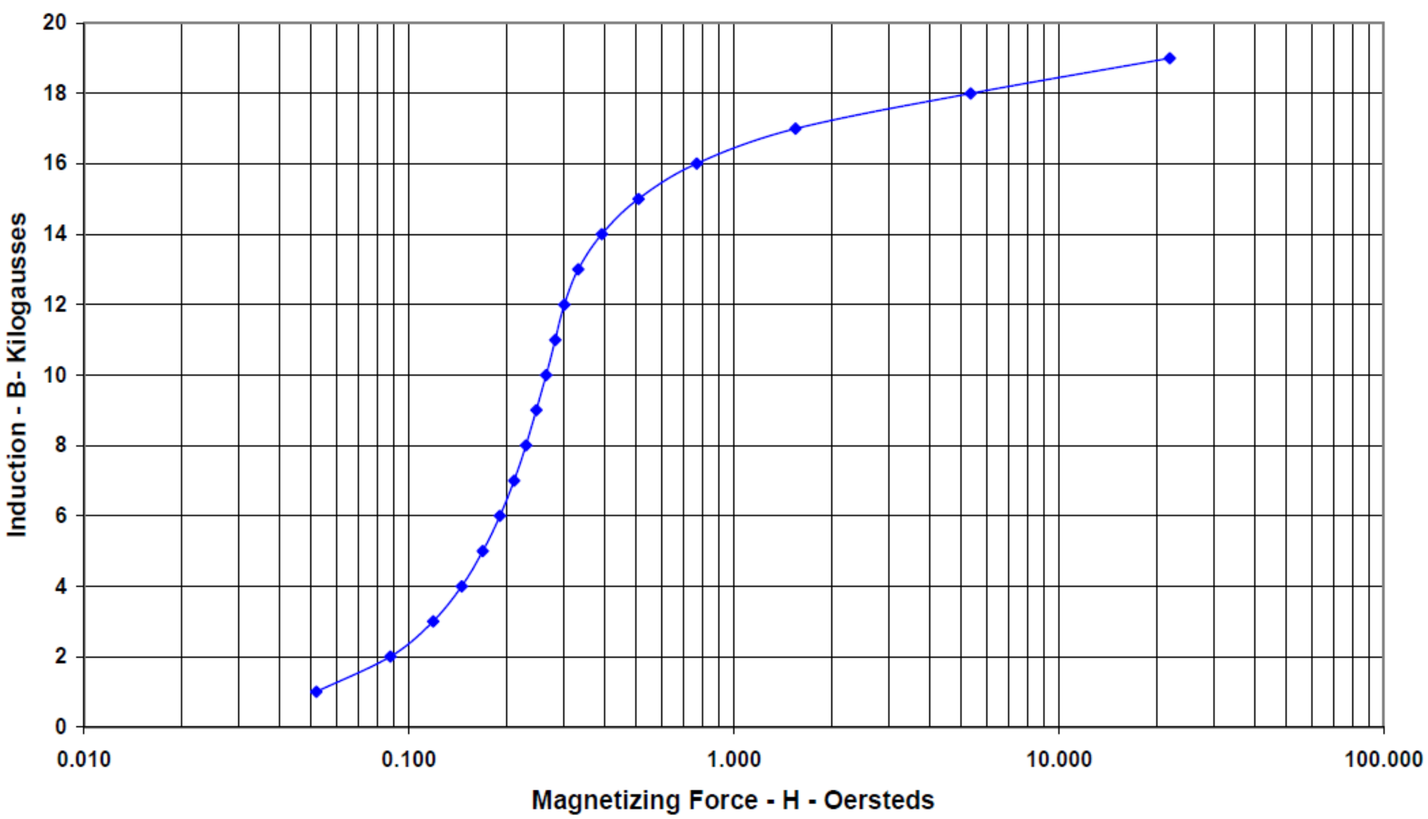
Transformer Design Data

Nominal 0.011 in. / 0.27 mm M-4 GOES

Typical Apparent Loss (VA/lb. at 60 Hertz) and (VA/kg at 50 Hertz)

	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5	1.6	1.7
VA/lb	0.076	0.103	0.132	0.166	0.204	0.243	0.291	0.346	0.409	0.490	0.608	0.840	1.430
VA/kg	0.127	0.172	0.221	0.277	0.340	0.406	0.486	0.577	0.683	0.818	1.015	1.403	2.388

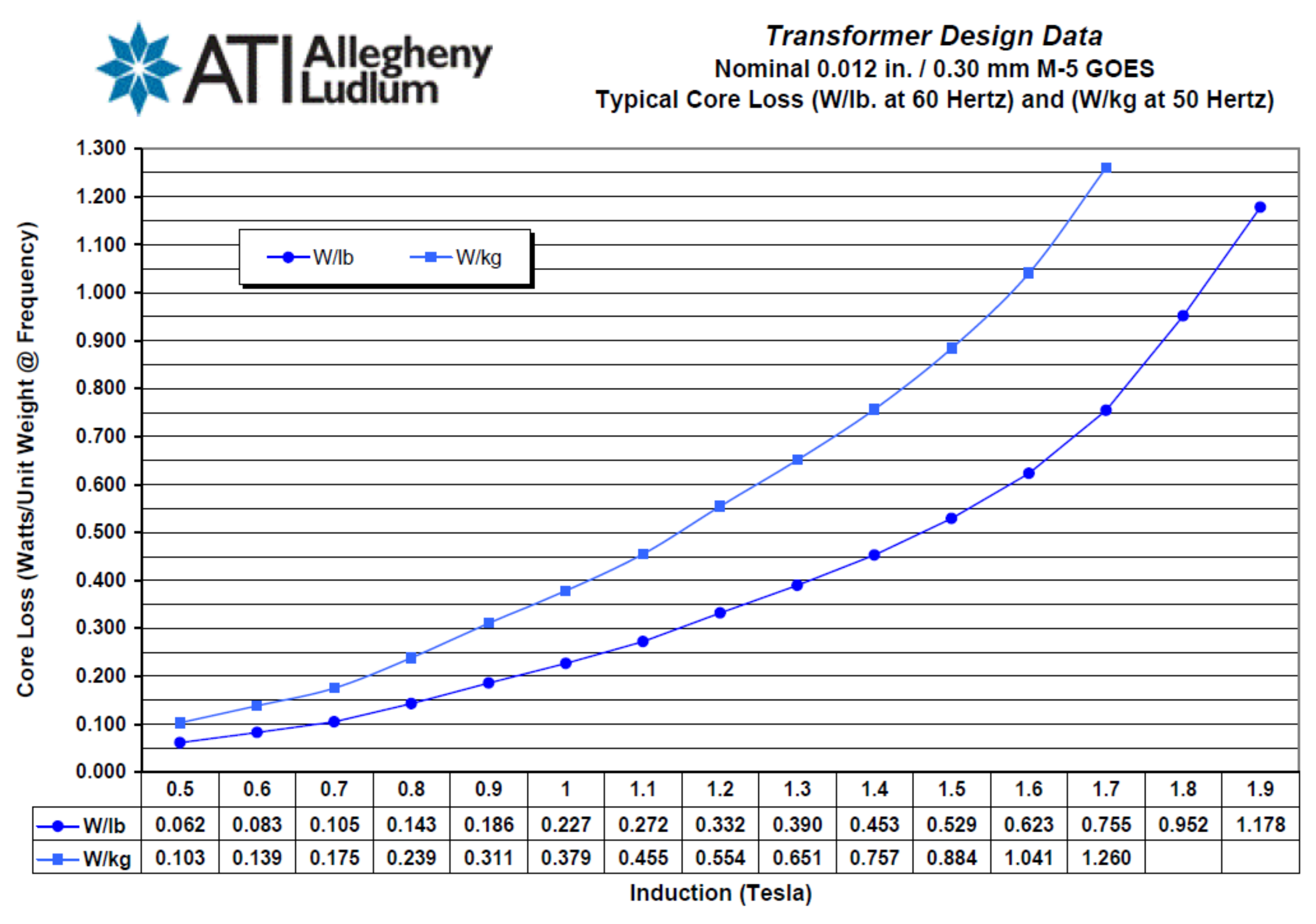
Induction (Tesla)



A.C. Magnetization Curve

Typical Permeability

Nominal 0.011 in. / 0.27 mm M-4 GOES



Transformer Design Data

Nominal 0.012 in. / 0.30 mm M-5 GOES

Typical Core Loss (W/lb. at 60 Hertz) and (W/kg at 50 Hertz)

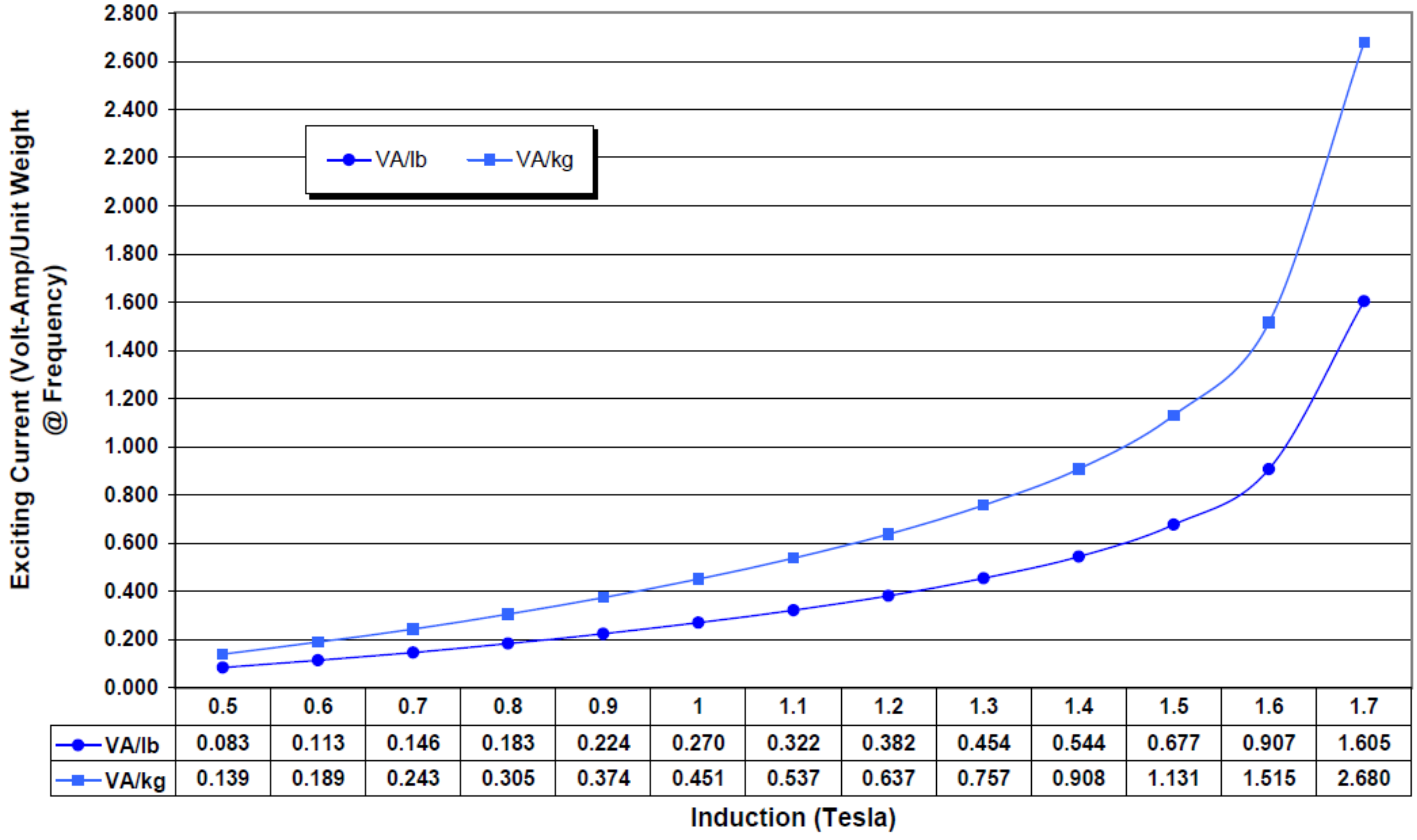
	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9
W/lb	0.062	0.083	0.105	0.143	0.186	0.227	0.272	0.332	0.390	0.453	0.529	0.623	0.755	0.952	1.178
W/kg	0.103	0.139	0.175	0.239	0.311	0.379	0.455	0.554	0.651	0.757	0.884	1.041	1.260		

Induction (Tesla)

ATI Allegheny Ludlum

Transformer Design Data

Nominal 0.012 in. / 0.30 mm M-5 GOES
Typical Apparent Loss (VA/lb. at 60 Hertz) and VA/kg at 50 Hertz)

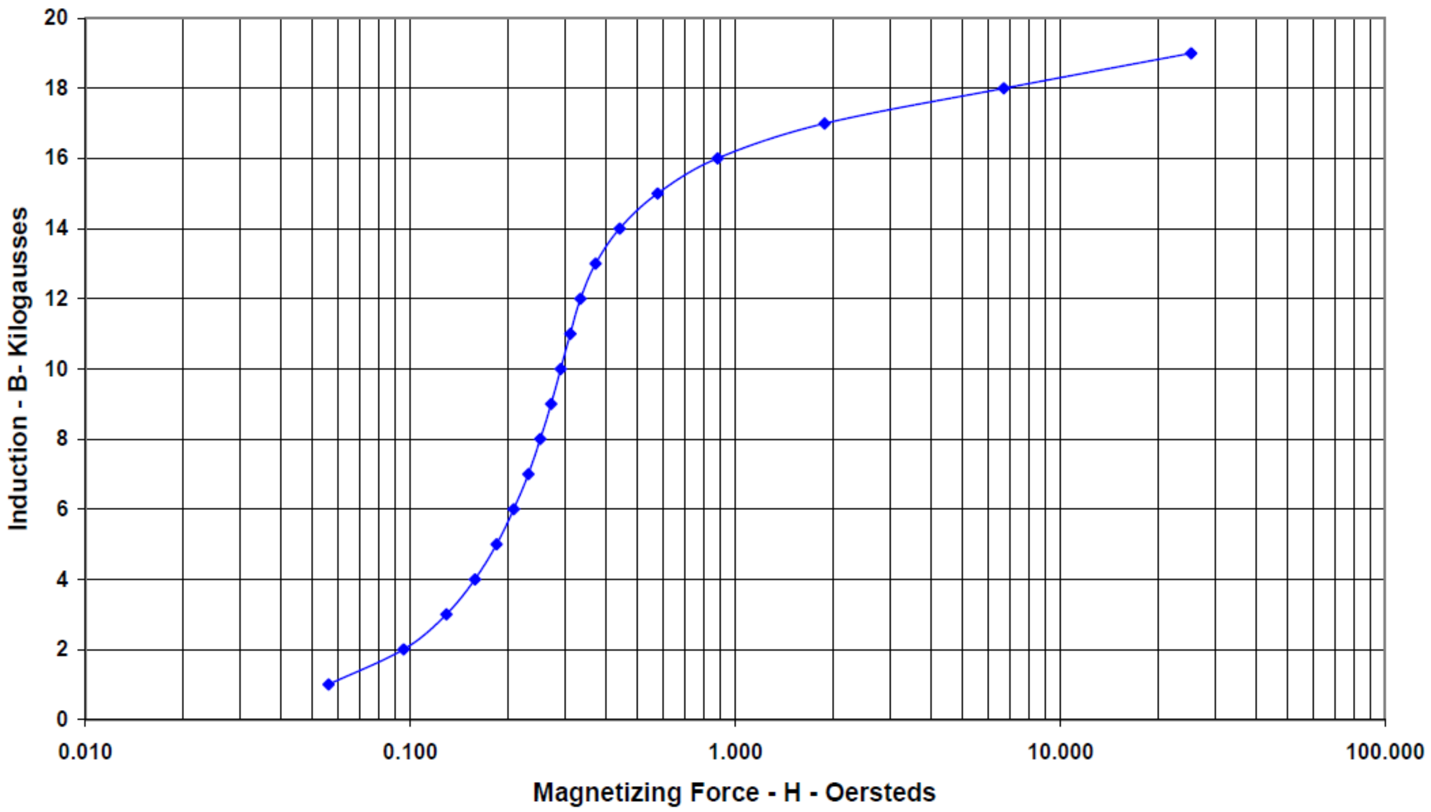


	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5	1.6	1.7
VA/lb	0.083	0.113	0.146	0.183	0.224	0.270	0.322	0.382	0.454	0.544	0.677	0.907	1.605
VA/kg	0.139	0.189	0.243	0.305	0.374	0.451	0.537	0.637	0.757	0.908	1.131	1.515	2.680

A.C. Magnetization Curve

Typical Permeability

Nominal 0.012 in. / 0.30 mm M-5 GOES

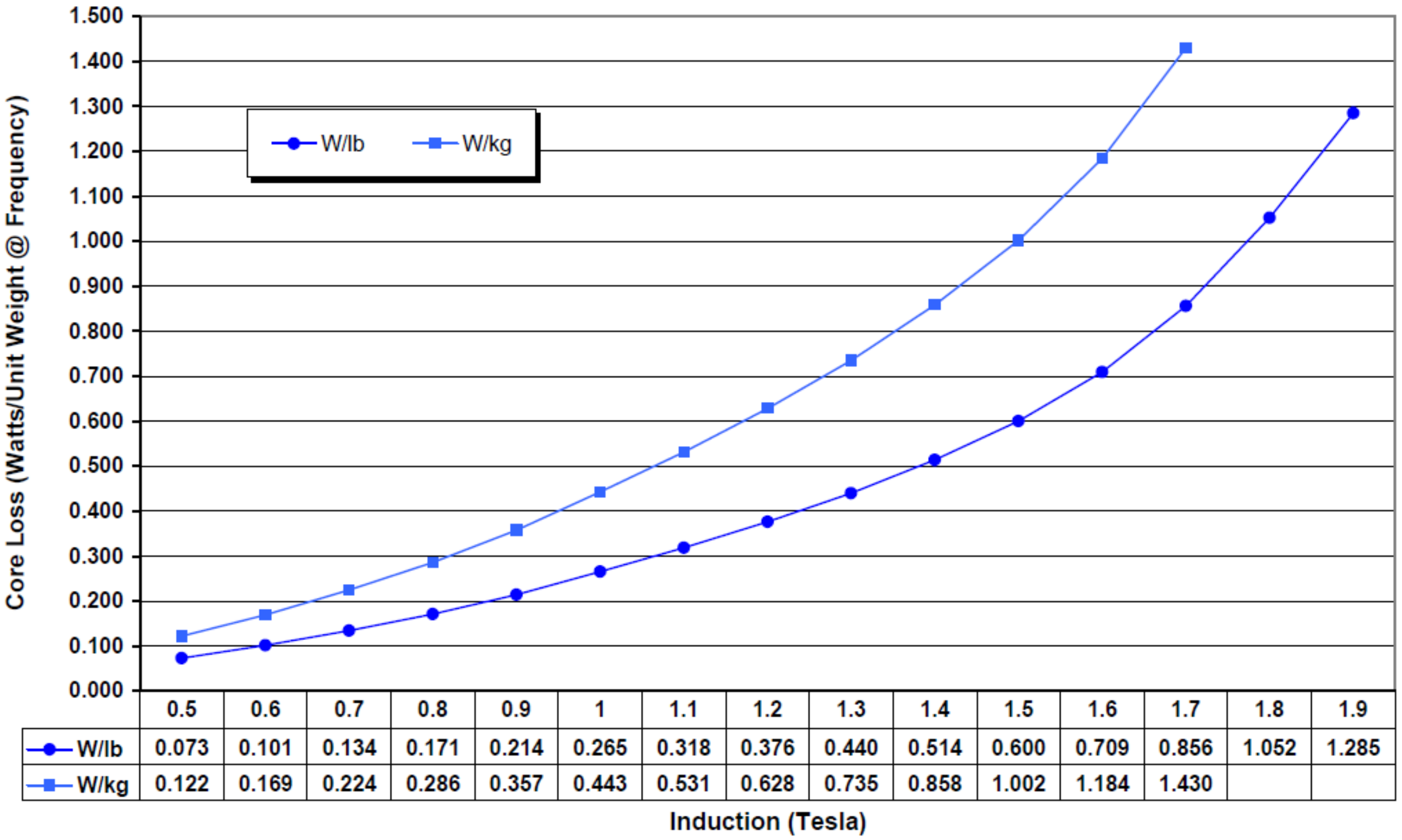


ATI Allegheny Ludlum

Transformer Design Data

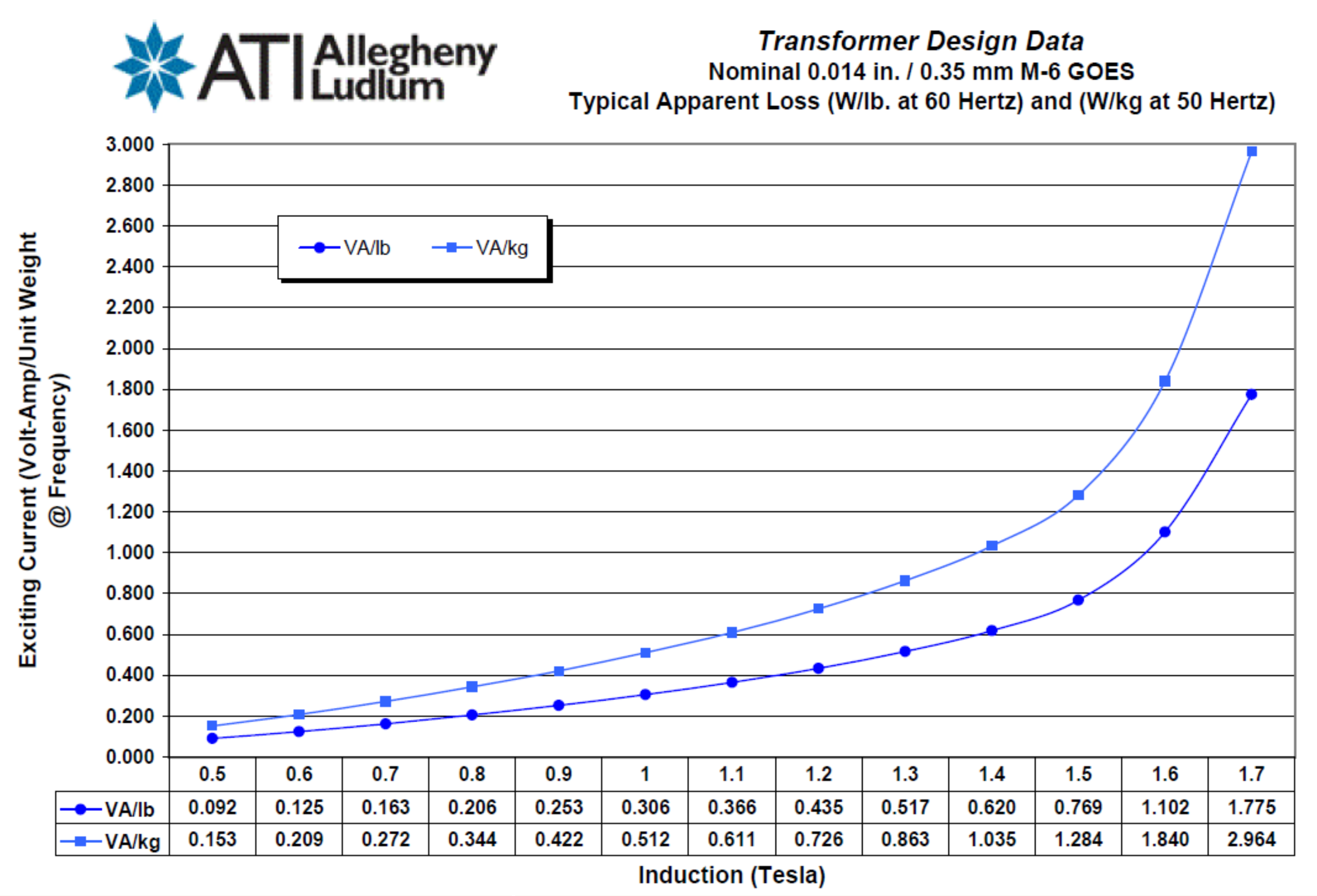
Nominal 0.014 in. / 0.35 mm M-6 GOES

Typical Core Loss (W/lb. at 60 Hertz) and W/kg at 50 Hertz)



	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9
● W/lb	0.073	0.101	0.134	0.171	0.214	0.265	0.318	0.376	0.440	0.514	0.600	0.709	0.856	1.052	1.285
■ W/kg	0.122	0.169	0.224	0.286	0.357	0.443	0.531	0.628	0.735	0.858	1.002	1.184	1.430		

Induction (Tesla)



Transformer Design Data

Nominal 0.014 in. / 0.35 mm M-6 GOES

Typical Apparent Loss (W/lb. at 60 Hertz) and (W/kg at 50 Hertz)

	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5	1.6	1.7
VA/lb	0.092	0.125	0.163	0.206	0.253	0.306	0.366	0.435	0.517	0.620	0.769	1.102	1.775
VA/kg	0.153	0.209	0.272	0.344	0.422	0.512	0.611	0.726	0.863	1.035	1.284	1.840	2.964

A.C. Magnetization Curve

Typical Permeability

Nominal 0.014 in. / 0.35 mm M-6 GOES